Risk analysis and a study of risk awareness and risk communication at LEAF Gävle concerning dust explosions

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Abstract
The purpose of this report is to study the risk of dust explosions at the candy manufacturing plant Leaf Sverige in Gävle, Sweden. The risk analysis was conducted with a preliminary hazard analysis, PHA and event trees. The analysis focuses only on the risk posed to employees and material damages at the plant. No third person injuries have been considered. Another purpose of this report is to study risk awareness and risk communication concerning dust explosions. The awareness study was conducted with a questionnaire. The communication part of this report was done by a literature study and focuses on communication from management to employees. A communication model specific to dust explosion awareness and risk information to staff at dust handling plants is also presented.

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Summary

Dust explosions are a relatively unknown phenomenon, both among laymen and scientists. The scientific maturity of this science field is relatively low. This report is a study of dust explosions at Leaf Sverige´s candy manufacturing facility in Gävle, Sweden. The study and this report are divided into three different yet intertwined parts. The first part consists of an analysis of the risk of dust explosions in the factory. The second part is a study of the employees and their level of awareness of the risk of dust explosions; questionnaires were used to obtain this information. The third and final part consists of the construction of a communication model, specially designed to communicate the risk of dust explosions between management and employees at dust handling plants.

The risk analysis was initiated with a traditional Preliminary Hazard Analysis, PHA. The PHA was conducted with a thorough walkthrough of all the dry powder systems at the plant. The result of the analysis is presented in two different risk matrixes: one for health and one for economic damages. From these two matrixes the most severe scenarios were selected. These scenarios were then quantified with the help of event trees and the calculation of dust explosion frequencies and consequences.

An uncertainty analysis was conducted on the quantified values, and it turned out that the uncertainty was very large. Calculating the frequency of dust explosions produced a large amount of uncertainties. The uncertainty was so large that the values could not be used in the risk assessment or to recommend actions. The rank of the different scenarios in the uncertainty analysis, from most to least risk, was nearly the same as in the PHA.
The recommended actions are based on the PHA and are thereby subjective to the author of this report.

The survey was conducted on two different groups in the factory, namely the operators and the maintenance crew. The results were fairly clear-cut; it was easy to conclude that the dust explosion awareness is very low among the employees. The maintenance crew showed a bit higher knowledge concerning dust explosions than the operators, but the awareness of both groups must be considered too low to guarantee a safe labour concerning dust explosions.

The last and final part of this report was initiated with a literature study of risk communication. It turned out that most literature on the subject is for the communication between authorities and companies to a broad public, not communication within a company. Parts of the different communication models and research were, however, judged to be usable for dust explosion risk communication within a company. A communication model was created for this purpose. The three most important parts in this model are:

- The introduction of an agent
- The introduction of goal lists and checklists
- The reporting culture

The agent is a coordinator; he or she must coordinate the reporting of accidents, damages and incidents. The agent should also make sure that employees report as much as possible. Finally, the agent should also make sure that everyone at Leaf International learns from accidents, damages and incidents.

Using goal lists and checklists is a way of dealing with the uncertainties that were found after conducting the risk analysis. Determining the amount of the risk is virtually impossible and therefore companies should improve safety by using goal lists. There are long-term goals for improved safety, and each piece of dry powder process equipment has a specific list associated with it. The list is in bulleted form and states the correct way to construct and maintain each piece of process equipment.

A good reporting culture is closely linked with a good learning culture and is a condition for the agent to be able to do his job correctly. As much as possible should be reported. For this to be possible the management must encourage the employees to report incidents and accidents; as well as inform them as to why it is so important to report everything. A seemingly unimportant incident might, in a larger perspective, be of great importance. It is the agent's job to see this big picture and recognize the possible significance of the incident. .

Sammanfattning

Dammexplosioner är ett ganska okänt fenomen, både bland lekmän och forskare. Den vetenskapliga mognadsgraden för detta forskningsområde är relativt låg. Denna rapport är en studie av dammexplosioner på Leaf Sveriges godisfabrik i Gävle. Rapporten och studien är uppdelad i tre olika men ändå sammanlänkade delar. Den första delen är en riskanalys av dammexplosionsrisken i fabriken. Den andra delen är en enkätundersökning av riskmedvetenheten om dammexplosioner hos de anställda på fabriken. Den tredje och avslutande delen är framtagandet av en kommunikationsmodell, speciellt framtagen för att kommunicera dammexplosionsrisker mellan ledning och anställda på dammhanterande fabriker.

Riskanalysen inleddes med en traditionell grovanalys. Grovanalysen genomfördes genom en grundlig genomgång av alla torra pulversystem på fabriken. Resultatet av analysen presenterades i två riskmatriser, en för ekonomisk skada och en för skador på människor. Ur riskmatriserna plockades de värsta scenarierna, eller rättare sagt de som bidrog mest till den totala risken. Dessa scenarier genomgick en kvantifiering med hjälp av händelseträd och beräkning av dammexplosionsfrekvens och konsekvenser.

En osäkerhetsanalys genomfördes på de kvantifierade värdena och det visade sig att osäkerheten var mycket stor. Detta gällde särskilt beräkningen av dammexplosionsfrekvensen. Osäkerheten var så stor att värdena inte kan användas i en riskbedömning eller för att rekommendera åtgärder. Rangordningen av de beräknade värdena för de olika scenarierna stämmer dock ganska väl överens med bedömningarna i grovanalysen. De rekommenderade åtgärderna baseras därför på grovanalysen och är därmed subjektiva.

Enkätundersökningen gjordes på två olika grupper i fabriken, dels på underhållsarbetarna, dels på operatörer/maskinister. Resultaten var ganska entydiga i att kunskaperna och medvetenheten om dammexplosioner är mycket låg. Underhållsarbetarna visade lite högre medvetenhet än operatörerna men båda gruppernas medvetenhet måste anses vara för låg för att ett säkert arbete med avseende på dammexplosionsrisken skall kunna garanteras.

Den sista och avslutande delen inleddes med en litteraturstudie av riskkommunikation. Det visade sig att det mesta som finns skrivet om riskkommunikation syftar till att kommunicera risker från myndigheter eller företag till en bred allmänhet, alltså inte kommunikation inom företaget. Delar av olika kommunikationsmodeller och kommunikationsforskning bedömdes ändå kunna användas vid internkommunikation av dammexplosionsrisken. En kommunikationsmodell togs fram. De tre viktigaste delarna i denna är:

- Införandet av en agent
- Införandet av mållistor och checklistor
- Rapporterandekulturen

Agenten skall fungera som en spindel i kommunikationsnätet. Han eller hon skall samordna rapporterandet av olyckor, skador och incidenter. Agenten skall även se till att så mycket som möjligt rapporteras. Till slut skall agenten även se till att lärdomar av olyckor, skador och incidenter komma de anställda på Leafs alla fabriker tillgodo.

Mållistor och checklistor är ett sätt att ta itu med den osäkra risken från riskanalysen. Det går inte att säga hur stor risken är därför skall säkerheten förbättras med mållistor. Detta är långsiktiga mål och innehåller i punktform det optimala sättet att konstruera och underhålla en viss typ av processutrustning.

En god rapporterandekultur är nära sammanlänkad med en god lärandekultur och är en förutsättning för agentens arbete. Så mycket som möjligt skall rapporteras och för att detta

skall bli möjligt måste de anställda dels uppmuntras till att rapportera incidenter och olyckor dels informeras om varför det är så viktigt att de skall rapportera. En tillsynes obetydlig incident kan i ett större sammanhang, som agent kan se, vara av stor betydelse.

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1 Introduction

1.1 Background

1.1.1 LEAF

Leaf Sverige AB is a company in the sugar confectionary manufacturing industry. Until May 2005 the company name was MalacoLeaf AB after which a transfer of ownership changed the name to Leaf Sverige. Leaf Sverige is a part of Leaf International that is owned by CVC Capital partners and Nordic capital with 15 factories in Europe. Foam candy and pastilles are the two most produced products by Leaf Sverige, but they also produce toffee and soft jelly candy. The two most well known products are Ahlgrens bilar and Läkerol.

The plant in Gävle was built by Fredrik Ahlgren in 1895 and the company was named *Firma F. Ahlgren*. Originally, it was a chemical and technical production company producing perfume and ink among other products. During the past century, the plant has specialized in candy manufacturing. At present time, the plant produces about 10,000 tonnes of candy annually from a production schedule of 24 hours a day, about six days a week.

The initiative for this report was taken by Leaf Sverige hence they saw a lack of dust explosion knowledge at the company.

1.1.2 Dust explosions

Dust explosions have been a known phenomenon for several centuries. One of the first documented dust explosions occurred in Italy in 1785. The explosion took place in a flour storage area at a bakery [1].

Even though dust explosions have been known for over two hundred years the maturity of this science field is low and the available statistics are, at best, poor. Very few countries keep specific statistics on dust explosions, hence the lack of statistical data [2].

Even in countries that do keep statistics on dust explosions, far from all dust explosion incidents are documented. In former West Germany, 357 dust explosions were reported between 1965 and 1980. This number has been estimated to be only 15% of the actual number of dust explosions. Factoring in the unreported 85% would make the actual number of dust explosions during these 15 years total about 2400 [1].

A study in the Netherlands indicated that approximately one dust explosion occurs every week in the country [2]. Other sources estimate the average frequency of a dust explosion in a manufacturing facility to be one in 20 years [3].

Dust explosions occur in a number of different industries, such as: wood, food processing and coal mining. In fact, dust explosions can occur in any industry that handles significant amounts of flammable dusts and powders.

Lack of awareness and knowledge is a significant problem in preventing dust explosions in processing industries. Most industries that handle flammable dusts are not aware of the dust explosion risk. Because of this they have not taken any measures to prevent or limit the consequences of a dust explosion [4].

One of the most well known dust explosions in Sweden happened in a wheat silo at Nord Mills in Malmö. No one was injured during this explosion but the material damage was extensive [1]. Another dust explosion occurred in November 2004 in the Cloetta chocolate factory in Norrköping, Sweden. This explosion happened in a filter attached to a moulding machine and resulted in two minor injuries. The ignition source was a worn down electrical cord that caused a spark discharge[6].

1.2 Objectives

This project consists of two parts:

1. A risk analysis of the Leaf factory in Gävle where an assessment of the risk of dust explosions will be performed. The results from the risk analysis will then be used to recommend measures to be taken to ensure an appropriate dust explosion risk level for the plant.

2. How to increase the awareness of dust explosions among the staff and how management can best communicate the risk to the staff. The following questions will be discussed: If risk awareness is low, how does that affect safety in the factory? How should management communicate the risk of dust explosions to their employees?

The results of this report are supposed to help Leaf increase its safety in Gävle through making staff aware of the dust explosion risk in the factory. The purpose is also to help Leaf and other companies in the food processing industry, and other industries that handle large quantities of flammable dust, to communicate the risk of dust explosions to their employees.

1.3 Methodology

The work was initiated by a literature study. This was followed by a three week site visit where data was collected and a preliminary hazard analysis was conducted. During the site visit a risk awareness survey was also conducted among the employees. After the visit to the plant further literature research on dust explosions and communication was conducted and an event tree analysis was performed. Consequence calculations and frequency estimations were performed. The event trees gave a quantitative estimation of the dust explosion risk at the plant. This risk was assessed and preventive actions were recommended to lessen the risk.

The choice of risk analysis methods was not an obvious choice. The research field of dust explosions is a relatively unexplored one. There are no obvious and widely used methods to analyse the risk of dust explosions. The preliminary hazard analysis was chosen because of its simplicity and because it seemed to fit the risk situation at the plant. The event tree method was chosen because of the complexity of dust explosions. An explosion can happen in a number of different ways and with a wide range of consequences, therefore the event tree methodology seemed fitting.

The results from the survey were analysed and compiled. The literature study of risk communication together with the results from the awareness survey then formed the basis for a communication model on the risk of dust explosions in food processing industries to employees.

1.4 Limitations

This report is limited to dust explosions; hence no other risks are discussed. Only the risk for employees and material damage due to dust explosions at Leaf Gävle are addressed. This means that no environmental, nor risks for third person injuries or damage will be discussed.

1.5 Disposition of report

The report is divided into two main parts: the first is the dust explosion risk analysis and the second part is the risk awareness and risk communication.

Chapter 2 is a basic introduction to dust explosions, their causes and how to prevent them. Chapter 3 describes the factory, the dry powder system and the different dusts used at the plant.

Chapters 4 through 7 include the actual risk analysis. The PHA and the event tree calculations are described in these chapters, as are the risk assessment and recommended actions.

Chapter 8 describes and discusses the dust explosion awareness survey. Chapter 9 discusses risk communication and chapter 10 provides a communication model for the communication of the dust explosion risk.

There are also several appendices in the end of this report where used values and assumptions, calculation methods and other important background information are listed and explained.

The opinions and thoughts of the author are present throughout the report in discussion chapters. Because it is necessary to continuously discuss and present opinions to be able to create a communication model, chapters 9 and 10 also contain opinions from the author. The opinions could have, of course, been presented in a discussion section as in the previous chapters, but this would have interrupted the reading flow, making it harder to read and understand.

2 Dust explosions

This chapter provides basic knowledge of dust explosions such as how they can occur and what parameters affect the consequence as well as the probability of a dust explosion.

First of all it is necessary to define what a dust explosion actually is. Below are two definitions of dust explosions found in different literature:

"…it is usually the rapid chemical oxidation of dust particles dispersed in the air that leads to a rapid energy release which increase the temperature of the system so rapidly that a pressure increase follows." [7]

"…small particles of sizes on the order of 0.1 mm or less and the particles are suspended in a sufficiently large volume of air to give each particle enough space for its unrestricted burning, the combustion rate is very fast and the energy required for ignition very small. Such a burning dust cloud is a dust explosion." [1]

2.1 The basic requirements for a dust explosion

There are five basic requirements that have to be met for a dust explosion to take place. These requirements are presented in Figure 1 in the Explosion Pentagon [8]

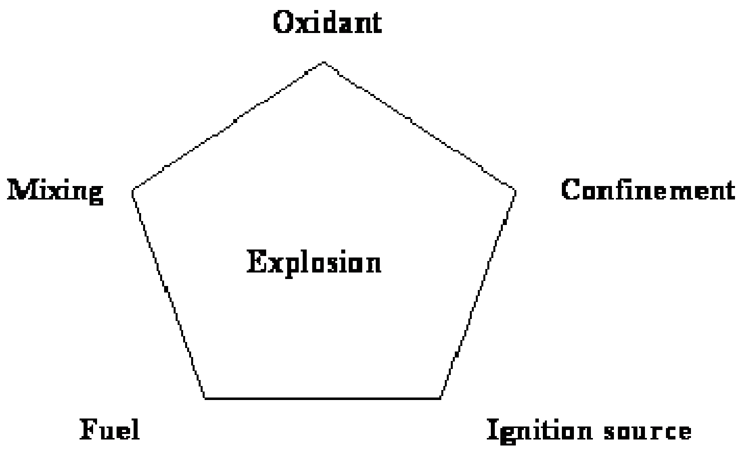

Figure 1. The explosion Pentagon [8]

The five factors that have to be present for a dust explosion to occur are: *oxidant*, *confinement*, *ignition source*, *fuel* and *mixing*.

When an explosion occurs in air, oxygen acts as the oxidant. Confinement or at least partial confinement [12] is required for a pressure wave to form. An ignition source is required to initiate the combustion. Fuel is, in the case of dust explosions, combustible powders such as organic, metal or plastic dusts. The mixing between air and fuel is required to give the separate particles "unrestricted burning". [1]

2.2 Flammability Limits

The explosion limits for dusts are in the magnitude between 100 g to 5000 g/m^3 of air for the lower explosion limit, LEL, and upper explosion limit, UEL. The limits are, however, very dependant on particle size and other factors affecting the explosion tendencies. These values are well above the industrial hygiene limits of particles in air which are in the magnitude between 0.01 and 0.001 g/m^3. In the dust explosion range concentration visibility is very low. As an example, you can hardly see a 25 W light bulb from a distance of 2 m if the air contains 40 g/m^3 of coal dust. Initial dust explosions require high concentrations, and therefore usually occur in process equipment where high concentrations often reside. [1]

Secondary explosions can, however, occur outside of process equipment, see chapter 2.5 for a discussion on secondary explosions.

2.3 Ignition sources

Five main ignition sources typically ignite dust clouds:

- Smouldering or burning dust/nests
- Flames
- Hot surfaces
- Heat from mechanical impacts
- Electrical discharges

Dust deposits or bulk stored dust can ignite from a number of different sources such as, hot surfaces, auto ignition due to microbiological activity and open flames. A burning or glowing nest can glow for a long time with only a very limited supply of oxygen. If a glowing nest then is transported in process equipment with high turbulence, such as pneumatic conveying systems or hoppers, the glowing dust is dispersed in air and an explosion can occur. [1]

Open flames can occur in processing industries during welding and cutting or from the use of matches or due to an initial fire somewhere in the plant. An open flame contains a lot more energy than what is required to initiate a dust explosion. [1]

Hot surfaces can normally occur in processes such as in dryers or due to mechanical wear and instability of machines. Hot surfaces can ignite both dust deposits and dust clouds. A hot surface requires a temperature in the magnitude of 400-500 ºC to ignite a dust cloud. Considerably lower temperatures can ignite dust deposits because of the isolating effect of dust layers. The ignition temperature depends on the thickness of the layer, the length of time the dust is exposed to the heat and the chemical composition of the dust. [1]

Mechanical impact can create heat, for example when a metal hits metal with high speed. This can create sparks with enough energy to cause a dust explosion.

Electrical sparks can come from broken electrical wires or appliances or simply from static electricity. In dust handling situations, static electricity is created when dust is transported in pneumatic conveying systems, hoppers and other process equipment where the dust rubs against a surface and electrical charges are exchanged between the powder and the surface. This creates an electrical potential difference. The difference can be equalized through an electric spark jumping between the surfaces. This spark can contain enough energy to initiate a dust explosion. Dusts can ignite from about 10 mJ of electrical energy and upwards depending on the present dust. For example, with this value being as low as it is, a human can accumulate static electricity to cause a spark of about 100 mJ, a road tanker about 450 mJ and a 200 litre drum over 100 mJ. [1]

2.4 Factors affecting the ignitability and the explosion effects

Many factors affect the potential for a dust explosion and the magnitude of a dust explosion:

- The chemistry of the dust
- Particle size

- Concentration
- Turbulence
- Initial temperature of dust cloud
- Initial pressure
- Hybrid mixtures
- Oxygen level

There are many types of dusts, each of which has a different tendency to explode, and the resulting explosion violence varies from dust to dust. This is because of the chemistry of each dust type; they burn with different speeds, give different heat releases and ignite at different energy levels. This results in different explosion pressures and violence for each dust type. [1]

Much literature ascribes the particle size distribution as most important when it comes to explosion probability and violence. Particles smaller than about 0.4 mm can take part in a dust explosion [9]. With few exceptions the smaller the particle size distribution in the dust the easier it is to ignite and the more violent the explosion will be. [1]

Depending on the concentration of dust in the air, the dust may ignite more or less easily, and the explosion power will be different. There is an optimal mixture of dust and air, somewhere between the LEL and the UEL, that will cause maximum explosion power. [7]

Turbulence, as in a pneumatic conveying system, increases the burning speed and, because of that, the explosion power. The turbulence mixes the burning particles with the unburned particles, increasing the burning speed. On the other hand, turbulence makes ignition more difficult. In this case the turbulence disturbs the heat transfer through the increased convection. [7]

If the initial temperature in a dust cloud is high, the minimum required dust concentration to cause a dust explosion is less than under normal conditions. The minimum required ignition energy is also lower than under normal conditions. On the other hand, an increased initial temperature lessens the explosion violence, i.e. the maximum pressure and pressure rise speed. This is because with a higher temperature the oxygen concentration per unit volume decreases. [1] [7]

Increased initial pressure affects the explosion violence a lot, both maximum pressure and pressure rise speed. The effect is in the magnitude of doubled maximum pressure with doubled initial pressure. [1] [7]

Hybrid mixtures and oxygen level has little relevance to Leaf Gävle. A hybrid mixture means, somewhat simplified, that a mixture of flammable gas and flammable dust causes more violent explosions than the sum of the two components. [1]

Oxygen level is a way of preventing dust explosions; less oxygen equals less explosion power. [1]

2.5 Secondary explosions

As mentioned before, most dust explosions occur within process equipment. There can, however, be a secondary explosion outside of process equipment, and this secondary explosion is often the most devastating. When the initial explosion happens, heat and a pressure wave are created. If there are dust deposits present in the premises the pressure wave from the initial explosion can disperse the deposits and dust clouds are formed. These clouds can then be ignited by the flame from the initial explosion. [1]

The secondary explosion is often very violent because there is usually a lot of turbulence present which increases the burning speed. The secondary explosion is the cause of most building collapses due to dust explosions.

A conservative rule of thumb is that if you can write with your finger in the dust deposit it could propagate an explosion [10]. A 1 mm thick layer of dust with a density of 500 kg/m^3 on the floor can, if dispersed, form a dust cloud with a density of 100 g/m^3 in an entire room with a ceiling height of 5 meters. These 100 g/m^3 is, for most dusts, well inside the flammability limits.[1]

2.6 Dust explosion standards

Dusts are divided into four dust explosion classes depending on their potential explosion violence or K_{st} value [11].

- St0: 0 — Non-explosive
- St1: $0 < K_{st} < 200$ — Weak to moderately explosive
- St2: $200 < K_{st} < 300$ — Strongly explosive
- St3: $K_{st} > 300$ — Very strongly explosive

The K_{st} value is a standard value used in dust explosion testing. The unit is *bar m/s*, and it is defined as the maximum pressure rise rate in the 1 m^3 standard testing vessel [1]. The value is fairly constant no matter the size of the test container used to measure the K_{st} value for a certain dust. The equation to calculate and the definition of the value is:

$(dP/dt)_{max}V^{1/3} = \text{constant} \equiv K_{st}$ [1].

Another standard dust class is the burning behaviour of different dusts. The dusts are divided into six classes [11]:

- Class 1: No Burning, no ignition
- Class 2: Brief Burning, rapid extinction
- Class 3: Localized combustion or smouldering (no or very minor propagation)
- Class 4: Spread of a smouldering fire or slow, flameless decomposition
- Class 5: Spread of an open fire (burning with flame development)
- Class 6: Very rapid burn through with flame development, flameless decomposition

2.7 Dangers with dust explosion

There are three dangers to buildings and humans in regards to dust explosions; the dangers are:

- Pressure
- Fire
- Projectiles

The pressure waves resulting from a dust explosion can cause extensive damage to buildings, machinery and people. The human ear drums and the lungs are the organs most sensitive to pressure [12]. A human can, however, normally withstand higher pressure than buildings.

Dust explosions release a lot of heat which can cause damage to both buildings and people. For further discussion on the damage to buildings and people due to pressure and heat radiation see chapter 5.3.

When a vessel ruptures due to a dust explosion the vessel ruptures into a number of smaller fragments that can fly far from the vessel due to the increased pressure. If struck by these fragments, humans can be severely injured.

2.8 Prevention of explosions

This chapter is meant to give an overview of the available methods for preventing dust explosions and the consequences of these explosions, for further reading *Dust explosions* by Barton [11] and *Dust explosions in the process industries* by Eckhoff [1] are recommended.

The methods used to prevent explosions are divided into two main categories: *preventing explosions* and *minimizing consequences*.

2.8.1 Preventing explosions

There are two main ways of preventing explosions [1]:

- Preventing ignition sources
- Preventing explosive dust clouds

Preventing ignition sources is a good start to having a good dust explosion safety. It is, however, very hard to eliminate all possible ignition sources; this is because it is hard to identify all sources and even if they are identified it is hard to eliminate them 100 %.

To minimize the number of ignition sources, good routines and maintenance is essential. Open flames can be avoided to a large extent by good routines, for example, making sure that hot work is done safely and according to regulations.

Hot surfaces can be avoided to a large extent through good and regular maintenance on machines and other process equipment that could cause hot surfaces if, for example, they are not properly oiled.

Electrical sparks can be avoided through maintenance and routines. It is important that all conducting parts in the dry powder system are properly grounded. It is further important that the connection to earth is reconnected after it has been disconnected during maintenance. This is, however, not always the case at Leaf, especially when using external maintenance staff [13]. Electrical equipment should also be properly maintained; it is important to make sure that damage to electrical equipment is reported and attended to as soon as possible. Good reporting routines make this easier.

Using metal detectors to prevent metal getting into the dry powder system can minimize the heat caused by mechanical impact, such as metal against metal impacts. This is especially important for Leaf when it comes to the grinding of Gum Arabic because metal parts in the raw gum are commonly found [13].

Preventing explosive dust clouds can be relatively hard to accomplish. It is difficult to adjust the processes to completely avoid dust clouds within the flammability limits in the entire dry powder system, especially in the pneumatic conveying systems, hoppers, silos and dust extraction systems.

Another way of preventing explosive dust clouds is to make the dust clouds inert; this can be done by adding an inert gas such as N_2 or CO_2 to the dry powder system or by adding an inert dust (a non flammable dust) to the process. [1] This can, however, be fairly expensive and complicated to achieve because it requires changing and reconstructing the entire dry powder system.

2.8.2 Minimizing consequences

There are many different ways and methods to minimize the consequences of an explosion [1]:

- Preventing spread between process units
- Explosion resistant equipment
- Explosion venting
- Automatic suppression
- House keeping
- Construction of buildings

2.8.3 Preventing spread

Preventing the spread of an explosion between different process equipments are very important in avoiding a large explosion. This is because if an explosion occurs in a vessel and the explosion spreads to another vessel and causes a new explosion in the second vessel the second explosion can be much more violent than the first explosion. [1]

There are a number of technical solutions for preventing explosion spread between vessels. There are special conveying screws that are designed to prevent spread of dust explosions and there are a lot of other different passive equipments that can be used in conveying pipes such as equipment that changes the flow of an explosion and vents the explosion to a safe place. [1]

There are also many active systems for preventing explosion spread. There are a number of different valves that can be installed inside pipes that detect an ongoing explosion; the valve then shuts, stopping the explosion from spreading through the pipe. Another active system that can be installed in both pipes and ducts is a system that detects an ongoing explosion and very quickly injects an extinguishing medium such as non flammable powder or an inert gas. [1]

2.8.4 Explosion resistant equipment

Explosion resistant equipment is built strong enough to withstand the maximum explosion pressure and not rupture. This is a very simple and effective safety precaution and it requires very little maintenance unlike other safety installations such as pressure vent panels. [14]

2.8.5 Explosion Venting

Explosion venting is a very simple but effective installation used to minimize the consequences of a dust explosion. Explosion venting is usually done by explosion vent panels mounted on the vessel that requires protection. The panels are designed to open at a certain overpressure depending on what the vessel in question is designed to withstand. The vents should always open to a safe place outdoors [15]. Leaf Gävle has explosion vents installed at seven places in the dry powder systems. Only three of these are, however, vented to the outside. There are two vents on the powder dryer and cooler, and two vents on process filters are directed to the inside. A sugar hopper in the grinding room has a relief panel vented to the outside and two relief panels on a process filter for the general ventilation is also vented to the outside.

An installation of a *Quenching-tube*, Q-tube, can dramatically reduce the risk of secondary explosions and injuries to people that would come in the way of an opening explosion vent panel. The Q-tube is filled with a web of a fine metal net that together has a very large surface area. This large area cools down the flames and prevents them from reaching outside of the vessel. The tube is mounted on the outside of the vessel and the explosion venting goes through the tube. [1] [14]

2.8.6 Automatic suppression

This is an active suppression method of vessels. The basic principal is that a detector that is mounted on the inside of the vessel very quickly detects an initiated dust explosion. A container filled with inert gas or inert powder is mounted on the outside of the vessel and opens and empties its contents into the vessel when the explosion detector activates. This sequence of events happens quickly enough to stop the initiated explosion before it can evolve into a full scale explosion and possibly rupture the vessel. [1]

2.8.7 House keeping

Good housekeeping is *extremely* essential to avoiding a secondary explosion. Floors, beams, machinery, shelves and any other place where dust is deposited in the factory should regularly be cleaned free of dust. As mentioned in chapter 2.5, even a very thin layer of dust could cause an extensive secondary explosion. [11]

2.8.8 Construction of buildings

Buildings where there is risk of an explosion should be built with only one floor to avoid a building collapse in case of an explosion [11]. When building a new factory or building, it is important to examine where dust explosions could occur and make sure that the building could withstand the explosion. For example, a building could have explosion panels on one wall that vent to a safe outside place while the other walls would be solid.

Another way of designing the building not to collapse in the event of a dust explosion is to use low weight wall panels and a really rigid frame structure. This allows the wall panels to give way instead of the whole building collapsing. [1]

2.8.9 Discussion on explosion prevention

Even if a company installs every type of technical safety equipment available on the market, it does not mean that a dust explosion can not occur. A lot of things can still go wrong, and the equipment must be installed correctly and regularly maintained. There has to be a motivated and working organisation that is constantly involved in maintaining and improving the safety [1]. This means that the communication has to work well and that people have to be motivated and feel that they can contribute to a safer place of work. For a further discussion on this matter see chapter 9 and 10.

3 Leaf

This chapter will give the reader basic knowledge of the Leaf factory in Gävle. The dry powder systems are thoroughly described.

3.1 The factory

The factory is situated in the outskirts of central Gävle in a mixed residential and industrial neighbourhood. Figure 2 shows the layout of the plant. The areas of the plant relevant to the dry powder or dust handling are marked in the figure. The total area of the buildings is about 25 000 m². Most of the factory consists of only a ground floor. Above the moulding line hall there are however a first and second floor. On the first floor there are kitchens and the powder dryer from the moulding line hall. On the second floor there is an attic where the ventilation system is located.

	Description	Building year and construction material	Average estimated number of people in the room
1	Grinding and sugar room	1991, supporting steel, steel and mineral wool walls and roof	0-1
2	Main sugar silo	1991, supporting steel, steel and mineral wool walls and roof	1-3 (in the storage room)
3	Azo room	1991, supporting steel, steel and mineral wool walls and roof	0-1
4	Foam Kitchen	1992, supporting concrete and steel, walls plaster and steel	1-2
5	Ako and brio kitchen	1991, supporting steel, steel and mineral wool walls and roof	1-2
6	GA-kitchen	1991, supporting steel, steel and mineral wool walls and roof	1
7	Automatic drageé	1991, supporting steel, steel and	1-2

		mineral wool walls and roof	
8	Manual drageé	1963, supporting concrete, bricks and steel roof, insulation mineral wool	1-4
9	Moulding Line Hall	1992, supporting concrete and steel, walls plaster and steel	2-5
10	Drying chambers	1978 and 1998, steel and isolating panel, supporting concrete, brick walls	1-2
11	Powder dryer	1992, supporting concrete and steel, walls plaster and steel	0-1

Figure 2. Plant layout

3.2 Description of the dry powder systems

The dry powder systems will be thoroughly described in this chapter.

3.2.1 Grinding room and main sugar silo

Sugar and Gum Arabic are delivered to and processed in the grinding room. Gum Arabic is delivered in fabric bags and the gum pieces are between 1 and 5 cm in diameter. In order to dissolve in liquid, the gum must first be ground into a fine powder. This is done in the grinding room.

The gum is poured into a funnel in the top of the grinder. After the funnel, the gum passes through a strong magnet that extracts ferrous materials before the gum enters the *plate beater grinder*.

The grinder crushes the gum into a fine powder, the powder then falls down into a hopper. From the hopper the gum powder is either screwed to a filling station and filled into *Big Bags* for storage, or is directly transported via the pneumatic conveying system to the main Gum Arabic storage silo in the Azo room, see chapter 3.2.2. Big Bags are large nylon-plastic bags that weigh between 800 and 1000kg when they are full.

In the grinding room sugar is also received and handled for distribution to the 60 m^3 main sugar silo. Sugar is delivered either in Big Bags or by bulk trucks. The Big Bags are emptied into a small hopper and the contents are then screwed in to the pneumatic conveying system and transported to the main sugar tank. The small sugar hopper is equipped with an explosion pressure relief vent to the outside.

If sugar is delivered by bulk truck**,** the pneumatic system blows the sugar from the truck directly into the main sugar silo.

Figure 3. Emptying sugar Big Bag to the left, filling of crushed Gum Arabic to Big Bags to the right

Figure 4. Gum Arabic mill

3.2.2 Azo Room

The Azo room is the main distribution centre for dry powder products in the factory. From here, the pneumatic conveying systems distribute salt, sal ammoniac or simply salmiak, starch, gelatine, xylitol and Gum Arabic throughout the plant. Starch, gelatine and Gum Arabic are stored in Big Bags. Each bag hangs over a hopper which is connected to a screw conveyor in the bottom of the hopper. The screw feeds the powder to the pneumatic conveying system, which distributes the powder to the different kitchens throughout the plant.

The main Gum Arabic silo, a smaller sugar silo and a sender for the foam line also reside in the Azo room. The gum tank is about 3.5 m high and 2.5 m in diameter. It connects to the pneumatic conveying system in the bottom via a screw conveyor.

The foam line sender connects to a scale tank that is placed above the sender and to the pneumatic pipe system below the sender. The scale tank is smaller than the main Gum Arabic silo.

Figure 5, Main Gum Arabic silo to the left, emptying of Big Bags into hoppers to the right

3.2.3 Pneumatic conveying system

The majority of powder transportation within the factory is done via pneumatic conveying. There are three different pneumatic conveying systems:

- Pressure system
- Vacuum system
- Pressurized sender system

The pressure system creates over pressure at the start of the pipe system and blows the powder through the system.

The vacuum system creates an under pressure at the end of the pipe system which sucks the powder through the system.

The pressurized sender system is only used to convey sugar from the two sugar silos and from the foam scale tank in the Azo room. Underneath the storage containers there are *sender* containers. The sender is first filled with powder and is then pressurized to 1.8 Bar. When the sender is fully pressurized the connection to the conveying pipe is opened and the powder is blown to its destination.

The systems connect senders and receivers with steel pipes of different dimensions. At a few locations in the factory there are rubber connections in bends, especially before *scale tanks*, to avoid error when measuring the weight of filled powder. The systems are grounded.

Figure 6, Pneumatic conveying pipes in the attic

3.2.4 Kitchens and drageé

The ingredients for the different products are mixed, processed and cooked in the kitchens. During the drageé-process, candy cores are covered with an outer candy layer.

3.2.4.1 Foam Kitchen

The foam kitchen produces all the foam candy. The powder products are first mixed in the foam tank in the Azo room. The pneumatic conveying system then transports the powder ingredients to a storage tank that is located between the first and second floor of the building. From this storage tank a screw conveyor transports the powder to a scale tank located just underneath the storage tank. In the scale tank the powder is mixed with liquid ingredients.

Figure 7, Sugar tank in the attic above the foam kitchen

3.2.4.2 AKO and Brio Kitchen

The AKO and Brio kitchen is located on the first floor. The pneumatic conveying system transports the sugar from the main sugar silo to the AKO and the Brio sugar tanks. The tanks are located in between the first and the second floor. From here the sugar is screwed to a scale tank where the sugar is mixed with liquid ingredients.

3.2.4.3 GA Kitchen

The GA kitchen produces the bases for gum-based products like pastilles. There are six dry powder tanks in the kitchen. The tanks are for Gum Arabic, starch, gelatine and xylitol, sugar, salt, and salmiak. Salt and salmiak are non-combustible materials and therefore pose no dust explosion risk [16]. The powder materials are screwed to a scale tank where they are mixed with liquid ingredients.

Figure 8, GA kitchen, dry powder containers to the left and screw conveyors in the centre

3.2.4.4 Brio Line, Automatic drageé

In the automatic drageé the Brio cores are coated with a sugar coat. This is made in two rotating drums. A liquid sugar and flavour mixture is sprayed on the cores. Fraction sugar (smaller particle size distribution than the other sugar) is sometimes added by hand if needed.

This process produces some fine dust. The dust consists mainly of sugar and is airborne. Point ventilation extracts most of the dust which is then transported to the main ventilation filter, see chapter 3.2.9.

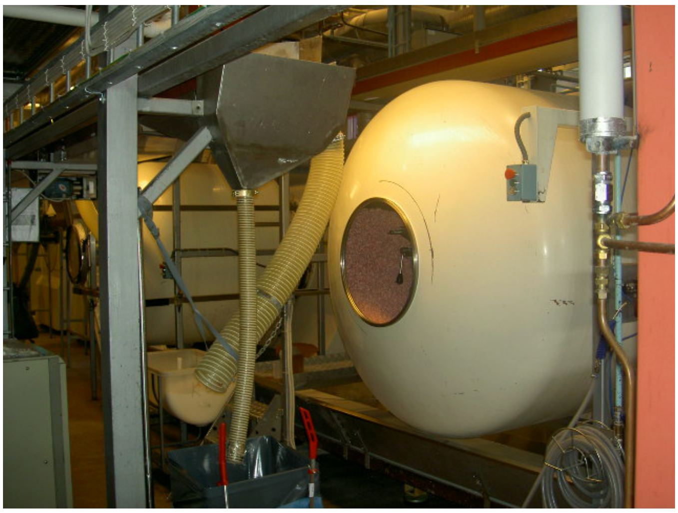

Figure 9, Automatic drageé barrel

3.2.4.5 Manual drageé

The principal process of the manual drageé is the same as for the automatic drageé, except that all coating ingredients are added by hand. The majority of the drageé drums are equipped with point ventilation; however nine drums do not have this. This process makes a lot of fine dust that spreads in the room, creating plenty of thick dust deposit layers.

The point ventilations in the manual drageé are served by a process filter located in the next room. The two rooms are connected with a large opening between them.

Figure 10, Manual Drageé barrels

3.2.5 Moulding line hall

Moulding trays filled with maize starch and dried candy that comes from the driers are placed at the start of the moulding line with a forklift. From here the trays are automatically picked up and turned over one by one. The candy and the starch then fall down into a rotating horizontal drum that separates the candy from the starch. The starch passes through a net and is then transported to a sieve via a screw conveyor. The sieve separates the starch from small pieces of candy and other impurities that have passed through the net. After the sieve, the starch falls down into a metal surge bin. From the bin the starch is transported back to the moulding line with a screw conveyor where moulding trays are refilled with the sieved starch. After this a mould is pressed into the starch. The mould pattern is then filled with candy *slurry*. The moulding trays are then transported with a forklift to a drying chamber, see chapter 3.2.6, where the product dries and hardens. From the drying chamber the dried trays are transported to the beginning of the moulding line again and the process starts over.

Figure 11, Start of the moulding line

Figure 12, The dried trays are flipped over

3.2.6 Drying chambers

There are two types of drying chambers: eleven old and 18 new chambers. In the old chambers the walls are made of perforated metal which allows air to flow through them. Inside the walls there are heating accumulators that heat the air with water steam at a pressure of three Bars. The fans reside inside a compartment above the ceiling. The drying chambers have an operating temperature between 70 and 80 ºC and standard drying time is twelve hours.

The primary design is the same in the new drying chambers as in the old, however, the operating temperature is lower, between 50-60 ºC and the fans are located at the floor level inside the drying compartment.

3.2.7 Dust extraction system

The moulding lines connect to a process filter to minimize dust from spreading in the room. Air is extracted from each moulding line at two different locations and is extracted to the process filter through suction. The process filter consists of bag filters that are self cleaning through "reverse jet" for continuous operation. When the filter bags are cleaned the starch dust falls down to the bottom of the process filter machine. From here a screw conveyor transports the dust to a surge bin. The process filter is equipped with an explosion vent panel to relieve pressure in case of a dust explosion. The vent panel is inside the moulding line hall and is directed up towards the ceiling; the distance between the panel and the ceiling is about 2 meters.

Figure 13, Process filter in the moulding line hall;
the explosion relief vent is seen in the right of the picture

3.2.8 Powder dryer

In the moulding line hall there are two different moulding lines, Nid 4 and Nid 5 that are identical with the exception that Nid 5 connects to a powder dryer on the first floor above the moulding line hall. When the starch separates from the dried candy, a screw conveyor transports the starch to the second floor and into the top of the powder dryer.

Inside the dryer there are three belt conveyor decks made of perforated metal to allow air to pass through the starch. The starch is slowly transported down to the bottom of the dryer. Air flows in the other direction, from the bottom to the top. Air is entrained at the bottom and is heated with water steam at about 100ºC. Heated to about 50ºC, the air passes through the perforated decks and exits the dryer at the top trough a filter.

The starch is dried and warm when it reaches the bottom of the dryer. A screw conveyor then transports the starch to the top of a powder cooler. The cooler is identical to the dryer but the used air is cooled with cold water instead of heated with steam.

Both the dryer and the cooler are equipped with a 1m by 1m explosion vent panel made of rubber. In case of an explosion, this vent will relieve the pressure into the room.

Figure 14, Powder dryer,
the top of the picture shows the explosion relief panel

3.2.9 Central ventilation filter

The central ventilation system connects to two process filters located in a small room on the second floor. The filters clean the air of dust particles. Each filter is equipped with an explosion vent panel connected to the outside. The panels are 0.5m by 0.68m.

3.2.10 Central vacuum cleaner

The central vacuum cleaner dust collector unit resides outdoors while the vacuum engine resides inside. There are a large number of vacuum cleaner sockets throughout the factory. The system consists of metal pipes and rubber tubes that are lined with metal thread. The system is completely grounded.

3.3 Powder information

Appendix A – Dust Data, lists the dust explosion data used in the consequence calculations. The data comes from the suppliers of the powder products unless otherwise specified. Where dust clouds with a fine particle size distribution is expected, as in hoppers and in silos, data for a finer dust is used for the calculations. These data are taken from the BGIA database [17] unless otherwise specified in Appendix A – Dust Data

3.3.1 Gum Arabic

Leaf uses Gum Arabic, a hydrocarbon with a very complex chemical structure ,in its pastilles. Gum Arabic is produced mainly in Sudan where it is extracted from Acacia Senegal trees. [18] The Gum normally consists of two fractions, 70% of it is composed of polysaccharide chains and the rest consists of more complex hydrocarbon structures with protein attached to the chemical structure. [19]

The gum is delivered to the plant in either spray dried powder form or in its raw form, as about 5 cm in diameter pieces that are crushed to a powder in the GA mill at the factory.

There are very few dust explosion tests done on Gum Arabic, however, the few that have been conducted show it to be explosive [20]. The tests have been done on a particle size that represents the finest fractions of the crushed Gum Arabic at Leaf, about the 10-50 % finest fraction. It is assumed that these finer particles could possibly form an explosive dust cloud in hoppers and silos when filled from the top.

3.3.2 Starch

Leaf uses starch both as an ingredient in products and also as a mould for foam candy and pastilles. In its factory, Leaf uses three main starches: maize starch, wheat starch and Maltodextrin. The later is based on potato starch. Starch is a carbohydrate.

Starch handling is one of the most common causes of dust explosions in the food processing industry [21]. The starch used in the food processing industry is usually of a very fine quality with fine particles.

Fine starch powder shows high sensitivity to ignition sources such as static electricity and hot surfaces. The explosion force (K_{st} and P_{max}) resulting from a starch dust explosion is also fairly large.

3.3.3 Sugar

Leaf uses sugar in larger quantity than any other powder at the plant. Although a few different kinds are used, the most widely used sugar has a more granulated than powdery consistency. The mean particle size is between 500 and 750 μm [22], which is considerably larger than most other powders used at the company.

Sugar with this particle size shows little or no propensity to explode [17]. It is however assumed that dust clouds with a finer particle fraction can arise in silos, for example, when the sugar is filled in from the top and then falls to the bottom.

Sugar is delivered to Leaf in either 1000 kg Big Bags or in 20 000 kg bulk trucks.

3.3.4 Xylitol

Xylitol is a carbohydrate, or more specifically, a polyol. It is widely used as a diet sweetener in many food products. [52] The Xylitol used at Leaf is more granulated than powdery and has a mean particle size between 400 and 600 μm. At this particle size it shows a mild tendency to take part in a dust explosion.

Xylitol is delivered in 800 kg Big Bags.

3.3.5 Gelatine

Gelatine is used to give sought consistency to food products. It is a protein that mainly is produced from pigskin. [18]

Leaf uses several kinds of gelatine that have varying particle size distribution; some are more akin to granulates than powders while a few others are relatively fine powders. Most of the gelatines do not pose a serious risk for dust explosions. Gelatine could nevertheless cause a dust explosion under certain circumstances; for example, dust clouds of the finest fractions can sometimes form in hoppers and silos. This is especially true for the gelatines with the finest particle size distribution.

Gelatine is delivered to Leaf in Big Bags.

3.3.6 Salt and Ammonium Chloride

Leaf uses Ammonium Chloride, or more commonly known as *salmiak*, to give candy a liquorish taste. S*almiak* is not flammable and therefore it can not cause a dust explosion on its own. [16].

The salt, sodium chloride, is not flammable and therefore it can not cause a dust explosion.

3.4 Safety policy

MalacoLeaf had a management system regarding safety and security in a document called "Property Risk Manual" [23]. In this document there is a relatively extensive and well written chapter on dust explosions as well as the company policy on handling the risk of dust explosions. It seems, however, that this document is not very well known in the company and is therefore not used very much. Another problem is that this document was developed centrally by the former owners CSM that owned more companies than MalacoLeaf. Due to the change in owners and the name change to Leaf it is uncertain if this document is still valid and if it should be used at all. [24]. This is a problem because this means that in reality Leaf does not have an up to date management system regarding safety issues at present time.

The Property Risk Manual does provide an extensive checklist on how to avoid different ignition sources in regards to the risk of dust explosions.

3.4.1 Comment to the Safety policy

The Property Risk Manual has checklists on how to avoid some ignition sources but it needs to be complemented with how to avoid all ignition sources and other checklists and information on, for example, what human errors can lead to a dust explosions and how to best perform maintenance in order to avoid dust explosions.

The fact that this document is unknown to, or at least not used by, most people at Leaf also needs addressing. Leaf needs to inform people of the document, how to use it and where they can find information on it. In addition, the manual requires updating. For example, Leaf needs to update the chapter on contact persons because today it refers to people that no longer works in the company. The dust explosion chapter also needs updating to be more comprehensive.

3.5 Technical safety installations at Leaf today

Although almost the entire plant has automatic water sprinklers, there are a few exceptions, for example there are no sprinklers in the grinding room.

The entire plant has an automatic fire alarm system that is directly connected to the fire rescue service via SOS alarm.

There are fire extinguishers throughout the plant; the majority of these are CO_2 extinguishers, however. Gas extinguishers are not preferred when it comes to putting out dust fires because the turbulence they cause could actually cause a dust explosion [11]. For dust explosions, a liquid extinguishing medium, such as water or foam is preferred.

Regarding dust explosions, there are seven process units in the plant that are equipped with explosion relief panels; only three of these are vented to the outside, the remaining four are vented inside the plant.

The entire dry powder system is made of conducting metal and is grounded with a few exceptions. These exceptions are a few bends before scale tanks that are made of rubber to allow for shock absorption. The rubber is not conductive and it is recommended that these bends be changed to flexible metal bends [11]

4 Preliminary Hazard Analysis, PHA

The Preliminary Hazard Analysis (PHA) method was used as a tool to, in a systematic way, identify and estimate the consequence of, and probability for, dust explosion incidents. A PHA identifies the most severe hazards without major consideration of technical details [25]. A PHA is usually done by a group of people with good knowledge of the process in the factory and of the risks involved.

4.1 PHA process

The PHA-group consisted of three individuals:

- Tobias Dahl Hansson, Risk management and Fire safety engineering student.

- Ove Lindeberg, Building technology manager. Has a very good knowledge of the processes in the factory and the building construction.

- Daniel Norman, Technical manager. Has good knowledge of the process equipment.

The PHA process started with a systematic walkthrough of the dry powder systems of the plant. During the walkthrough the group noted places and processes where dust clouds above the Lower Explosion Limit, the *LEL* could possibly occur. The group also identified possible ignition sources, both during normal process operation and following accidents or other abnormal incidents.

The identified possible dust explosion scenarios were listed in a PHA-table, see Appendix B – Preliminary Hazard analysis. The group then had a meeting and discussed the scenarios and possible consequences. About five new scenarios were added during the meeting. When the group had agreed on the scenarios, the group discussed the risk evaluation criteria. The group agreed on the criteria presented in chapter 4.2 and 4.3.

During the meeting the group discussed each scenario for its probability, and estimated the health and economic consequences on a scale from one to five; one meant a small consequence or low probability and five meant catastrophic consequences or large probability.

4.2 Probability estimation

Estimating the probability in the preliminary hazard analysis was done according to the probability criteria in Table 1[26].

Table 1, Probability criteria for PHA from SRV [26]

1	Small probability	< Once in 1000 years
2		Once in 100-1000 years
3	Probable	Once in 10-1000 years
4		Once in 1-10 years
5	Large probability	> Once in 1 year

Several factors were considered when estimating the probability for a dust explosion:

- Characteristics of the dust
- Present ignition sources and the dust's sensitivity to them
    - Minimum ignition energy

    - Minimum ignition temperature
- Statistics
    - Which processes are most prone to cause a dust explosion
- How often does a dust cloud form
    - Continuously during normal process
    - A few times a day
    - Only from accidental release

4.3 Consequence estimation

Estimating the consequence to people's health in the preliminary hazard analysis was done according to the probability criteria in Table 2 [26].

Table 2, Health consequence criteria for PHA from SRV [26]

1	Small	Temporary mild discomfort
2	Mild	Some injuries, lasting discomfort
3	Large	Some serious injuries, severe discomfort
4	Very large	Some deaths, several serious injuries
5	Catastrophic	Several deaths, tenths of serious injuries

Estimating the consequence to economic damage in the preliminary hazard analysis was done according to the probability criteria in Table 3.

Table 3, Economic consequence criteria for the PHA, criteria's decided by the PHA expert group

1	Small	€ 25 000
2	Mild	€ 100 000
3	Large	€ 500 000
4	Very large	€ 1000 000
5	Catastrophic	€ 20 000 000

In the consequence estimation, consideration was taken for several factors affecting the consequence of a dust explosion:

- The quantity of present dust
- Statistics
- Building and process equipment characteristics
- Number of people that normally is in the premises
- Risk for a secondary explosion
- Turbulence in process
- Dust data
    - Maximum overpressure, P_{max}
    - Rate of explosion pressure rise, K_{st}

For the economic consequences, additional considerations were taken than those mentioned above:

- Value of damaged equipment, buildings and stored goods
- Excess
- Stoppage times

4.4 Results

The results from the PHA are presented in two risk matrixes: one for economical damage, Figure 15, and one for health damages, Figure 16. In the matrixes the Y-axis represents the PHA probability and the X-axis represents the PHA consequence.

There are three fields in the matrixes— white, light grey and dark grey— that represent the three different decision criteria:

- White – **Low Risk** – No further investigation will be conducted
- Light Grey – **Medium Risk** – The scenarios will be further investigated with event trees.
- Dark Grey – **High Risk** – The scenarios will be further investigated with event trees.

The results are somewhat different for the economic and the health consequences; the economic consequences are dependant on the value of damaged machines and stoppage times, etcetera while the consequences on people's health are dependent on how many people could be close to an explosion, etcetera.

4.4.1 Economic risk

The PHA matrix shows three areas of the factory estimated to have High Risk for dust explosion scenarios. The three areas are the *moulding line hall*, *the grinding and sugar room,* and the *manual drageé*. The process filters and the powder dryer in the moulding line hall were estimated to pose the highest risk. In the grinding and sugar room an explosion in the main sugar silo or in the Gum Arabic mill pose the highest risk.

In the medium risk field in the matrix there are four more dust explosion scenarios in the moulding line hall, starch explosion in the GA-kitchen, explosion in the new drying chambers and explosion in the manual drageé. The economic risk matrix is presented in Figure 15, economic risk matrix. The Y-axis represents the probability and the X-axis represents the consequence. The different scenarios are described in Appendix B – Preliminary Hazard analysis. The scenarios that were estimated to contribute mostly to the risk, i.e. the scenarios in the two grey areas in Figure 15 and Figure 16 are presented in chapter 5.1.

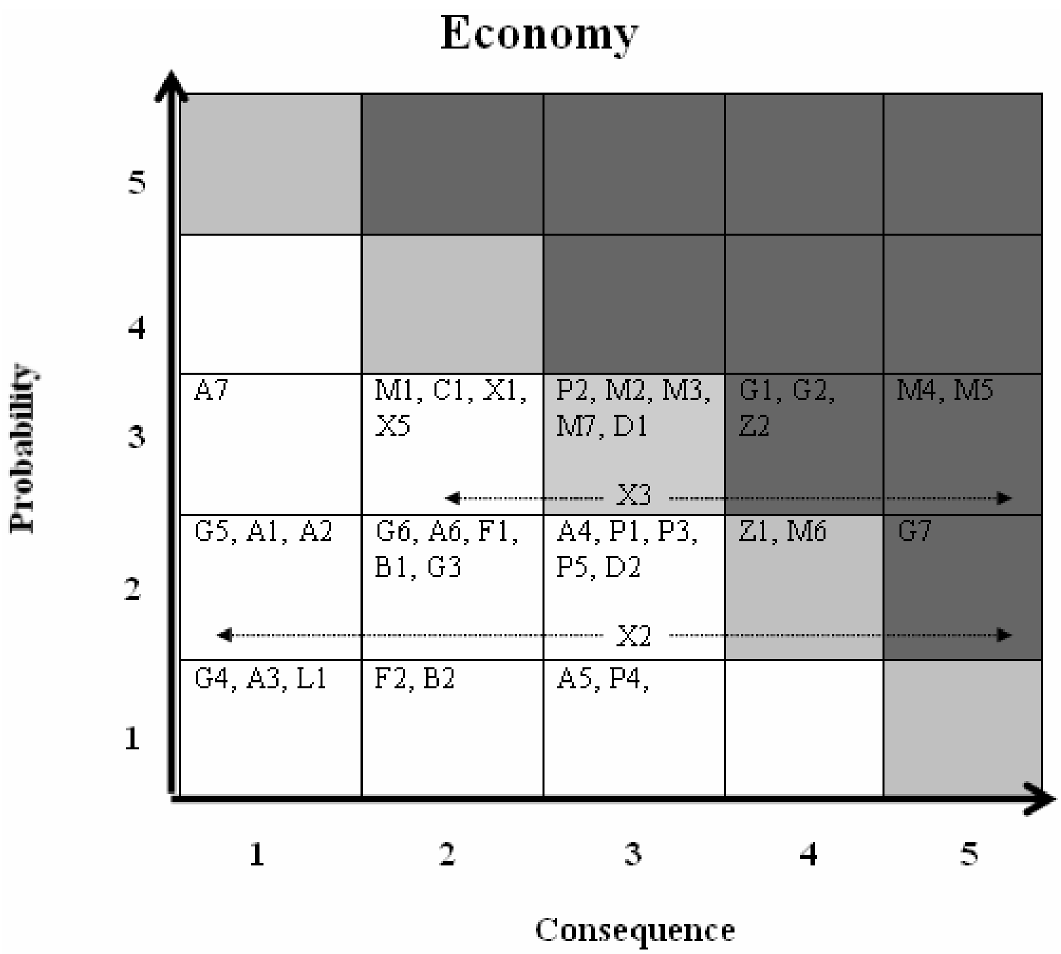

Figure 15, economic risk matrix. The Y-axis represents the probability and the X-axis represents the consequence

4.4.2 Health risk

The highest estimated risk is an explosion in the manual drageé. The high estimate of this risk is because the whole room is estimated to be involved in an assumed explosion and because there usually are people in the room. An explosion in the process filters in the moulding line hall is also a scenario judged to be *high risk*.

Medium risk scenarios are found in the grinding and sugar room, the moulding line hall and in the drying chambers.

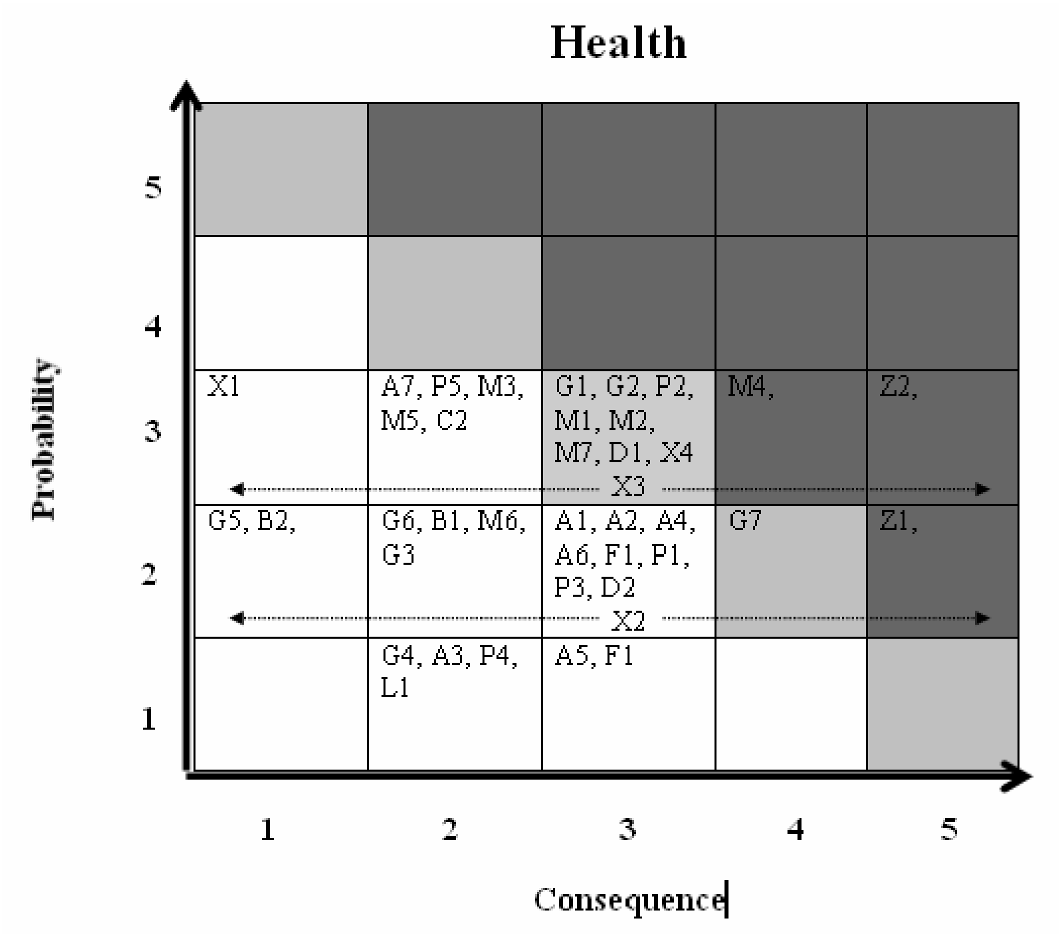

Figure 16, Health risk matrix, The Y-axis represents the probability and the X-axis represents the consequence

4.4.3 Comment to the PHA

The dust explosion scenarios judged to have medium or high risk in the risk matrixes will be further examined with event trees. The locations in the factory that will be further examined are:

- Manual drageé
- Moulding line hall + powder dryer/cooler
- Grinding and sugar room
- Ga-kitchen
- Drying chambers

In addition to the above mentioned locations, the AZO room will also be further examined, even though all of the AZO room scenarios were estimated to have low risk. This is because quite a few scenarios in the AZO room are just below the medium risk in the risk matrixes; this means that even though no single scenario presents a high or medium risk, the total sum of the scenarios could be fairly high.

PHA is a rough way to estimate risks. It is important to note that a PHA at best gives a subjective educated guess. Because of this the results from the PHA should not be taken too literally. In this report, the PHA was used as a systematic tool to roughly identify problem areas. This has been done by answering questions like; if a dust explosion would occur in the plant, where could it cause the most damage to people and machinery? Which dust has the greatest tendency to cause a dust explosion and which dust would cause the most severe effects?

The scenarios identified with the PHA as posing the largest risk will be further investigated. This is a common way of doing a risk assessment, to thin out the number of scenarios that are further investigated to include only the ones that mostly contributes to the risk. In this report the scenarios estimated to have high or medium risk as well as the scenarios in the AZO room will be further investigated.

5 Event Tree

An event tree is a common method used to assess risks; it is especially useful when an initial accident can have several different outcomes. This is usually the case with dust explosions. An initial dust explosion usually occurs inside process equipment; after the initial explosion, different scenarios can happen:

- Large or small explosion, depending on available dust quantity and concentration
- The explosion can spread to another container, depending on dust transport system used and the concentration of dust in the pipes
- If a pressure relief panel is present the explosion could safely be vented to the outside or not as safely to the inside
- The vessel containing the initial explosion could rupture from the pressure rise
- A secondary explosion could occur in dust deposits in the room where the initial explosion occurred

In this report the event trees have different appearances because some scenarios are not expected to, for example, cause a secondary explosion in another vessel, or it is assumed that there is not enough dust present to cause a large initial dust explosion. All the event trees, however, have a similar structure; the following diagram illustrates the fundamental structure.

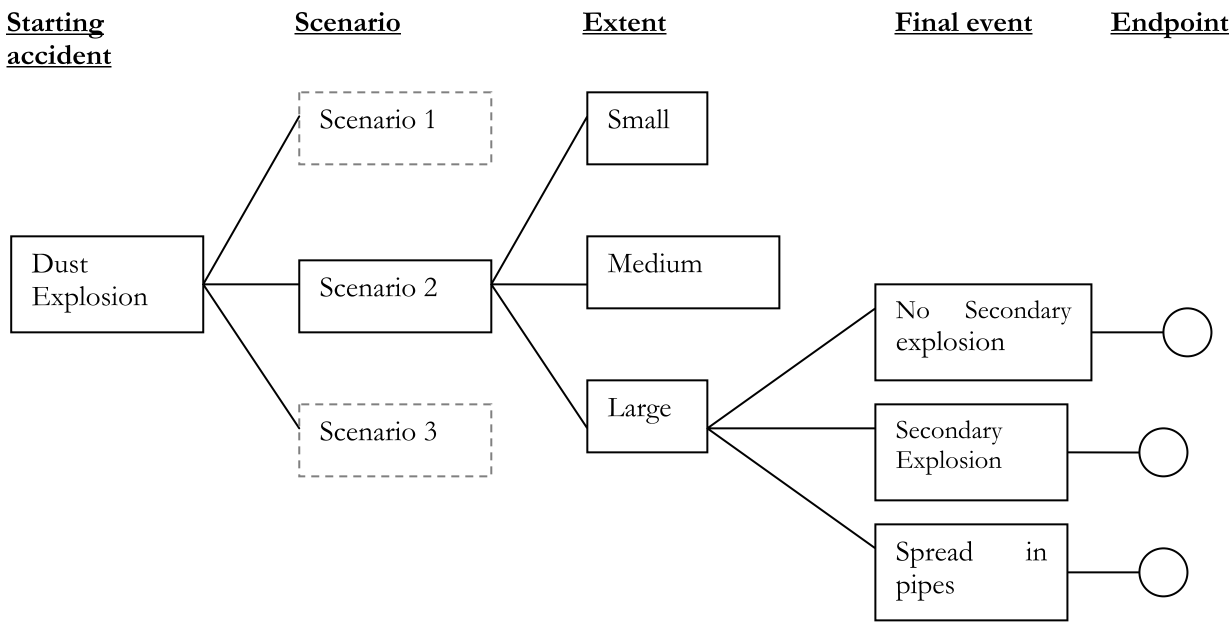

Figure 17, Principal description of an event tree

Event trees always start with an accident; in this case, a dust explosion is the starting event. From the initial event or accident, the tree parts into a number of dust explosion scenarios. Each scenario then branches into the small, medium and large extent of the dust explosion. In the last step the tree parts into a number of branches concerning secondary explosion outside the initial dust explosion vessel and spread to other vessels.

Each branch in the event tree is assigned a probability in percent; the branch probabilities will be discussed further in chapter 5.2.

A software program named *Precision Tree* [27] constructs the trees and calculates the endpoints. The probabilities and consequences has to be entered by the user.

A consequence is assigned to each final event in the event tree. In this case three different consequences were assigned: one for the estimated number of injured, one for the number of estimated deaths and one for the estimated economic consequence.

Precision Tree provides the probability for each endpoint to occur given a dust explosion and multiplies it with the endpoint consequence for each end scenario. This gives the expected number of injuries, deaths and the economical damage for each tree.

Assigning consequences will be further discussed in chapter 5.3 and 5.4 and the event trees are presented in Appendix G – Event Trees.

5.1 Scenarios

The scenarios that were analyzed with event trees were chosen with the PHA and are discussed in chapter 4.4. The scenarios are:

- Manual drageé
  - Z1, Process filter
  - Z2, Dust deposit
- Moulding line hall
  - M1, Starch separating drum
  - M2, Sieve
  - M3, Surge bin
  - M4, Process filter
  - M5, Powder dryer
  - M6, Powder cooler
  - M7, Fine sieve
- Grinding and sugar room
  - G1, Grinder
  - G2, Hopper
  - G7, Main sugar silo
- Ga-kitchen
  - P2, Starch tank
- Drying chambers
  - D1, New chamber
  - D2, Old chamber

5.2 Branch probabilities

The probability for the first branch separation in the event tree, i.e. dust explosion scenarios, has been decided using the dust explosion frequencies calculated in chapter 5.5.

The probability in the second branch separation, i.e. the probability for small, medium or large dust explosion, is mainly based on statistics. According to German dust explosion statistics collected between 1965 and 1980, 357 dust explosions occurred in Germany. This number has been estimated to be only 15 % of the actual number of dust explosions that occurred in Germany during these years [1]. It is assumed that the 15 % of the dust explosions that actually were reported and recorded were the most serious dust explosions and correspond to medium and large explosions in the event trees in this report. Another support for this assumption is that the consequences in the German statistics were very serious; there were for example in average 0.43 fatalities and 1.44 injuries per explosion in the *food and feed* industry [1].

The base probability used for small explosions is from the reasoning 85 %, for medium explosions 10 % and for large explosions 5 %. These probabilities were however adjusted depending on the dust explosion sensitivity of the present dust, the number of present ignition sources, the quantity of present dust and the dust explosion sensitivity of the particular process unit in each scenario. For example, the powder dryer in the moulding line was assigned a higher probability for large (10 %) and medium (20%) dust explosions due to the number of present ignition sources, the amount of present dust and statistics showing that dryers are relatively prone to cause dust explosions [1].

The probabilities for secondary explosion are based on the amount of present dust outside the process equipment involved in the different scenarios. There is for example a lot of dust deposits in the manual drageé, because of this a 70 % probability for a secondary explosion in the drageé room is used given an explosion in the process filter. Secondary explosion is on the other hand not present in the event tree for the grinding room hence there where no dust deposits during any of the site visits at Leaf Gävle.

5.3 Critical conditions

To be able to decide the endpoint consequences in the event tree, damage criteria or critical conditions must be decided. This report uses two damage criteria: radiation and pressure.

In the event trees three different extents of the dust explosions can occur, small, medium and large. The extent of damage for small, medium and large explosions are:

- **Small explosion** – the explosion vessel is assumed to be damaged only to the extent that process equipment can be repaired swiftly by the maintenance crew, no injuries are assumed
- **Medium explosion** – the explosion vessel is massively damaged and has to be replaced by a new vessel, injuries only if explosion occurs in the open
- **Large explosion** – rupture of the explosion vessel, flames and pressure wave spread in the surrounding room, radiation and pressure damage, and injuries to surrounding staff and machinery.

5.3.1 Radiation

When a dust explosion occurs in a vessel the pressure will be relieved by either the pressure relief panels, or in the absence of these, simply through the vessel rupturing. This will lead to flames spreading in the surrounding room. The flames radiate heat to their surrounding which can cause injuries to people. Two different damage criteria are used for radiation: death and injury.

- **Death** – Following a dust explosion, people are assumed to die if they are expected to be trapped in the flames.
- **Injury** – People are assumed injured if their exposure to radiation is more than 20 kW/m^2.

Table 4 shows the effect of radiation for different exposure times and different radiation levels. The value used as a critical condition for injury is somewhat higher than the radiation level that gives blisters after five seconds. The reason for this is that the initial flames from a dust explosion are only expected to last for one or two seconds.

Table 4, Radiation effects for different radiation levels and exposure times [28]

Radiation Intensity (kW/m^2)	Observed Effect
1	Maximum for indefinite exposure
6.4	Pain after 8 s exposure
10.4	Pain after 3 s exposure
16	Blistering of skin after 5 s
52	Fibreboard ignites spontaneously in 5 s

5.3.2 Pressure

The pressure will spread from a relief panel that opens inside or a vessel rupture in the whole room. Humans can normally endure larger amounts of pressure than buildings. Buildings start collapsing at about 15 kPa overpressure and complete building collapse occurs at about 30-50 kPa. [29]

For humans, the ear drums and lungs are the body parts most sensitive to pressure. Ear drums start breaking at about 35 kPa and at 70 kPa anyone exposed gets lung damage. Humans start dying at about 180 kPa and 50 % mortality is reached at about 260 kPa of overpressure. [12]

The consequence calculations, see chapter 5.4 and Appendix C, show that the pressure rise does not exceed the mortality level except for really close to the explosion; at that distance people are already assumed to have died from the flames.

Two critical conditions are assumed for pressure:

- **Building damage – 30 kPa**, walls, ceiling and machinery exposed to this pressure are assumed to collapse; humans are injured from building collapse
- **Injuries – 70 kPa**, everyone exposed to this pressure or greater is assumed to be injured

In the event of a ceiling collapse, 20 % are assumed killed and 80 % injured. These values come from studies on building collapses caused by earthquakes [30]. The values should however be reasonable to use for building collapse due to explosions.

Table 5 shows the consequences of overpressure due to an explosion. All pressure values presented in this chapter and in the table are for pressure waves and not static pressure. Pressure reflection makes pressure waves more harmful than static pressure. For example, a pressure wave is reflected from a wall. The total pressure load on the wall is therefore the sum of the pressure wave hitting the wall and the reflected pressure [1].

Table 5, Consequences due to overpressure from an explosion, the three first are from [29] and the three last from [12]

Overpressure (kPa)	Effect
2.1	Typical pressure of glass breakage
15	Partial collapse of walls and roof
36-50	Nearly complete destruction of houses
70	Limit for lung damage (100% injured)
260	50 % killed
350	99 % killed

5.4 Consequence calculations

As a scientific field dust explosions are not studied nearly as much as gas and vapour explosions. This becomes very obvious considering the lack of equations, especially empirical equations, for calculating the effects of dust explosions when compared to the vast number of equations for calculating the consequences of gas explosions.

There are nevertheless some equations available for dust explosions. *Dust Explosion – Prevention and Protection* [11] offers quite a few empirical formulas for calculating the consequences of dust explosion relief through explosion relief panels. These equations have been used to calculate flame length and flame width from an assumed dust explosion in a vessel with relief panels, for example, from the process filters in the moulding line hall. They have also been used to calculate the pressure on ceilings and walls in the cases where the pressure relief will occur indoors. These equations are further described in Appendix C.

The equations from *Dust Explosion – Prevention and Protection* [11] have also been used to calculate the flame length and flame width from vessel ruptures following an explosion in a vessel not protected by explosion relief panels. In this case it is assumed that the weakest part of the vessel gives way first, for example an inspection hatch or a filter mounted on the top of the vessel. The effect on flame spread from the vessel would then be similar to a case with pressure relief panels.

In the case of pressure waves from vessels without vent panels a TNT-equivalence method was used. This is a common way to calculate the consequences from both gas and dust explosions. The method is based on the amount of energy that could be released during an explosion, or more precisely, the amount of TNT that is equivalent to the energy that could be released. The reason for converting the energy to TNT is that military research has produced a lot of empirical data and equations for TNT explosions.

The particular TNT-method that this report uses is taken from *Guidelines for Consequence Analysis of Chemical Releases* [31] and is further described in Appendix C.

Radiation calculations were conducted with a method from *The SFPE Handbook of Fire Protection Engineering* [32]. This method is also further described in Appendix C.

5.4.1 General assumptions

There are a few general assumptions used in the calculations:

T_a, outside temperature 293 K

T_i, inside temperature 293 K

Speed of sound in air	340 m/s
Atmospheric pressure	101.3 kPa
Flame temperature	1000 K, The value was varied between 900 K and 1200 K in the sensitivity analysis; it had little effect on the number of injured
Vessel rupture at	1 Bar (overpressure) if nothing else is mentioned

5.5 Frequency for a dust explosion

There is a major lack of dust explosion statistics. One main reason for this is that most countries do not keep specific dust explosion records [2]. One country that does keep dust explosion records is Germany. During a 15 year period, 357 dust explosion incidents were reported. Beck and Jeske estimated the 357 reported cases to be only 15 % of the actual number of dust explosions in Germany during these 15 years. [1] If this estimate is correct it would mean that about 2400 dust explosions actually occurred.

An unofficial dust explosion record indicates that about one dust explosion occurs every week in the Netherlands [2]. The Netherlands has a population of about 15 million people.

Better statistics are kept for gas explosions. In *Classification of Hazardous Locations* by Cox et al. [33], ignition probabilities given a flammable gas leak and explosion probabilities given ignition are discussed.

According to Cox et al, the ignition probability of a flammable gas leak becomes smaller the weaker the leak is. For a minor leak (< 1 kg/s) an ignition probability of 0.01 is given. For a small gas cloud, 0.1-0.01 is given as the probability for explosion given ignition. [33]

The dust inside the process equipment at Leaf Gävle is transported at about 0.2-2.4 kg/s depending on equipment and dust. The majority of the dusts are however transported with less than 1 kg/s. The only exception is sugar that is transported with about 2.4 kg/s; the sugar particles are however relatively large and it is assumed that the largest particles will not take part in the explosion. Therefore it is assumed that less than 1 kg/s of the sugar takes part in the explosion. This corresponds to a minor leak of gas according to Cox et al. [33] and has the ignition probability of 0.01.

Flammable gases that leak from within process equipment to the outside spread in a volume that normally does not contain flammable gases. In addition, there are more potential ignition sources outside the process equipment than inside. An initial dust explosion, on the other hand, usually occurs inside process equipment [1]. In this paper it is assumed that 100 times more ignition sources exist outside than inside a process device, such as a silo. A *base* ignition probability is therefore assumed to be 0.01/100 = 0.0001 for the dusts at Leaf. This report will adjust the value for each individual dust and process equipment according to the sensitivity to ignition as well as the number of ignition sources present.

The lowest required ignition energy to cause an explosion is between 0.01 and 0.2 mJ for flammable gases, the later value is for methane [1][34]. For the dusts at Leaf the lower flammability limit is between 30 and 10 000 mJ, this is between 150 and 1000 000 times more energy than what is required to ignite a gas cloud.

An explosion will not automatically occur even if there is an ignition of a dust or gas cloud. This is for several reasons: the ignition can occur in a volume of gas or dust that is above or below the explosion limits; the volume might not be confined; there might not be enough flammable dust or gas to accelerate the flames to an explosion; etcetera. A small cloud of flammable gas has a probability of 0.1 for an explosion given ignition; this value corresponds to gases with low ignition energy [33].

The calculations use 0.2 mJ (methane) for the minimum ignition energy for gases. This is a conservative value to use because the higher the MIE for gas, as in the equation below, the higher the dust explosion frequency becomes.

Appendix E – Number of ignitable dust clouds, presents the number of times per year an ignitable dust cloud is estimated to form in the different process units.

Careful consideration must also be given to the number and the severity of the different ignition sources that are present in the different process units. It is very difficult to estimate the number of ignition sources and their severity. As a result, a semi-quantitative value, $F_{ignition}$, is introduced, see Table 6.

Table 6, Semi-quantitative ignition source variables

	$F_{ignition}$
Very few possible ignition sources	0.5
Some possible ignition sources	1
Many possible ignition sources	2
Many sever possible ignition sources	4

All the above mentioned factors affect the probability and by that the frequency for dust explosions. All the factors were combined in a formula constructed for this report. A sensitivity analysis was conducted on the formula to determine how uncertain it is. The sensitivity analysis is presented in chapter 6.2. The formula is:

$$f_{ex} = \frac{P_{base}}{MIE_{dust} / MIE_{gas}} \cdot F_{ignition} \cdot N_{atm} \cdot P_{ex}$$

where:

f_{ex}	frequency for a dust explosion (times/year)
P_{base}	base ignition probability (0.0001 is used in the calculations)
MIE_{dust}	Minimum ignition energy for the dust (mJ)
MIE_{gas}	Minimum ignition energy gas (0.2 mJ is used in the calculations)
$F_{ignition}$	Ignition source factor
N_{atm}	Estimated number of ignitable dust clouds per year
P_{ex}	Probability for explosion given ignition (0.1 is used in the calculations)

MIE for dust through MIE for gas equals how many times more energy is required to ignite the dust compared to a gas. The base probability is divided with this number and multiplied with the number of times an ignitable dust cloud occurs per year, the probability for an explosion given ignition, and a correction factor for how many and how sever ignition sources are present. This gives the frequency for a dust explosion for each scenario from the Event Tree, as presented in Table 7.

Table 7, Results from dust explosion frequency calculations

Process unit	Present dust	MIE_{dust} (mJ)	$F_{ignition}$	N_{atm}	f_{ex}
Moulding Line Hall (PHA scenario)					**∑ 4.7×10^{-3}**
Starch separating drum (**M1**)	Maize Starch	30	1	30	2×10^{-6}
Sieve (**M2**)	Maize Starch	30	1	2000	1.3×10^{-4}
Surge Bin (**M3**)	Maize Starch	30	0.5	50	1.6×10^{-6}
Process Filter (**M4**)	Maize Starch	30	2	3000	4×10^{-4}
Powder Dryer (**M5**)	Maize Starch	30	4	9000	2.4×10^{-3}
Powder Cooler (**M6**)	Maize Starch	30	2	9000	1.2×10^{-3}
Fine Sieve (**M7**)	Maize Starch	30	1	9000	6×10^{-4}
Manuell Drageé					**∑ 1.3×10^{-4}**
Process filter (**Z2**)	Mainly fine sugar dust	30	2	1000	1.3×10^{-4}
Dust deposit (**Z1**)	Mainly fine sugar dust	30	0.5	2	6.6×10^{-8}
Grinding and Sugar room					**∑ 9.9×10^{-4}**
Grinder (**G1**)	Gum Arabic	100	4	6000	4.8×10^{-4}
Hopper (**G2**)	Gum Arabic	100	4	6000	4.8×10^{-4}
Main sugar silo (**G7**)	Sugar	300 (finest fractions)	1	5000	3.3×10^{-5}
AZO room					**∑ 2.7×10^{-4}**
Starch Cloud in room (**A1**)	Starch	30	0.5	0.5	$1{,}7\times10^{-8}$
Pipe or Screw (**A2**)	Starch (worst case)	30	0.5	3000	10^{-4}
Gum Arabic tank (**A4**)	Gum Arabic	100	0.5	6000	6×10^{-5}
Foam tank (**A6**)	Starch (worst case)	30	0.5	3000	10^{-4}
Aspiration filter (**A7**)	Fine Starch (worst case)	20	2	50	10^{-5}
GA-Kitchen	Starch	30	1	8000	**∑ 5.3×10^{-4}**

(P2)					
Drying Chambers					**∑ 4×10^{-7}**
New (**D1**)	Maize Starch	30	1	5	3.3×10^{-7}
Old (**D2**)	Maize Starch	30	0.5	2	6.6×10^{-8}
All					**∑ 5.7×10^{-3}**

6 Results and risk evaluation

In this chapter results will be discussed and a sensitivity analysis is presented.

6.1 Results from event trees

The event trees provide an estimated number of the damage, given that a dust explosion has occurred for each location or event tree. The damage was given in number of injured, killed and the economic damage in euro (€) for each event tree. The mean value results from the event trees are presented in Table 8 together with the estimated scenario frequencies from chapter 5.5. The highest values are presented in bold typeface.

The frequency, mean number of injured and the economic damage is superiorly higher for the moulding line hall scenarios than any other location. The mean number of injured is 0.28 persons given an explosion in the moulding line hall and the mean economic damage given an explosion is € 1 267 000. A few reasons can explain the relatively *high* values for injuries: there are usually quite a few people in the moulding line hall compared to other areas examined in this report, there are quite a few different dust explosion risk sources in the moulding line hall area where the powder cooler, the powder dryer and the process filter reside, contributing to the majority of the consequence. One last reason for the high consequences is that the pressure relief vents mounted on the powder cooler, the powder dryer and the process filter are all vented indoors which leads to flame spread and pressure waves inside, and in some scenarios, to a partial collapse of the building.

The manual drageé is estimated to have the highest death rate given an explosion at 0.11. This high value has two main reasons. First of all there are usually a lot of people in the room; according to observations during the three week visit to the plant there were between 2 and 5 people in the room depending on the current production level. The second reason is that there are a lot of extensive dust deposits in the room. If an initial dust explosion, any other explosion or in some cases a fire would occur, the probability for a large secondary explosion would be high.

The values from the grinding room must also be considered high. Especially since there are only two different dust explosion risks there.

Table 8. Frequency estimations and mean consequences from the event tree, highest values are in bold.

Event Tree (location)	**∑ frequency (f_{ex})**	**Mean number of injured given an explosion**	**Mean number of deaths given an explosion**	**Mean Economic damage given explosion (€)**
Moulding line hall	**$\sum 4.7\times10^{-3}$**	**0.28**	0.07	**1267000**
Manuell Drageé	$\sum 1.3\times10^{-4}$	0.05	**0.11**	39960
Grinding and sugar room	$\sum 9.9\times10^{-4}$	0.04	0.04	91160
Azo room	$\sum 2.7\times10^{-4}$	0.09	0.04	10960
Ga kitchen	$\sum 5.3\times10^{-4}$	0.05	0.003	42450
Drying chambers	$\sum 4\times10^{-7}$	0.10	0.05	36000

The frequencies and the consequences are alone hard to compare with each other. When multiplying the frequency and the consequence for each scenario and each different consequence the result given is a damage frequency per year. It gives the annual estimated consequences for each year. The damage frequencies are presented in Table 9.

Table 9. Estimated damage frequencies, highest values and the summarized values are in bold.

Event Tree (location)	Estimated injured per year	Estimated deaths per year	Estimated economic damage per year (€)
Moulding line hall	**1.3×10^{-3}**	**3.3×10^{-4}**	**5950**
Manuell Drageé	6.5×10^{-6}	1.4×10^{-5}	5
Grinding and sugar room	4.0×10^{-5}	4.0×10^{-5}	90
Azo room	2.4×10^{-5}	1.1×10^{-5}	3
Ga kitchen	2.7×10^{-5}	1.6×10^{-6}	22
Drying chambers	4.0×10^{-8}	2.0×10^{-8}	< 1
∑	**1.4×10^{-3}**	**4.0×10^{-4}**	**6070**

Table 9 shows that the moulding line hall contributes massively to the total risk. 92 % of the total expected number of injuries, 83 % of the deaths and all of 98 % of the economic damage is due to the moulding line hall scenarios. This represents a sensationally high part of the total expected loss.

The reasons for the high values in Table 9 for the moulding line hall are many. As mentioned before in this chapter, there are a lot of risk sources in this hall, with many ignition sources, and dust clouds are virtually continuous. On top of this the explosion pressure relief for the equipment is indoors and there are quite a lot of dust deposits present that can cause a secondary explosion. Maize starch, the most commonly handled dust, has serious explosion characteristics [22] [1]. Starch was the cause of all dust explosions reported from the food processing industry according to arbetsmiljöförordningen § 2 [35] between 2004 and 2005, up until June 2005 [21]. This explains why the consequence and the probability for a dust explosion in the moulding line hall scenarios are high compared to the other scenarios.

Other noticeable results from the event tree calculations are that the risk in the GA-kitchen is low and the risk in the drying chambers is very low. The calculated value for the drying chambers at 2.0×10^{-8} deaths per year means that there is one expected dust explosion every 50 million years.

The total risk for injuries is calculated to 1.4×10^{-3}; this is equivalent to one injury due to dust explosions about once every 700 years. The total risk for death due to a dust explosion comes to 4.0×10^{-4}, which is once in 2500 years. The economic risk due to dust explosions is about € 6000 per year.

With only one type of risk being addressed in this report, the total risk must be considered as high when it comes to injuries and deaths. In reality there are probably other risks, such as fire and fall accidents, that are greater.

For the economic damage € 6000 might not seem very high but in the long run it ads up to quite a lot of money. The calculated amount could be seen as a very rough estimate of what Leaf could reasonably invest every year in dust explosion precautions. For a further discussion on acceptable risk see chapter 6.3.

6.2 Sensitivity analysis and uncertainties

Risks in the moulding line hall dominate the calculated value for the risk at Leaf. Because of this a sensitivity and uncertainty analysis was performed for these dust explosion scenarios. The risk consists of two parts: the consequence and the probability. Each of these parts then consists of a number of different parameters, values and assumptions. Some of the values are fairly exact values, for example, the volume of the vessels, which is a parameter used in the calculation of the consequences. Other parameters are more uncertain and have been roughly estimated; examples of such parameters are the number of ignitable dust clouds per year and the entire estimation of the ignition probability. These roughly estimated values contribute mostly to the uncertainty and therefore need to be addressed with a sensitivity and uncertainty analysis.

6.2.1 Dust explosion frequency

The estimation of dust explosion frequencies that were calculated in chapter 5.5 is probably the most uncertain value in the entire risk estimation. Therefore, all the variables are changed to determine which values have the largest influence on the final result. The first value for each variable below is the value used in the original calculations and the values in parenthesis are the maximum and minimum value used in the sensitivity analysis.

- Base ignition probability: 0.0001 (0.001 : 0.00001)
- Minimum ignition energy: (± 50%)
- Ignition source factor (times 1/4 : times 4)
- Number of dust clouds (± 50%)

The base ignition probability and the ignition source factor were given the largest span, because these values are estimated to have the largest number of uncertainties. The values are first changed one at a time and then the two values with the largest effect on the final result are then changed at the same time.

The two most influential values were found to be the base ignition probability and ignition source factor. If these two values are changed at the same time in the most favourable and worst way this gives a minimum and a maximum ignition probability. The results for the moulding line hall are presented in Table 10.

Table 10. Dust explosion frequencies, sensitivity analysis for the moulding line hall

Process unit	Maximum frequency	Minimum frequency	Expected value
Moulding Line Hall (PHA scenario)	**∑ 1.8×10^{-1}**	**∑ 1.2×10^{-4}**	**∑ 4.7×10^{-3}**
Starch separating drum (**M1**)	8×10^{-5}	5×10^{-8}	2×10^{-6}
Sieve (**M2**)	5×10^{-3}	3.3×10^{-6}	1.3×10^{-4}
Surge Bin (**M3**)	6.4×10^{-5}	4×10^{-8}	1.6×10^{-6}
Process Filter (**M4**)	1.6×10^{-2}	1×10^{-5}	4×10^{-4}
Powder Dryer (**M5**)	9.6×10^{-2}	6×10^{-5}	2.4×10^{-3}
Powder Cooler (**M6**)	4.8×10^{-2}	3×10^{-5}	1.2×10^{-3}
Fine Sieve (**M7**)	2.4×10^{-2}	1.5×10^{-5}	6×10^{-4}

6.2.2 Consequences

The consequence calculations must be considered to be conservative; the formulas used for the pressure waves from a rupturing vessel are based on TNT-equivalence models that are conservative for dust explosions [31] and on the assumption that there is enough dust evenly distributed in the air to burn off all oxygen down to 10 %. This represents a worst-case scenario and should be fairly conservative.

The radiation calculations are also fairly conservative especially because the model used to calculate the flame lengths is conservative. [11]

Because conservative formulas were used no sensitivity analysis was performed on the consequence calculations except in regard to the flame temperature. The radiation from a flame is very dependent on the flame temperature. The flame temperature was changed between 900 K and 1200 K. The distance to injuries was changed slightly, but it did not affect the number of injuries due to the low number of staff density in the investigated locations.

6.2.3 Event tree

The branch probabilities in the event trees are based on statistics and other assumptions such as the number of available ignition sources and the dust's sensitivity to them. The branch probabilities were changed in the way that the worst scenarios, i.e. the large explosions, were increased and decreased by 50 %, and the same thing was done with the probabilities for a secondary explosion.

For the moulding line hall scenario, given a dust explosion, the number of dead would be between 0.036 and 0.094 compared to the original value of 0.066 given an explosion. Combining these values with the probabilities in Table 10 will give an estimated risk for the moulding line hall to be between 4.3×10^{-6} and 1.7×10^{-2}. This means that there will be one death due to dust explosions in the moulding line hall every 59 to 232,558 years. This should be compared with the original estimate of one death in 2,500 years.

6.2.4 Discussion on uncertainties

It can easily be concluded that the uncertainties are enormous, and that is a fact. Many of the values used in the calculations are very uncertain. In the uncertainty analysis the values have been changed and then combined in the most favourable and the worst way. This gives the very large span of the risk. It is not likely that the end values would represent the actual risk at the plant because of the favourable and unfavourable combination of values. The only thing that can be said is that the risk is somewhere in between the end values.

There are so many uncertainties in the calculations that it is difficult to use them to give exact recommendations on improving the dust explosion safety or to suggest improvements in the dry powder system. As a result, the risk analysis section of this report can only be seen as a tool to point out possible hazards in the plant. Some conclusions can be drawn on what processes are the most dangerous, but how dangerous they are, is hard to say.

6.3 Risk assessment

What is an acceptable risk? It is very hard to answer this question. Different organisations and standards have different criteria for what is acceptable. Comparing the estimated risk to one of these standards is a method often used, but in this case, the estimated risk is very uncertain. Because of this large uncertainty, a comparison with standard risk criteria might not be extremely meaningful, but it at least says something about the risk. One can also compare the estimated risk to the statistical risk in similar industries, but in the case of dust explosions, statistical records are very few.

A quote that very well sums up the difficulties that have been encountered during the work with this report is:

"In practice, the assessment of dust explosion hazards is bound to be subjective, because the problem is too complex for quantitative analytical methods to yield an indisputable answer" [1]

The calculated results in this report are, of course, not indisputable and they are based on assumptions, and the uncertainty is large. Because of this the recommended actions in chapter 7 are subjective to the author of this report.

Even though it is impossible to do a good quantitative risk assessment on dust explosions, it is still important to compare the values calculated, keeping the uncertainties in mind.

A common way of presenting risk is by *individual risk,IR*. The individual risk is usually expressed in terms of the risk of dying per year. There are several different kinds of individual risk standards, for example, the *place-specific individual risk* is the most common. This gives the probability of dying for a hypothetical person standing in a certain place all the time. [36]

The individual risk used in this report is the *Average individual risk* which defines as the number of deaths per year (statistical or estimated) divided by number of people exposed to the risk.[36]

In this case the number of deaths per year due to dust explosions was estimated as 4.0×10^{-4}. There are about 150 people working in the factory and this would make the IR 2.7×10^{-6}. Compare this to, for example, *Resecentrum* in Linköping, Sweden that has a maximum tolerable risk of 10^{-4} for employees, or BP/OK Refinery in Gothenburg, Sweden that has a maximum tolerable risk for employees of 10^{-3}. [36]

The calculated risk at Leaf is well below these values, but there are two factors that influence the risk assessment and make the risk at Leaf higher. The first is that the calculated IR is only calculated for dust explosions; the employees are also exposed to other risks that should be taken into account in the IR. The second factor is that some employees are exposed to the dust explosion risk more than others. A rough estimate is that about 35 individuals are exposed to the dust explosion risk more often, depending on their place of work in the factory. This would give an IR for these people of 1.1×10^{-5} which is considerably larger than 2.7×10^{-6}.

The risk is not estimated as extremely high, but because this is just one of several risks, it is estimated to be too high and requires some actions.

7 Recommended actions

The risk due to possible dust explosions is a bit too high. The moulding line and the mill — especially the powder dryer, the powder cooler, the process filters, the mill and possibly the main sugar tank— contributes a lot to the risk. These process equipments require a technical solution to attain an acceptable risk. In other parts of the plant, Leaf can implement non technical solutions to increase the safety considerably. For example, improving housekeeping, increasing dust explosion awareness, and making maintenance better and more aware can all add to the safety of the plant.

7.1 Housekeeping

Most dust explosion literature talks about the enormous importance of good housekeeping to prevent the largest and most powerful and destructive dust explosions [1] [11]. This must be considered to be a relatively easy and cheap protection against damages due to dust explosions. In reality it can, however, be hard to achieve and maintain a good housekeeping. Observations during the visit at Leaf identified a few reasons why a good housekeeping is hard to achieve. The processes in a plant like Leaf Gävle produce a large quantity of dust that continuously spread in the facilities. This requires a very regular cleaning that might be hard to maintain during times of high production rate.

Providing the employees with information as to why it is important to get rid of the dust can help ensure that even in the busiest of production schedules, cleaning remains regular. Chapter 9 presents more information on this communication to the employees. The problem can also be lessened by installing ventilation and modifying process equipment so that they run in a cleaner way and do not spread the dust as much in the facilities. There is a project going on to seal the process equipment in the moulding line hall to avoid powder spread in the facility. The reason for this project is to insure high powder quality and minimize powder wastage. A positive side effect of the project will hopefully be a smaller probability of a secondary explosion in the moulding line hall. The possibility of expanding the project to concerning other parts of the plant must be considered. It could for example include the gum emptying equipment in the AZO room and the manual drageé. This would minimize the dust accumulation in these locations.

Another problem is that dust deposits in areas that are hard to reach, for example on beams and pipes in the ceiling, behind, on top and underneath machines. In this case it is once again important to relay communication as to why it is important to clean up the dust, but it is also important to provide proper equipment and tools so that all areas can be easily accessed for cleaning. Leaf should identify areas that are hard to reach, and make sure that proper equipment, such as ladders, is readily available in these areas.

In the survey described in chapter 8 some of the staff said that lack of time was a factor that prevented a good housekeeping. If providing information and equipment does not solve the problem, Leaf should consider increasing the number of cleaners employed.

7.2 Technical actions

Six areas of the factory were identified as needing technical solutions. These are

- Rubber bends in the pneumatic conveying system
- Powder dryer
- Powder cooler
- Process filters in the moulding line hall
- Mill
- Main sugar Tank

Leaf should change all rubber bends to flexible metal bends to avoid static electricity build up. The metal pipes are grounded, but the rubber parts are non conducting. This can lead to a build up of different electric potentials, and this can lead to a static electricity spark jumping between rubber and metal and that could ignite a dust cloud. [11]

The explosion vents on the powder cooler and the powder dryer should be fitted so that they open up to a safe place outdoors. This could probably be relatively easy to achieve for the powder cooler, because this is placed next to an outside wall. The powder dryer, however, is not placed next to an outside wall. If it is not possible to change this, Leaf must consider other technical solutions such as auto-inerting.

The problem with the process filters in the moulding line hall is similar to the problem with the powder dryer. They are not next to an outside wall and the pressure relief vents open indoors. Leaf should also consider an auto-inerting system or explosion resistant equipment for the process filters.

The GA-mill could cause a severe explosion, because of this a technical solution should be considered. One possibility is to install a auto-inerting system.

The possibility of installing a pressure relief vent on the main sugar tank should be considered. The probability of an explosion here was estimated to be low, but the consequences could be devastating.

7.3 Awareness

Leaf must increase the dust explosion awareness among all employees that have any contact with the dry powder system in order to ensure a safe behaviour when it comes to the risk of dust explosions. Chapter 9 continues the discussion on the awareness communication.

7.4 Maintenance

The maintenance crew's lack of dust explosion knowledge, as described in chapter 8.4, certainly decreases the safety at Leaf. As it is today, the staff does not know what can cause dust explosions and they do not know the circumstances that increase the likelihood of a dust explosion. Leaf must consider this a very serious knowledge gap, address it and improve this knowledge. If the maintenance crew becomes more aware of the dust explosion risk, the dry powder system will become safer. If they know what can cause a dust explosion and why, they can perform the maintenance in a safer way and they would know why they have to maintain dust explosion equipment. Today, for example, there is little to no maintenance performed on pressure relief panels. Leaf needs to create routines for regular maintenance on dust explosion equipment and other equipment relative to dust explosion safety.

The maintenance crew needs to know how all dry powder process equipment is designed, and should be maintained, to avoid dust explosions. If they would know this they would probably to a much larger extent perform the required maintenance and change the equipment that is not dust explosion safe. Chapter 9 continues the discussion on how to achieve this increased knowledge.

7.5 Long-term improvements

Over time there are a lot of changes that Leaf can do to continuously improve the safety. As in any other plant, equipment will get old and worn and need changing or replacing. It is important to consider the safety aspects when making changes or buying new equipment. It is often much cheaper to buy dust explosion safe or resistant equipment from the beginning than doing modifications afterwards.

It is also important to have a management system that works. The management system should include goals with deadlines to continuously improve the safety. It is important that the management system is well known by the employees and by the management and that it is continuously updated.

8 Dust Explosion Awareness Survey

When the work of this report was started it was announced by Daniel Norman [24] in the Leaf company news letter that a study of the dust explosion risks at the plant had been started. Norman received a phone call shortly after the news letter was published from a co-worker at the plant. The caller expressed concern about the cleaning of the offices in the factory and wanted the study to include the filth dust in the offices. This was the first indication that the dust explosion awareness at the plant could be low.

Knowing the staff's level of risk awareness is essential to conducting good and effective risk communication. What does the staff actually know about the risk? In the case of this report the risk is the risk of dust explosions. How high or low is the awareness of dust explosions among the staff at a factory that handles large quantities of dust? Although this question is very important to answer in order to conduct high-quality risk management work, there is no literature or reports that discuss this exact subject. There is some work that touches upon the subject when discussing risk awareness in general but it is not specific enough. In the available literature it seems that most authors have the impression that the risk awareness among staff at dust handling plants is low, see for example Barton [11], and Mitchell [4].

8.1 The Survey

Using a traditional questionnaire, see Appendix H - Survey, the survey examined two target groups. The first step in creating the questionnaire was deciding what parameters to examine, in this case, the parameters that affect communication regarding the risk of dust explosions. It was decided that the questionnaire should address seven key areas:

1. General information
2. Awareness of dust explosions
3. Awareness of fire control
4. Awareness of who they can turn to with questions and information
5. Safety
6. Responsibility and housekeeping
7. Reporting culture

When this was decided the *Administrativ S-H-M revision* [37] was used as a benchmark to create the exact questions for each area.

8.1.1 General information

The general information section in the questionnaire is used to find out basic information about the respondents, i.e. sex, what position they have at Leaf , in what way they have contact with the dry powders (cleaning, maintenance etc.) and how long they have worked at Leaf.

8.1.2 Awareness of dust explosions

This section of the questionnaire asks what the respondents know about dust explosions. Have they ever heard of this phenomenon? How well do they know the circumstances that can cause a dust explosion to occur? Do they know of any dust explosion that has happened? And which dusts and what ignition sources at Leaf could cause a dust explosion?

8.1.3 Awareness of fire control

This section asks how they would act in case of a fire and if they have had any training in fire extinguishing. Do they know what to do in case of a fire?

8.1.4 Awareness of who to turn to with questions

This section inquires about the risk communication at the company and if the staff knows who they can turn to if they have questions or information to give regarding dust explosions.

8.1.5 Safety

This section is about how the respondents feel about the safety at the plant.

8.1.6 Responsibility and housekeeping

This section asks the respondents how they feel about the removal (cleaning) of dust in the plant, if they are encouraged by their superiors to clean their work place, and if they think the current cleaning routines work. There is also a question about how much personal responsibility they feel about the safety at the factory.

8.1.7 Reporting culture

This section has three questions on how the respondents would act in different situations and if they would report the incident. Would they report an incident that could have resulted in an accident but did not? Would they report a colleague that caused an incident? Would they report damages to a machine or other process unit that works despite the damage?

8.2 The questionnaire

The questionnaire consists of a few Yes or No questions plus a few questions that require a written answer in a few words or maybe a full sentence. The majority of questions, however, have multiple choice options. There are five choices for each multiple choice question ranging from poor/never/a lot/bad to very-good/always/very-little depending on the question. When the questionnaires are graded poor/never/a lot/bad gets 1 point and very-good/always/very-little gets 5 points. The answers are given points in order to calculate average values from the answers.

The survey questionnaire is presented in Appendix H - Survey, and the complete results from the questionnaires are presented in Appendix I – Survey results for operators and Appendix J – Survey results for maintenance crew.

8.3 Two different survey groups

The staff at Leaf was divided into two groups: maintenance crew and operators. The reason for this is that the two groups perform very different tasks and come in contact with the dry powder system in different ways. The maintenance crew consists of 19 people and they do repairs, installations and any other form of maintenance. There are about 150 operators and they operate the machines, do housekeeping and perform many other tasks in the factory with the exception of maintenance.

The questionnaire was given to everyone in the maintenance crew (19 people) and 17 crew members returned an answered questionnaire. The questionnaire was also given to 39 randomly selected operators of the total 110 operators; 26 operators returned an answered form. The low answering frequency can possibly to some extent be explained by the fact that the study was conducted during vacation times.

8.4 Results for maintenance crew

In this chapter the results from the survey conducted on the maintenance crew will be presented.

8.4.1 General information

There are only male people working in the maintenance crew and the average person has worked at Leaf for 11 years. Eight people stated that they, in addition to general maintenance, also do welding.

8.4.2 Awareness of dust explosions

Everyone has heard of dust explosions and knows what it means. Regarding the question of how well they know the circumstances that can cause a dust explosion to occur, the average value is 2.7 which means between pretty good and poor on the multiple choice scale for this question.

Only three of the respondents knew of any dust explosion that has happened. On the question regarding how much information they have received from Leaf about dust explosions the average value is 1.4 which is between very little and none.

The actual knowledge about the dust explosion risk at Leaf was tested via two multiple choice questions. The first question asked respondents to select the dust that they thought could cause a dust explosion from a list of all present dusts at Leaf. The average person knew 1.3 out of the six possible explosive dusts[1]. The next question had the same structure as the first; five ignition sources were listed, all of them could initiate a dust explosion, and the average person knew 2.8 out of the five.

8.4.3 Awareness of fire control

Regarding the question of how they would extinguish a fire, the majority answered that they would use the closest available extinguisher. All respondents except three has had education in fire extinguishing and everyone says that they know what to do if a fire should occur.

8.4.4 Awareness of who to turn to with questions

A surprising result is that eight people said that they do not know who they should turn to if they have safety questions. Everyone said, however, that they knew who to turn to if they found a damaged machine or other process equipment.

8.4.5 Safety

Regarding the question of how they view the safety at the plant the average answer was 3.1 which correspond to *pretty good* in the multiple choices. They also seem to estimate their personal risk of getting injured as pretty small (3.1).

8.4.6 Responsibility and housekeeping

The survey answers show that people feel that they are *pretty much* (2.8) encouraged by their superiors to clean up dust but they think that the dust cleaning is *poorly* (2.3) done in the plant.

They further seem to feel in-between *much* and *pretty much* (3.5) regarding their personal responsibility for the safety at the factory.

8.4.7 Reporting culture

The respondents say that they *very likely* would report incidents that could have led to an accident but did not with a score of 3.9. They would also very likely report a damaged machine that was still working with a very high score of 4.5. A little lower willingness to

[1] It should be noted that when marking a dust as explosive when it is not (salt and salmiak) they received -1 point for that mark.

report co-workers that caused an incident that could have become an accident but did not is clear at a score of 3.4.

8.5 Results for the operators

In this chapter the results from the survey conducted on the operators will be presented.

8.5.1 General information

Among the respondents there are eight females and 18 males working as operators and the average person has worked at Leaf for almost nine years. The operators' handling of dust varies a lot from individual to individual. In addition to operating the processes they do cleaning, vacuuming, and a few of them state that they also do some maintenance.

8.5.2 Awareness of dust explosions

16 of the 26 responding operators have heard of the phenomenon dust explosion. Regarding the question of how well they know the circumstances that could cause a dust explosion to occur, the average value is 1.8 which means between *little* and *not at all* on the multiple choice scale for this question.

Only one of the respondents stated that he knew of a dust explosion that had happened. Regarding the question regarding how much information they have received from Leaf about dust explosions the average value is 1.3 which is in-between *very little* and *none*.

The actual knowledge about the dust explosion risk at Leaf was tested via two multiple choice questions. The first question asked respondents to select the dust that they thought could cause a dust explosion from a list of all present dusts at Leaf. The average person knew 0.5 out of the six possible explosive dusts[2]. The next question had the same structure as the first; five ignition sources were listed, all of them could initiate a dust explosion, and the average person knew 1.6 out of the five.

8.5.3 Awareness of fire control

Regarding the question of how they would extinguish a fire the answers varied; seven answered that they did not know, three answered that they would use the closest available extinguisher, while the rest of the responses varied between using foam, water and powder extinguishers. The operators do not get education in using a fire extinguisher from Leaf, as the maintenance crew do [24]; seven of the operators have, however, had some form of fire extinguishing education. Only four respondents said that they do not know what to do in case of a fire, two respondents did not answer this question.

8.5.4 Awareness of who to turn to with questions

Only six people out of the 26 respondents answered that they knew who to turn to if they had questions about fire and safety. Almost all respondents except two knew who they should turn to in case a machine was damaged.

8.5.5 Safety

Regarding the question of how they view the safety at the plant, the average answer was 2.9 which corresponds to *pretty good* in the multiple choices. Furthermore, they seem to estimate their personal risk of getting injured as *pretty small* (2.8).

[2] It should be noted that when marking a dust as explosive when it is not (salt and salmiak) they received -1 point for that mark.

8.5.6 Responsibility and housekeeping

The survey answers show that people feel that they are *pretty much* (3.2) encouraged by their superiors to clean up dust and they think that the dust cleaning done in the plant is *pretty good* (3.0).

Furthermore, they seem to *pretty much* feel (3.1) personal responsibility for the safety at the factory.

8.5.7 Reporting culture

The respondents said that they *very likely* would report incidents that could have led to an accident but did not with a score of 4.1. They would also very likely report a damaged machine that was still working with a very high score of 4.4. The willingness to report co-workers that caused an incident that could have become an accident but did not was scored a little lower at a 3.6.

8.6 Discussion and conclusions

It can easily be said that the dust explosion awareness and knowledge is very low, especially for the operators. It is a bit higher for the maintenance crew, but even their results must be considered low. The maintenance crew judge their own knowledge as 2.7 which corresponds to *pretty good* but the questions relating to which dust at Leaf could possibly cause a dust explosion and what ignition sources could initiate it tell another story. The answers from this question show that the knowledge actually is low.

The knowledge about dust explosions is considered too low for the staff to be able to act in a safe manner when it comes to the handling of dusts. Everyone at the plant does not have to know everything about dust explosions, but they do need to have a basic knowledge and awareness of the risk. The amount of knowledge that would be appropriate varies from person to person depending on their specific type of work. The maintenance crew will need more knowledge than the operators. This is because it is important to understand under what circumstances a dust explosion can occur and what can be done to prevent one when doing installations and maintenance. As an example, if a machine breaks down, or for any other reason needs to be modified or changed, it is important to understand what the modifications will do to the risk of a dust explosion. If they have this knowledge they could do the changes in a safer way.

On the other hand, for an operator whose only contact with dust is during vacuuming, it might be sufficient if they are aware of dust explosions and that they should avoid sucking up metal parts, hot material and glowing particles during vacuuming.

Adjusting the amount of information and education that each group of employees needs is important. If too much information is given there might be a risk that some things are ignored and important information is missed.

The awareness of fire extinguishing is relatively high for the maintenance crew but pretty low for the operators. It is important that a sufficient number of employees with dust extinguishing knowledge are always in the plant. A very high number of respondents, both among operators and maintenance crew, answered that they would use the closest available fire extinguisher in case of a fire. This is a problem that needs addressing because there are mainly CO_2 extinguishers in the plant and these are not recommended for use on burning dust or powder [11]. The staff should get information on how to put out fires in dust and/or the extinguishers should simply be changed to water or foam extinguishers.

Almost everyone seems to know who to turn to if a machine breaks down, but a relatively large number of respondents said that they did not know who to turn to with safety questions. This is also a matter that will need addressing.

The experience of safety seems to be pretty high, and superiors seem to encourage their staff to clean away dust deposits in the premises. People, however, seem to think that the dust cleaning is not working very well.

The respondents show a very high willingness to report accidents and they feel a large personal responsibility for the safety in the plant which is very good. There is, however, a possible *bias* present in the answers about personal responsibility and reporting culture. There could be a connection between the people that have chosen to fill out and return this survey and the willingness to report incidents, accidents and failures. It is not unlikely that the people with the highest willingness to report something also have a higher willingness to fill out questionnaires than the average worker.

9 Risk Communication

Risk communication is essential to be able to improve the safety in any company. Risk Communication is however very complex and a lot of parameters must be considered. For example [38]:

- What is the message that should be communicated?
- How do the receivers perceive the risk and the message?
- What knowledge do the receivers have of the risk?
- How can the communication be evaluated?

In chapter 9.1 different risk communication methods will be discussed and in chapter 9.2 risk perception will be discussed.

9.1 Different risk communication approaches

There are numerous different risk communication methods and approaches described in different literature, for example, *Risk Communication* by Lundgren and McMakin [38] and *Risk Communication* by Morgan & Fischhoff et al. [39]. The various methods and approaches are designed for use in different risk communications situations.

Although there are a lot more risk communication approaches than the ones described in chapter9.1.1-9.1.7, the approaches discussed have been assessed to be relevant to the risk communication of dust explosions to factory employees.

9.1.1 Communication Process Approach

The *communication process approach* is a classical and very basic approach to communication. It consists of a sender and a receiver of a message and the message passes between the two in a channel. [38]

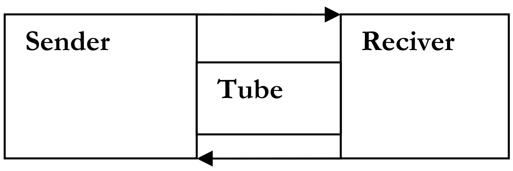

Figure 18. Illustration of the Communication process approach.

This is a very simple description of the risk communication process, but it is an effective way of showing the important parts and emphasising that all three parts— sender, receiver and tube— must be identified and considered. Questions to consider are: What is the message of the sender? How is the message presented to the receiver? Has the receiver understood the message? [38]

In the case of dust explosion risk communication at Leaf in Gävle the sender is the company's management. The tube could be any medium that is used to communicate the risk, for example, warning signs, lectures, brochures and seminars. The receivers at Leaf are the Operators and the maintenance crew.

9.1.2 Mental Models Approach

The principal for the *mental models approach* is to inform the receivers of the risk communication so that they can make educated decisions.

The first step is to examine what the public, employees or any other receivers actually know about a certain risk and their attitudes towards that risk. Surveys, questionnaires and interviews can provide this information. Upon learning what the receivers actually know, the risk communication is designed to give the receivers the information that they lack. This is not done to form consensus between experts and so called "lay people" but it is instead done so that the lay people or receivers can make informed decisions for themselves.

As a last step it is important to evaluate the risk communication by examining whether the receivers understood and absorbed the information. [39]

9.1.3 Comment to the mental models approach

The mental models approach is designed more as a mechanism to inform a general public of health hazards, such as eating fast food or sunbathing, rather than informing employees at production plants of the risk of accidents or, in this case, dust explosions.

The mental models approach is, however, not useless in the case of dust explosions as it emphasises some important communication aspects. The first aspect is to find out what the receivers actually know and their attitudes, and with that, decide what additional information to provide them. The second aspect is to evaluate the results of the risk communication and determine if the staff has understood the information and changed any unsafe behaviours or delusions.

When developing dust explosion information to provide to the employees at Leaf Gävle, it is more important to reach consensus about the risk than what the mental models approach suggests. This is because the risk that unsafe behaviour, delusions or lack of knowledge pose could affect the lives and health of other employees as well as company property.

9.1.4 Three-Challenge Approach

The *three-challenge approach* outlines three important parts or *challenges* of the communication process, they are:

- "**knowledge challenge** – the audience needs to be able to understand the technical information surrounding the risk assessment"
- "**a process challenge** – the audience needs to feel involved in the risk management process"
- "**communication skills challenge** – the audience and those who are communicating the risk need to be able to communicate effectively"

The above quotations are taken from Risk Communication by Lundgren & McMakin [38]

9.1.5 Comment to the Three–Challenge Approach

This approach addresses the risk communication from a somewhat different perspective than the other approaches described before. It focuses more on the softer parts of the communication process such as the mutual understanding between the communicating parties.

All three challenges must be considered important in the communication of the risk for dust explosions; the latter two challenges are, however, considered to be more important than the first. It is not always necessary for the receivers to understand the technical background of a risk; it can however sometimes make the communication easier. Communication with the maintenance crew at Leaf regarding the technical background will probably be easier since the crew already has some knowledge of the material being presented, see chapter 8. When providing the appropriate information to the operators, adhering to the principle *less is more* is perhaps the most effective. They should of course get enough background information to take the risk seriously, but giving them too much information could most likely lead to information being ignored.

The second challenge, involving employees in the risk management process, is considered to be of great importance. A feeling of involvement is considered to be a factor that generally contributes to making a workplace safer. [40]

The third and last challenge, though seemingly obvious, can sometimes pose a large challenge to many communicators. Obviously, communicating efficiently is preferable, but language barriers such as different educational backgrounds can make this challenge difficult. At Leaf the risk communication mainly comes from the management who are usually university graduates while the receivers of the communication, the employees, usually only have high school diplomas. Therefore, it is important to consider this divider when developing the communication, and a post evaluation of the communication can show if it was successful.

9.1.6 Social Network Contagion Approach

The *social network contagion approach* is based on studies that show that people dealing with a risk usually do what the other people present do. As a result, social networks are very important, especially the values in a network, because this is usually similar throughout all in the network. The approach suggests targeting "key social leaders" as the receivers for the communication. This method is especially useful in crisis communication when time is limited. [38]

9.1.7 Comment to the Social Network Contagion Approach

Even though this approach is meant for crisis communication it stresses the importance of social leaders. For instance, people will often follow those they look up to even if they act in an incorrect manner.

At Leaf there are individuals who are so called "*coordinators*"; they lead about five people. It is uncertain, however, how the subordinates view their coordinators, and whether they are considered social leaders. When using this approach, the above mentioned questions should be investigated. It is nevertheless important that these coordinators have good knowledge and act in a safe and appropriate manner. One way of ensuring this is to give them targeted extra information, for example, through lectures.

9.2 Risk perception

It is essential to understand the basics of risk perception in order to successfully accomplish a risk communication. Risk perception is an extensive and debated research field. Scientists have different opinions on what factors affect people's perception of risk and how large an effect the different factors have. Even though researchers disagree on the extent on the influence magnitude of different parameters there is consensus on the basic factors.

9.2.1 Parameters affecting risk perception

The perception of risk is very personal and differs from person to person. Some people are worried and afraid of flying while others really enjoy it. The reasons for this are many, if a risk can arise in many different ways or if mass media have reported a lot on a certain risk people tend to worry more about the risk. On the other hand, a risk that is well known tends to cause less worrying. This explains why people worry more about radiation from cell phones than driving a car even though scientists do not agree on the possible damages due to cell phone usage and everyone knows the risks of driving. [41]

Dread and if the risk is *unknown or known* are two of the most important parameters on how people perceive risks, according to Paul Slovic [42]. Sjöberg et al. however says that:

"Dread is probably a consequence of perceived risk, not a cause of it, and therefore it should not be used as an explanatory variable." [43]

Other factors that commonly ascribe to the risk perception are: [44]

- Familiarity with the risk source
- If the risk is voluntary
- Ability to control the risk
- Personal benefit from the risk source

9.2.2 Comments to risk perception

This chapter about risk perception is intentionally very basic, a lot more could have been said about the different parameters. The purpose of the chapter is basically just to say that people perceive risks differently. Understanding why people view the risk the way they do and how to potentially change that view is important for the risk communication of dust explosions.

As the survey in chapter 8 shows, the knowledge of dust explosions is very low among the staff at Leaf and people do not seem to worry very much of the risk. In fact, it is that very lack of knowledge that can perhaps, in large extent, explain why people do not worry; they simple are unaware of the risk. The basic risk perception parameters can also explain why employees worry little about dust explosions. First of all, the risk is not new and mass media pays so little attention to the risk that people don't even know it exists.

Secondly the risk source being *very* familiar is another very important reason for the lack of fear of dust explosions. The risk itself is not familiar, as the survey in chapter 8 shows, but the risk *source* is very familiar, i.e. dusts or powders. The powders at Leaf are mostly normal household food ingredients; most people are very familiar with sugar and flour and would not associate them with any explosion risk. The risk is simply not dreaded.

Most risk communication has the purpose of calming people down [53], it might be smart in this case to actually scare people a little bit, creating some dread.

One last factor explaining the lack of fright of dust explosions is that the employees benefit from the risk source; it is their work that gives cause to the risk. This is a common factor that explains a greater acceptance to risks [44].

9.3 Important communication parameters

Conducting effective risk prevention requires meaningful communication between involved staff categories and management [45]. Communication must be considered high priority if a company wants to achieve an increased safety. It does not make a difference if a company installs all the technical explosion prevention equipment in the world if that equipment is not installed and maintained correctly. Ensuring that the equipment is fully functional and that people behave in a safe way is essential to a company's level of safety.

Only two out of all 17 explosions that occurred during the period between 2003 and 2005 were due to technical failure; the majority was due to human error [21]. This shows that information and communication aimed to avoid human error is of great importance and can significantly improve the safety at a plant.

It is not uncommon that people inside an organisation communicate so poorly with each other that they simply do not get each others messages. [53]

9.3.1 Giving and receiving information

Eckhoff [45] lists three different requirements for people to receive and value information on dust explosions in an effective way. They are:

- Adequate knowledge
- Adequate motivation
- Adequate recourses and deciding power

Adequate knowledge is given through information in some form. It is important that the correct information is given and that it is given in a correct order. For example, it would not be wise to start with information on dust explosion prevention equipment if the receiving audience does not have basic knowledge about dust explosions or maybe does not even know of the phenomenon. The communication provider should start with the audience's basic knowledge and build from there.

Good lectures and good quality information can increase the employee's motivation to act more safely as well as report any problems. [45] An example of how to increase motivation and maybe awareness depending on what people know from the beginning is by using video [1] [11]. Video is a powerful way of showing how great the damaging forces are during a dust explosion. Most people have never seen a dust explosion in real life, nor on video or TV. To see the effects of a dust explosion would most definitely make people more aware of the seriousness of the phenomenon and, as a result, motivation would probably increase.

Resources and deciding power is a management issue [45]. Management must decide to get enough resources. It is also important that enough deciding power is present in the company to make changes in regard to safety precautions. At Leaf Gävle today, decisions and investments up to a certain amount can be decided locally, but if this limit is exceeded the decision must be made by the owners.

9.3.2 Common mistakes

It has been said that the technical work of a risk analysis is the easy part, the hard part is translating the analysis to understandable information [46]

"An effective communication must focus on the things that people need to know but do not already" [39]

The above quotation might seem very obvious but it is often violated. Very often the risk communicator, often the management, does not find out what the receivers of the communication actually know. They just communicate what they think the receivers should know. [39] This could lead to the receivers not getting the optimal information in an effective way. The receivers might ignore some of the information because part of it may be too basic or the company may give too much communication during one presentation.

Another common mistake is that the communicators talk down on the receivers. This could be very dangerous because people could ignore the information if the communicators have the wrong attitude. The communicators should always assume that the receivers are interested in the information [39].

It is common for the communicators to focus on what they are saying and not on what the receivers are hearing. [46] The communicators often simply say what they want to communicate and leave it to the receivers to freely interpret. It is important to avoid this and make sure that the correct message has been received. Using a good post-communication evaluation, for example interviews or questionnaires, can determine if the communication was effective.

Another common mistake is that the communication is not a dialogue but a monologue. It is very important with two way communication to avoid misunderstandings and to identify risks. A very effective way of achieving this dialogue is to have a good reporting and learning culture at the company. [47] For a further discussion on this see chapter 9.3.3 and 9.3.4.

9.3.3 Learning culture

It is of great importance that a company is continuously learning and improving its processes and defences. This will give the competitive edge in the market and hopefully guarantee the success and survival of the company. In the case of safety it is very important to learn from previous mistakes and miss-happenings. A person who makes a mistake is probably going to learn from this and not repeat it in the future, but it is of great significance that other people also learn from the mistake. Figure 19 illustrates organisational learning on three different levels. The lowest level is individual SLL or Single Loop Learning. This means that only the person who made a mistake learns from it.

The second level is Organisational SLL which means that the mistake or the accident is reported to an agent, and that agent compiles all information he or she receives and informs other concerned people in the company. This means that the whole company learns from one person's mistake and that the same mistake will probably not be repeated any where in the company.

The highest level in Figure 19 is organisational DLL or Double Loop Learning. This works the same way as the organisational SLL but instead of just changing routines and equipment it goes one step further. It questions the governing parameters established by the top management or by society and the government. [40]

The single and double loop learning is only a simplified illustration of how a company can work to increase safety and learning. The method, however, requires that the company appoints an agent to compile results from mistakes and accidents and communicate the results and findings to the rest of the company. The key factor is, however, a good reporting culture.

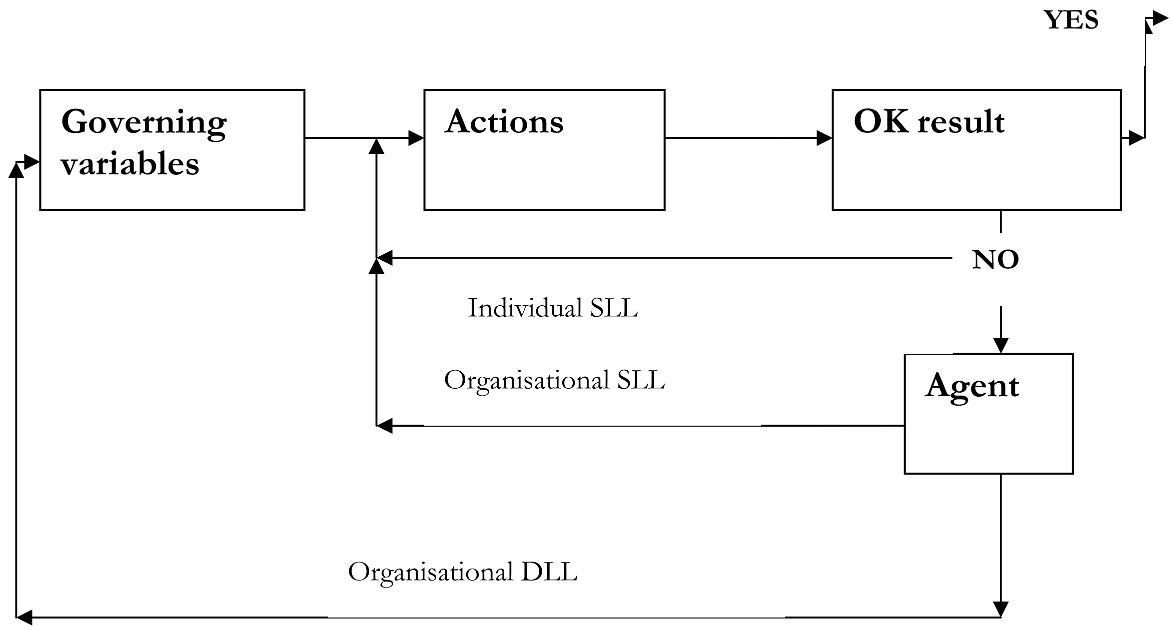

Figure 19. Double loop and single loop learning within an organisation [40][48]

9.3.4 Reporting Culture

The dust explosion awareness study presented in chapter 8 shows that there is willingness to report accidents and incidents among the staff at Leaf. There seems, however, as if the reporting culture is relatively primitive due to lack of communication paths. There are no working standard paths for reporting accidents at the company. An example of this, which was observed at the three week plant visit, was a rumour of an explosion. A person in a managerial position at the company had heard from a colleague at the sister factory in Denmark that there had been an explosion there with one serious injury. When I tried to find out if this was in any way relevant to dust explosions, no one seemed to know if it had even happened. I made several phone calls to the plant in Denmark, but until this day I still do not know if it happened. If there was a good reporting culture at the company, they would have known who to turn to with a question like this.

There is a computerised reporting system for failures and accidents at the company, but this can be made more effective and to also include incidents. It is important that *everything* is reported no matter how unimportant it might seem.

Most accidents send out early warning signals, such as a machine breaking down more frequently or a machine being damaged for several weeks or years before a major accident occurs. The people who are most likely to discover these warnings are the people in the factory who work with or close to the machines every day. Therefore, it is important to make sure that they report damages and incidents to the management. [47]

To ensure that people actually report damages and incidents, it is important to have a *fair* organisation. A company should avoid punishments for mistakes or carelessness, except in the case of actual crimes being committed. Reward systems could also be a way of increasing the reporting likeliness. A person who reports something could be rewarded with a small symbolic gift or acknowledgement.

It is important to make people report what might seem unimportant in their eyes but in actuality may be a sign that something is seriously wrong. [47]

10 Communication model for dust explosions

Chapter 9 presented important communication parameters and other important communication factors relevant to the communication of dust explosions. One of the goals of the work of this report is to create a communication model specific to the *communication of the risk of dust explosions to employees at dust handling factories*, especially in the food processing industry such as Leaf Sverige. Different existing communication models and important factors have been presented and relative parts of them, with relevance to dust explosion communication, were emphasised.

These parts have all been taken into account in the forming of a communication model. The model is meant as a communication tool for the management at dust handling plants to be able to effectively communicate dust explosion hazards to employees.

The model is presented schematically in Figure 20, and the different steps in the model are explained in chapter 10.1-10.5.

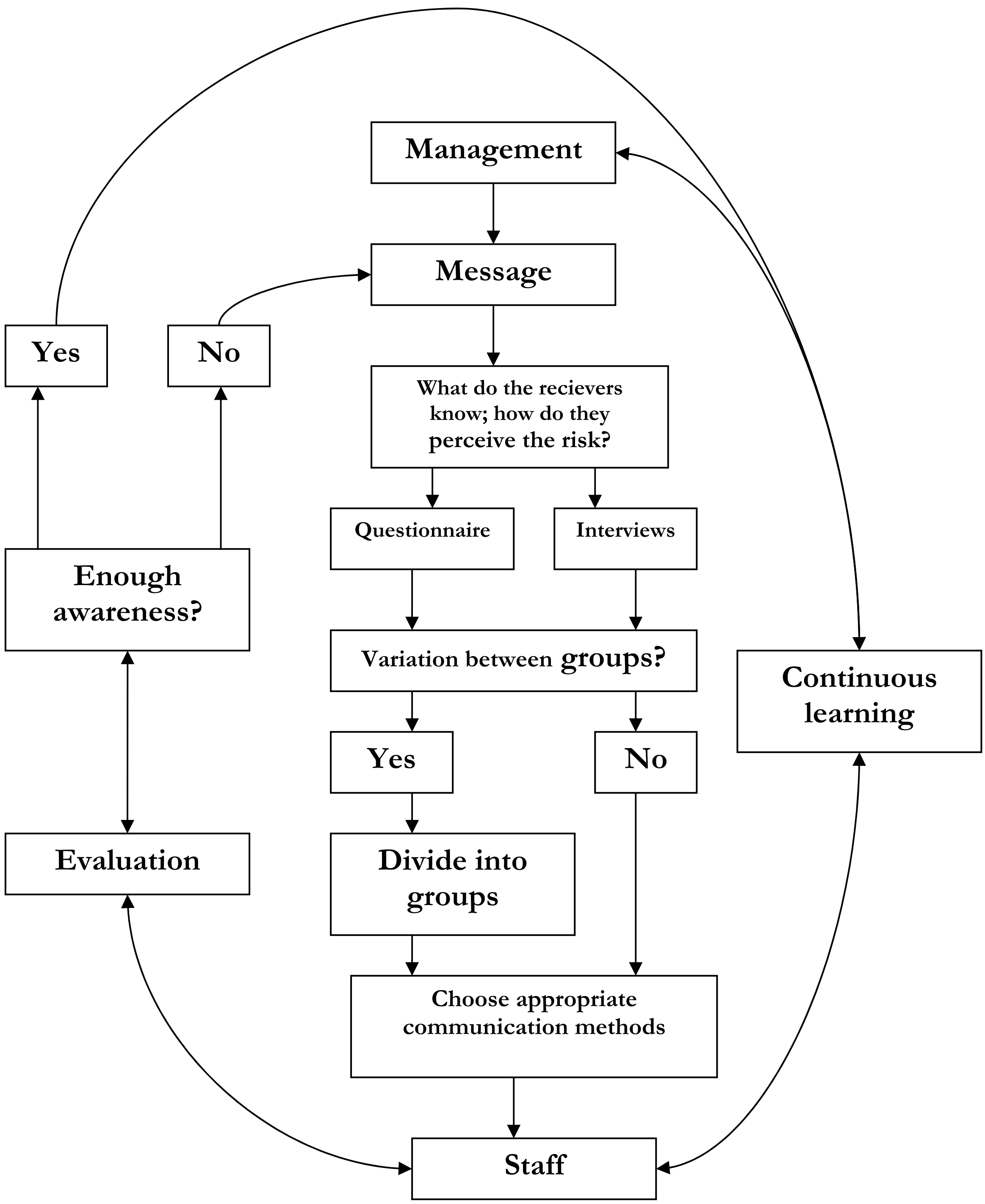

Figure 20. Schematic description of the communication model

10.1 Management

The communication model starts with the **management**, as shown in a box at the top of Figure 20. Schematic description of the communication model. This is because the model is designed as a tool for communication from the management. The management has the authority, and must take the initiative for the communication and decide to increase the dust explosion awareness at the factory.

The management must provide *motivation* and *resources* to the employees for the communication work to be satisfying and to improve the dust explosion safety. Without a motivated and goal-oriented management, the communication will probably not be effective.

The second step in the communication model is the **message**. This means that the management has to decide what message or information they want to communicate to the receivers/staff. They have to ask themselves what the staff members need to know to be able to perform their work in a safe manner when it comes to dry powder handling and dust explosions.

In the case of Leaf Gävle it is first and foremost important that the staff is aware of the phenomenon dust explosions, which not everybody is. This is the first step. The staff also needs to be aware of the possible causes of a dust explosion and how to prevent one from happening. They also need to know how to extinguish a fire in dry powders or dusts. Everyone also needs to be aware of the risk of, and how to prevent, dust explosions in the central vacuum cleaner.

What staff members need to know varies depending on the specific type of work they do at the plant. Determining what information the staff needs is the second step in the communication model. In this report a distinction was made between the maintenance crew and the operators. The maintenance staff needs more dust explosion knowledge than the operators because the maintenance staff maintains, installs and modifies process equipment. In addition to this they also perform hot work such as welding.

10.2 Knowledge and perception

When management decides what the staff needs to know to conduct safe work regarding dust explosions, it is time to find out what the knowledge level is at present and how the risk is perceived. This is the third step in the communication model. Management can obtain this information by conducting interviews or using questionnaires.

In this report the knowledge and perception study was mainly done by using questionnaires. The results from the study are further presented in chapter 8 and in Appendix I – Survey results for operators and Appendix J – Survey results for maintenance crew. The results of the study show that the dust explosion knowledge was very low, and in many cases, was totally non-existent, especially among the operators. The maintenance crew had somewhat better knowledge, but it must still be considered to be too low.

The risk of a dust explosion is, according to the survey, perceived as very small by the employees. This can lead to the notion that the risk does not exist and that they can perform work at the plant in a dangerous way, increasing the risk of a dust explosion. Therefore, it is important to create *some dread*. The staff should, of course, not be scared to the extent that they would be constantly afraid of an explosion, but just a little dread can be useful.

10.3 Appropriate communication methods

The operators that have any contact with dusts in the factory need to get a basic knowledge about dust explosions. The company can present this with a short informational letter (preferably not longer than one page to ensure that everything is read) in combination with a single short lecture.

The paper and the lecture should address the most basic information about dust explosions:

- The fact that the phenomenon exists
- The very basic physics and causes of dust explosions
- How to put out a fire in powders
- Why to avoid using the vacuum cleaner system on glowing materials and metals
- Secondary explosions and why it is important with good housekeeping
- Why it is important to report accidents, damages, etc.

The lecture could probably be performed in about half an hour. Showing dust explosions on video is recommended. This will effectively show the explosion forces that can occur and will probably create just a little dread.

The maintenance crew will need more information on dust explosion and prevention. In this case an informational letter and a lecture is also recommended, however, the content should be somewhat more extensive. Video will be very effective in this case as well because most people have never seen a dust explosion in real life or on TV or video.

In addition to the bulleted information listed above for the operators, the maintenance crew also need information on:

- Why maintenance is important
- How to maintain dust explosion prevention equipment
- The importance of grounding
- How to ideally construct and maintain the different process equipments
- How to perform hot work, such as welding, in a safe manner

10.3.1 Goal list and check list

There are a lot of different dry powder process equipments at the plant and it would be hard for the maintenance people to learn and memorize the appropriate dust explosion measures for all the equipment. Because of this I suggest that a **goal list** and a **check list** are introduced for all the different dry powder process equipments.

The goal list should describe the ideal construction and maintenance for the specific process equipment. It should be a long term goal to fulfil all the goals on the list. Appendix K – Example of Goal list for mills presents example of a goal list for a mill. The company should make the goal list easily accessible for the maintenance crew, preferably posting it on the different process equipments. Crew members should read the list before each interface with the equipment. The goal list should also say if the process equipment in question is in compliance with each requirement. The goal is to be completely compliant with the goals.

In addition to the goal list the company should also post a checklist on each piece of process equipment. The check list should consist of all measures that the crew should repeat regularly, and the crew should fill it out after each interface or check up. Appendix L – Example of Check list for mills presents an example of a check list for a mill.

To create the check lists and the goal lists I recommend the book Dust Explosion Prevention and Protection by Barton [11]. The book lists, in bulleted form, what to think about and how to ideally maintain and construct different process equipments. Using this book as a benchmark makes constructing check lists and goal lists easy.

It is important to notice that the example check list and goal list in the appendices are just examples. The company should construct the goal lists, and especially the checklists, in cooperation with maintenance crew members who have good knowledge about the different process equipments. This is important because most of the equipment is modified from its original state and is individual. The maintenance crew has good knowledge about these things and what needs regular maintenance. The company should also decide, in cooperation with the maintenance crew, how often to perform the maintenance. It is important that it is done regularly according to a schedule to avoid forgetting anything.

10.4 Evaluation

The next step in the communication model is evaluation. After communicating the message to the staff, it is important to evaluate whether the message was appropriately received and understood. The company can do this by either using a simple questionnaire or by conducting interviews.

If it turns out that the awareness and knowledge among the workers regarding dust explosions is not sufficient, the company should restart the communication process. In the communication model, the communicator should return to the message step because the wrong message might have been communicated.

If the awareness and knowledge is judged to be sufficient the company should go to the last step in the communication model which is **continuous learning**.

10.5 Continuous learning

It is of great importance that the learning and communication process is not just a one time happening. It must be always ongoing. There are four steps or parameters that are the most important for continuous learning, they are:

- Motivation
- Communication
- Reporting
- Resources

The motivation must come from the management. Leaf seems to be good at, and have a system that works for, motivating the staff to work towards fulfilling production goals. Leaf should apply the same type of system to fulfil safety goals. An example of this could be to publish safety improvements in the company newsletter as well as present the next goals, as is done today for production goals.

It is also important to have a working management system where the goals also are presented. The management system must be *alive*, and people should know how to use it and where to find it.

A continuous communication is of major importance. The staff must know who to turn to with questions regarding safety. This is not the case today according to the survey presented in chapter 8. The coordinators at the plant play an important role in this communication. They should get information on who to turn to with safety questions, who to give safety information to and who to turn to with any other questions. The other staff can then know that they always can turn to their coordinator no matter what question they have or information they have to give.

Reporting is closely connected with the communication and should also go via the coordinators. It is, however, important that the reporting is done in written form. Today, there are standard forms for the reporting of injuries and damages, but it should also include incidents. Similar forms should also be applied to damages to machines and any other process equipment. It is essential that the staff understands the importance of reporting all damages no matter how insignificant they might seem. Today this is not done in a sufficient way. An example of this is an unreported small damage to an explosion vent on a process filter. Damages to explosion vents can affect their performance in a major way [11].

Resources are also essential. The management must provide enough resources. Resources work positively in at least two different ways; first, enough resources make it easier to perform a safe work, for example it can make the dust removal easier. Secondly, if the staff feel that they get a lot of resources it can increase motivation.

Returning to the learning model presented in chapter 9.3.3, this model is integrated in the communication model in Figure 20. The continuous learning box connects the staff and the management but the figure shows only schematically how the continuous learning should work.

Figure 21 presents a closer look at the continuous learning. The key person in the continuous learning process is the *agent*. This person should coordinate the information given to him by the staff via the coordinators. Coordinating the information makes it possible to detect patterns. Some accidents and damages can be somewhat frequent; the company needs to investigate why as well as determine what can be done to prevent them from happening.

The agent will work as a spider in the communication web. He has to report and inform the management of the plant to be able to get more resources and funds, if needed. The management in its turn will have to communicate with the group management if needed, i.e. Leaf International. The agent also needs to communicate with agents at other factories, both to share and receive new safety knowledge. Finally, the agent must pass on the learning and knowledge received from the reporting at Leaf Sverige and other factories to the employees. This will enable the staff to learn from mistakes made from a large number of people.

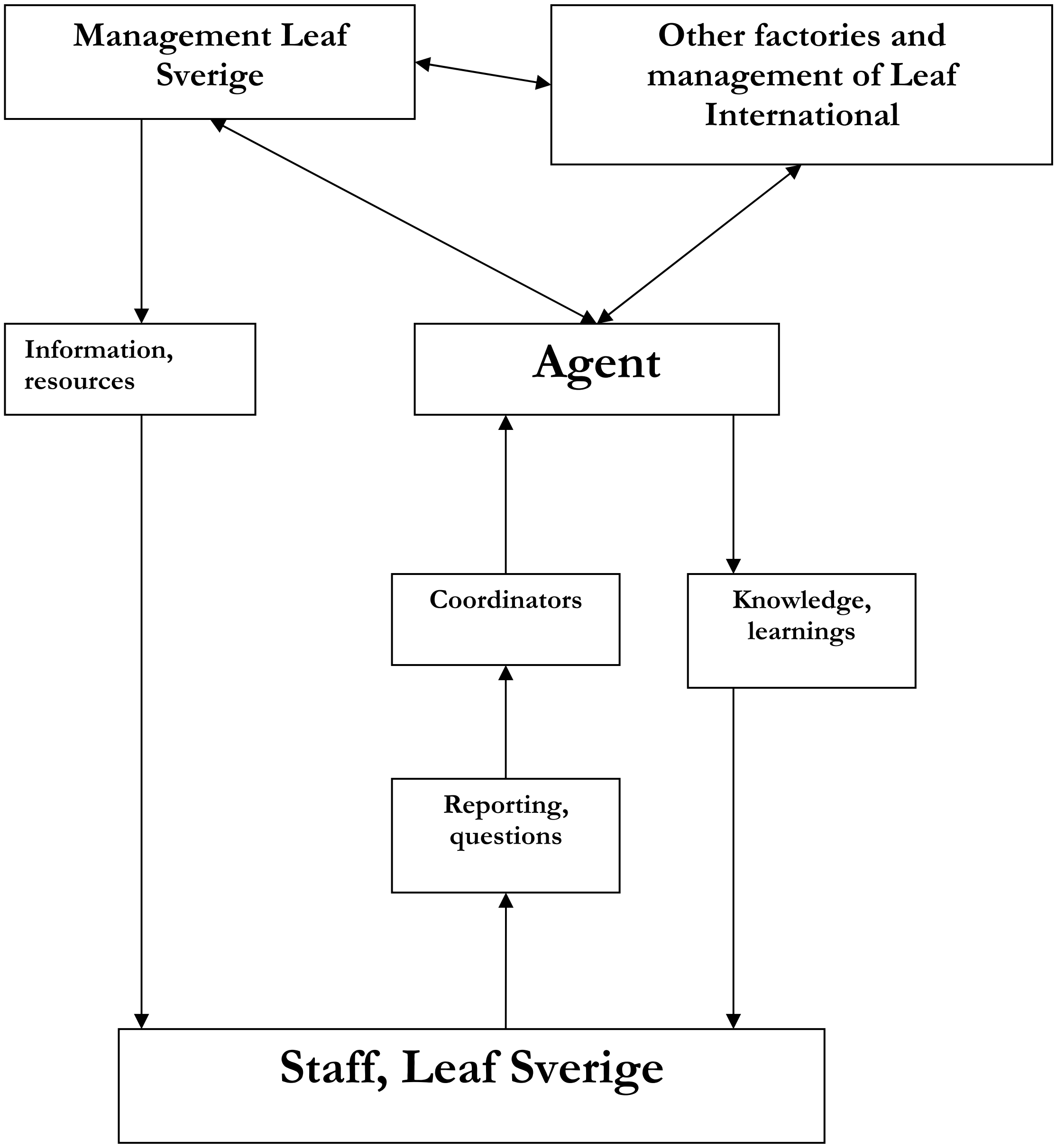

Figure 21. A closer look at the continuous learning part of the communication model in Figure 20

11 Conclusions and discussion

This report consists of three main parts: risk analysis, dust awareness and risk communication. All three are intertwined with each other. The risk analysis provides a result that needs to be communicated to the staff and to be able to do this the present risk awareness needs to be examined.

11.1 Risk analysis

The PHA showed to be an effective tool for identifying the worst dust explosion scenarios at the plant. The PHA facilitated a systematic walk through of the entire dry powder system and most dust explosion risks were identified. It cannot be said with 100 % certainty that every single possible dust explosion scenario was identified. The largest scarcity with any PHA is that the assessment will always be subjective to the PHA group. Another group would most certainly reach somewhat different conclusions.

The next step in the analysis was to quantify the risks with the help of event trees. These calculations showed to be full of uncertainties. The uncertainty analysis showed that the calculated risks where so uncertain that it is questionable if the quantified results can be used at all. With an uncertainty this large the quantification might not have contributed very much to the risk analysis; the results from the PHA can be said to be as good as the quantified results.

The quantification did contribute to the precedence of the risks even if it can not be said how large the risks are. To some extent the results can be used to say that one risk is larger than another. For example, the dust explosion risk in the moulding line hall is definitely larger than the dust explosion risk in the drying chambers.

The recommended actions must be seen as subjective because they are based on a subjective risk assessment.

Overall, it can be concluded that the risk analysis has not generated exact enough answers to recommend actions or to carefully rank the risks. The results from the analysis should just be seen as an indicator of problem areas. The analysis identified areas that have the potential to cause a dust explosion and the effects of an explosion in these areas were estimated.

11.2 Risk awareness

The risk awareness study conducted for this report is pretty unique. I have not found any study of dust explosion awareness anywhere during the extensive literature study conducted for this report. The study is, however, very limited. Only staff from one single dust handling factory were studied.

The risk awareness concerning dust explosions is, in most literature, just assumed to be very low, but no study has been conducted.

The study shows that the dust explosion awareness is in fact very low among the employees at Leaf Sverige. A surprisingly large number of respondents have not even heard of the phenomenon dust explosion and the ones who have, do not seem to know much about it.

The maintenance crew have larger knowledge about dust explosions than the operators; this is good, but the knowledge is not high enough. The work that the maintenance crew performs actually requires higher knowledge about safety and dust explosions than what the operators need. It can be concluded that currently both groups have insufficient knowledge about dust explosions. Most dust explosions happen because of human mistakes and not technical problems [21]. If the knowledge at the plant would increase so would the dust explosion safety; mistakes could simply be avoided to a large extent.

11.3 Risk Communication

Risk communication is extensively researched and many different reports and communication models are available. The majority of the research, however, has been focused on communication from governments, companies and other authorities to a general public. In the case of this report a model for communication between management and employees at dust handling plants concerning the risk of dust explosions has been developed. The model is in some parts specific to the food processing industry in general and to Leaf Sverige in particular. It should, however, be possible to use the communication model with slight modifications in any dust handling industry.

The communication model is based on a literature study of existing communication models and other literature on communication. Bits and pieces have been used from other communication models to construct the communication model for dust explosions. The learning gained from the awareness study and interviews during the site visit have also been intertwined into the model.

In direct opposition to most other communication models [53], this model is constructed to create some dread for the communicated risk. There are, however, other examples of this, such as the risk communication on smoking and skin cancer.

The three most important parts of the communication model to improve the safety at Leaf are:

- Continuous learning
- The introduction of goal lists and check lists as a mean for communication
- The Introduction of an agent

The continuous learning is of very great importance. To maintain a continuous learning it is very important to have a good reporting culture. To be able to have a good reporting culture there must be standards and routines on reporting and there needs to be an agent present. The agent is a person who collects and analyzes reports on injuries, damages, incidents, etc. The agent should then make sure that the whole organisation learns from previous mistakes and errors.

The goal lists should provide a target to work towards. It should be a list, specific to each individual type of process equipment that states how to properly construct and maintain the equipment.

The check lists should be posted on each piece of process equipment and they should be filled out after maintenance. The check list should say what maintenance the particular equipment needs and how often to conduct a certain maintenance procedure.

A schematic model of the communication model is presented in Figure 22.

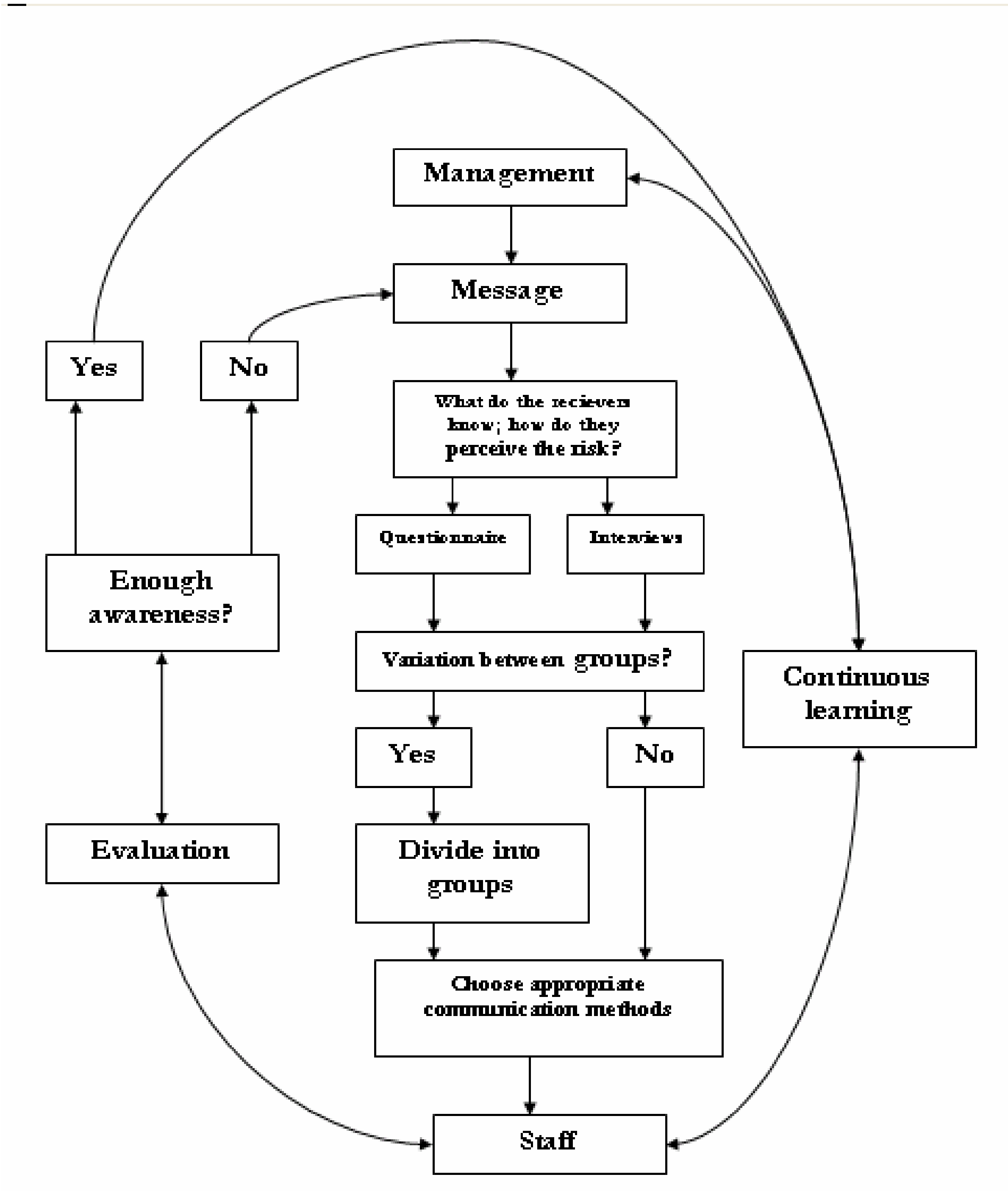

Figure 22. Schematic description of the communication model

12 Further research

The dust explosion research field is, as mentioned before in this report, relatively limited, especially in comparison to fire research. There are two main fields that need improvement when it comes to dust explosion prevention. They are:

- Statistics
- Risk analysis methods

The statistical data for dust explosions is at best very limited. Dust explosion data needs to be systematically collected to give a good and solid base to determine different powders and process equipments risk of dust explosions. It is also important to have good statistics to be able to convince companies and people of the actual dangers.

There is no really good risk analysis method to use for dust explosions. This is largely because of the difficulties of calculating or estimating dust explosion frequencies and how often ignition sources are present. Research should be conducted to develop a method for the calculation of dust explosion frequencies.

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14 Appendices

Appendix A – Dust Data

All values are from the supplier product data sheet or from emails from the suppliers unless other source is specified.

Product	Particle size (mean)	C_{min} (g/m³)	P_{max} (Bar)	K_{st} (bar m/s)	Dust Cloud ignition temp. (ºC)	Dust Layer ignition temp. (ºC)	MIE (mJ)	Heat of combustion (MJ/Kg)	Expl. Class	Flam. Class (BZ)
Xylitol	400-600	30-60	6.4	85	440		360	10	St1	
Spray Gum	125	$60^{\pm}$	8.9	81			$100^{\pm}$	44.9^{+}	St1	2
Gummi Arabicum	180	$60^{\pm}$	$8.1^{\pm}$	56 assuming 20 l standard sphere ($207^{\pm}$ bar/s)	$500^{\pm}$		$100^{\pm}$	44.9^{+}	St1-2	2
Moulding powder (maize starch)		60	9.5	170		170 (above this it will self heat)	>30	17.6^{+}	St1	2-3
Maize Starch A		60	9.5	170		170(above this it will self heat)	>30	17.6^{+}	St1	2-3
Modified wheat starch B		60	9.5	170		170(above this it will self heat)	>30	17.6^{+}	St1	3
Maize Starch C								17.6^{+}		2-3
Maltodextrin		60	9.5	180		>450	>30		St1	2-3
Ammonium Chloride (Salmiak)	Not flammable									1

Sugar	300-320 (actually 500-750)	500-750	4.0-4.1	12-18			10^6<2*10^6	16.49[+]	St1	2
Fraction sugar	250-330							16.49		2
Gelatine A	10% is <0.1mm		10	0-200	560	450 (uncertain)	>100 (J)	15	St1	2
Gelatine B			5	17	600		34.5(kJ)	15	St1	2
Gelatine C	3% is <0.1mm Median ca. 500-800							15	St1	2
Gelatin D	Values for < 40 Mesh (5% finest only)	30	7.5	79			50	15	St1	2

± = från Field, P. Dust Explosions. (1982) [20]

[+] Values from SFPE handbook Appendix C [32]

Appendix B – Preliminary Hazard analysis

Preliminary Hazard Analysis *GA-Grinding and sugar room*

Dust explosion incident	Possible cause	Consequence	Measures performed	Risk estimation			Possible measures
				Prob.	Health	Economic	
G1: Explosion in grinder	Heat or spark from friction, foreign object like aluminum in grinder, static electricity	Grinder very robust but explosion could spread to hopper, hopper rupture Projectiles, flames and shockwave in room.	Magnet separates ferrous materials before grinding, connection to earth (c.e)	**3**	**3**	**4**	Pressure relief vent, automatic explosion suppression , regular maintenance of grinder, regular testing of c.e
G2: Explosion in grinder-hopper	Initial explosion in grinder, static electricity, fire	Funnel rupture, spread to pneumatic conveying system	Magnet separates ferrous materials before grinding, c.e	**3**	**3**	**4**	Earthen and bonding, pressure relief vent, automatic explosion suppression , regular maintenance of grinder, regular testing of c.e
G3: Fire in Grinder or hopper	Hot surface from friction in grinder, smoldering nest from grinder	Damaged grinding system, spread of fire to the pneumatic conveying system	non	**2**	**2**	**2**	Automatic fire extinction system in hopper
G4: Explosion when filling gum into Big Bag	Static electricity from plastic Big Bag, smoldering nest from funnel or screw	Primary explosion in Big Bag, possible secondary explosion in room	non	**1**	**2**	**1**	Use other material than plastic in Bags
G5: Explosion in sugar hopper	Static electricity, damaged electrical equipment	Heat and pressure at ground level outside room from pressure relief	Pressure relief vent to outside, c.e	**2**	**1**	**1**	regular maintenance of electrical equipment, regular testing of c.e

Preliminary Hazard Analysis *Grinding and sugar room*

Dust explosion incident	**Possible cause**	**Consequence**	**Measures performed**	**Risk estimation**			**Possible measures**
				Prob.	Health	Economic	
G6: Explosion in sugar screw or rotary valve	Static electricity, hot surface from friction	Spread of explosion to hopper and into Big Bag, secondary explosion in Big Bag	Pressure relief vent in hopper	**2**	**2**	**1**	Earthen and bonding, regular maintenance of screw
G7: Explosion in main sugar silo	Static electricity during filling, smoldering nest, fire in room	Damaged silo, building damage, projectiles, shockwave, fire	c.e	**2**	**4**	**5**	Pressure relief vent, regular testing of c.e, automatic explosion suppression

Preliminary Hazard Analysis *Azo Room*

Dust explosion incident	Possible cause	Consequence	Measures performed	Risk estimation			Possible measures
				Prob.	Health	Economic	
A1: Large sudden release of starch, xylitol or Gelatine into the room from Big Bag	Inspection hatch not closed when filling starts. Ignition from static electricity or hot surface	dust explosion, building damage, injuries to staff and possible deaths	non	**2**	**3**	**1**	Good routines to make sure hatch is closed. Pressure relief panel in the room
A2: Explosion in pipe or screw under Big Bags	Mechanical spark or heat from broken screw, static electricity	Possible secondary explosion in the Azo room,	c.e	**2**	**3**	**1**	Use screws with choke, automatic or passive system to avoid spread of explosion in pipe system, regular testing of c.e
A3: Ignition of powder in big bags when emptying bags	Static electricity from plastic Big Bag	Small explosion in bag, possible secondary explosion	Slow emptying of bags	**1**	**2**	**1**	Use other material in Bags than plastic.
A4: Explosion in gum arabicum tank	Static electricity, smoldering nest from grinder	Possible tank rupture, explosion spreading back to grinder or out in the pneumatic conveying system, secondary explosion in the room	c.e	**2**	**3**	**3**	system for stopping spread through pipes, auto inert tank, regular testing of c.e

Preliminary Hazard Analysis *Azo Room*

Dust explosion incident	**Possible cause**	**Consequence**	**Measures performed**	**Risk estimation**			**Possible measures**
				Prob.	Health	Economic	
A5: Explosion in sugar tank	Static electricity	Possible vessel rupture, damage to building and staff, possible secondary explosion in the room	c.e	**1**	**3**	**3**	regular testing of c.e, pressure venting, auto inerting
A6: Explosion in foam sender or foam tank	Static electricity, smoldering nest	Possible vessel rupture, damage to building and staff, possible secondary explosion in the room	c.e	**2**	**3**	**2**	regular testing of c.e, pressure venting, auto inerting
A7: Explosion in aspiration filter	Static electricity, broken electrical equipment, possible secondary explosion, dust layer on electric motor	Possible vessel rupture, projectiles, shockwave	c.e	**3**	**2**	**1**	regular testing of c.e, pressure venting, auto inerting

Preliminary Hazard Analysis *Foam kitchen*

Dust explosion incident	Possible cause	Consequence	Measures performed	Risk estimation			Possible measures
				Prob.	Health	Economic	
F1: explosion in dry powder tank or filter	Static electricity, initial explosion or smoldering nest in pneumatic conveying pipe	Possible rupture of tank, damages to foam kitchen and attic above kitchen, building damage	c.e	**2**	**3**	**2**	pressure relief, automatic explosion suppression, passive or active device to stop explosion in pipe, regular testing of c.e
F2: explosion in screw conveyor	Smoldering nest, static electricity, mechanical heat	Explosions spreads to the tank above and the tank below, possible vessel rupture – damage to kitchen, building and injured staff	c.e	**1**	**3**	**2**	pressure relief of vessels, screw conveyor with choke, regular testing of c.e

Preliminary Hazard Analysis *AKO and Brio kitchen*

Dust explosion incident	**Possible cause**	**Consequence**	**Measures performed**	**Risk estimation**			**Possible measures**
				Prob.	Health	Economic	
B1: Explosion in sugar tank or filter	Static electricity, initial explosion in pneumatic conveying system	Possible vessel rupture, shockwave, projectiles, damage to building and kitchen equipment	c.e	**2**	**2**	**2**	regular testing of c.e , pressure relief, automatic explosion suppression
B2: Explosion in sugar screw	Static electricity, heat from friction	Secondary explosion in sugar tank	c.e	**1**	**2**	**2**	regular testing of c.e , regular service of screw

Preliminary Hazard Analysis *GA kitchen*

Dust explosion incident	Possible cause	Consequence	Measures performed	Risk estimation			Possible measures
				Prob.	Health	Economic	
P1: Explosion in gum tank or filter	Static electricity, initial explosion in pneumatic conveying system	Possible vessel rupture, shockwave, damage to building, kitchen and staff	c.e	**2**	**3**	**3**	regular testing of c.e , pressure relief, automatic explosion suppression
P2: Explosion in starch tank or filter	Static electricity, initial explosion in pneumatic conveying system	Possible vessel rupture, shockwave, damage to building, kitchen and staff	c.e	**3**	**3**	**3**	regular testing of c.e , pressure relief, automatic explosion suppression
P3: Explosion in Gelatine and xylitol tank or filter	Static electricity, initial explosion in pneumatic conveying system	Possible vessel rupture, shockwave, damage to building, kitchen and staff	c.e	**2**	**3**	**3**	regular testing of c.e , pressure relief, automatic explosion suppression
P4: Explosion in sugar tank or filter	Static electricity, initial explosion in pneumatic conveying system	Possible vessel rupture, shockwave, damage to building, kitchen and staff	c.e	**1**	**2**	**3**	regular testing of c.e , pressure relief, automatic explosion suppression
P5: Explosion in screw	Static electricity, heat from friction	Possible secondary explosion in tank	c.e	**2**	**3**	**3**	regular testing of c.e , regular maintenance of screw

Preliminary Hazard Analysis *Brio Line, Automatic Drageé*

Dust explosion incident	Possible cause	Consequence	Measures performed	Risk estimation			Possible measures
				Prob.	Health	Economic	
L1: Ignition of dust layer	Hot surface, spark from broken electric equipment or cord.	Small dust explosion	Housekeeping	**1**	**2**	**1**	Good housekeeping routines

Preliminary Hazard Analysis *Manual Drageé*

Dust explosion incident	Possible cause	Consequence	Measures performed	Risk estimation			Possible measures
				Prob.	Health	Economic	
Z1: explosion in dust deposits	Formation of dust cloud from turbulence Ignition from smoldering nest, static electricity, broken electric equipment or cord	Possible secondary explosion, injured staff, damage to building	non	**2**	**5**	**4**	Good housekeeping, remove all hot surfaces, regular maintenance
Z2: explosion in process filter	Static electricity, failure of electric equipment	Filter casing can rupture, possible secondary explosion, injured staff from explosion, fire and projectiles, building damage	c.e	**3**	**5**	**4**	Good housekeeping, regular testing of c.e , separate filter from drageé room, explosion relief on filter, automatic explosion suppression

Preliminary Hazard Analysis *Moulding Line hall*

Dust explosion incident	Possible cause	Consequence	Measures performed	Risk estimation			Possible measures
				Prob.	Health	Economic	
M1: Nid 4 and 5, explosion in starch separating drum	Static electricity, smoldering nest from drying room	Machine damage, possible injured staff	c.e	3	3	2	Regular testing of c.e, avoid longer drying periods than normal
M2: explosion in sieve	Static electricity	Damage to sieve, possible injured staff Possible secondary explosion	c.e	3	3	3	Regular testing of c.e , pressure relief, automatic explosion suppression
M3: explosion in surge bin	Static electricity	Damage to machinery, possible injured staff Possible secondary explosion	c.e	3	2	3	Earth and bond
M4: Nid 4 and 5, explosion in process filter	Static electricity	Relief panel will open into building, damage to building, possible secondary explosion,	Explosion relief panel, c.e	3	4	5	Regular testing of c.e , maintenance of relief panel, automatic suppression of explosion, vent to outside
M5: Explosion in powder dryer	Static electricity, hot surface, overheating, self ignition of stationary dust deposits inside the dryer	Relief panel open into building, damaged building and machinery	Explosion relief panel, c.e	3	2	5	Regular testing of c.e , vent to outside, automatic suppression of explosion
M6: Explosion in powder cooler	Static electricity, smoldering nest from dryer	Relief panel open into building, damaged building and machinery	Explosion relief panel, c.e	2	2	4	Regular testing of c.e , vent to outside, automatic suppression of explosion
M7: Explosion in fine sieve	Static electricity, hot surface, damaged electrical equipment	Damaged machine, possible secondary explosion, flames, fire	c.e	3	3	3	Regular testing of c.e, maintenance of electric equipment, regular maintenance of sieve

Preliminary Hazard Analysis *Drying chambers*

Dust explosion incident	**Possible cause**	**Consequence**	**Measures performed**	**Risk estimation**			**Possible measures**
				Prob.	Health	Economic	
D1: Explosion in new drying chamber	Pallet is overturned and dust cloud is created. Ignition from static electricity, hot surface on forklift or fan	Possible large secondary explosion, damage to building and staff, several chambers damaged	non	**3**	**3**	**3**	Physical protection to avoid pallet overturning over fan, good housekeeping
D2: Explosion in old drying chamber	Pallet is overturned and dust cloud is created. Ignition from static electricity, hot surface on forklift	Possible large secondary explosion, damage to building and staff, several chambers damaged	non	**2**	**3**	**3**	Good housekeeping

Preliminary Hazard Analysis *Central Vacuum cleaner*

Dust explosion incident	Possible cause	Consequence	Measures performed	Risk estimation			Possible measures
				Prob.	Health	Economic	
C1: Explosion in vacuum cleaner system	Static electricity, smoldering nest is vacuumed, metal pieces vacuumed	Possible rupture of dust collection vessel, projectiles pressure wave, damage to outside of building	Connection to earth	**3**	**2**	**2**	Regular testing of c.e , information about dust explosion to staff

Preliminary Hazard Analysis

General dust explosion risks around the factory

Dust explosion incident	Possible cause	Consequence	Measures performed	Risk estimation			Possible measures
				Prob.	Health	Economic	
X1: explosion in general ventilation filter	Static electricity, fire in another part of building that spreads via the ventilation system,	Damage to process filters if relief panel does not open or from recoil forces from the explosion venting	Pressure relief panel, c.e, fire dampers in ventilation system	**3**	**1**	**2**	Regular testing of c.e , regular maintenance of pressure relief panel
X2: ignition of dust deposit layers	Hot surface or pipe, auto ignition, fire, explosion in the process, CO_2 extinguisher on dust fire	Massive damages to plant and staff, very dependant on where in the plant and the extent of dust layers	housekeeping	**2**	**1-5**	**1-5**	Improve housekeeping, remove dust layers from pipes, machines and floors, information to employees
X3: explosion in conveying pipe	Static electricity, smoldering nest, fire in plant	Very dependant on where in the plant the explosion occur	c.e	**3**	**1-5**	**2-5**	Regular c.e testing, replace rubber connections with flexible metal parts, auto explosion suppression
X4: Explosion in process filters not mentioned above	Static electricity	Damage to process filters, filter rupture, projectiles, fire	c.e	**3**	**3**	**2**	

Appendix C – Calculations

TNT-method – pressure wave from a vessel rupture

The TNT-method was used to calculate the magnitude of a shockwave following an explosion in a vessel with no pressure relief panel. The Method is based on empirical research and is described in *Guidelines for Consequence Analysis of Chemical Releases* [31].

The first step is to calculate the amount of energy that could be involved in an explosion in a certain vessel.

A simple way to estimate the amount of energy involved in a worst probable case or simply in a large explosion is to determine how much oxygen is present in a vessel. Under atmospheric conditions there is about 8.7 moles of O_2 per cubic meter of air [1]. The mole weight of O_2 is 32 grams per mole [49]. This means that about 278.4g of O_2 is present in each cubic meter of air. There is about 23 % oxygen in air, assuming that during an explosion oxygen is consumed down to 10 % this means that about 156 grams of oxygen is consumed per cubic meter of air.

When hydrocarbons burn about 13100 kJ of energy is released for every kilogram of oxygen consumed. This is accurate to +/- 5 % for most hydrocarbons [50]. The powders at Leaf are all hydrocarbons, and assuming 13100 kJ of energy release per kilo of oxygen consumed gives 2044 kJ when 156 grams of oxygen is consumed per cubic meter.

When one kilogram of TNT explodes about 4022 kJ of energy is released [31]. This leads to the assumption that a dust explosion could result in an energy release equal to 0.5 kilograms of TNT per each cubic meter of air involved in the explosion.

A scaled over pressure is calculated using equation /1/, where the peak over pressure is 30 kPa and 70 kPa. Figure 3.3 in *Guidelines for Consequence Analysis of Chemical Relaeases* [31] gives a Scaled distance, Z fom the scaled over pressure. Equation /2/ gives the actual distance, R to the peak over pressure.

$$p_s = \frac{p^0}{p_a} \qquad /1/$$

$$Z = \frac{R}{W^{1/3}} \qquad /2/$$

p_s	scaled over pressure (Pa)
p^0	peak over pressure (Pa),
p_a	Atmospheric pressure (Pa)
W	equivalent mass of TNT (kg)
Z	scaled distance

R actual distance

Consequence calculation of pressure venting indoors and flames from a vessel rupture

Equations /3/ through /11/ are taken from *Dust explosion, prevention and protection* by John Barton [11]. These formulas are empirical based on dust explosion tests on explosion venting with explosion relief panels. In this report they have also been used to calculate flame length and flame width for the cases with vessel rupture with no pressure relief panels. This is based on an assumption that if an explosion would occur inside a vessel the weakest part of the vessel would first give way. This could for example be a process filter on top of the vessel or an inspection hatch on the side of the vessel. The pressure and flame release into a room would than be similar to a scenario with a pressure relief panel.

$$X_{fl,\max} = Q \cdot V^{1/3} \qquad /3/$$

Q = 10 (for vertically discharging vents)
Q = 8 (for horizontally discharging vents)

$$W_{fl,\max} \approx 1.3 \cdot (10V)^{1/3} \qquad \text{(used when flame do not hit obstacles)} \qquad /4/$$

$$P_{s,\max} = 0.2 \cdot P_{red,\max} \cdot A^{0.1} \cdot V^{0.18} \qquad /5/$$

$$X_{s,up} = 0.25 \cdot X_{fl,\max} \qquad /6/$$

$$X_{s,hor} = 0.2 \cdot X_{fl,\max} \qquad /7/$$

$$P_{r,\max} = \frac{X_s}{r} \cdot P_{s,\max} \qquad \text{(used when flame do not hit obstacles)} \qquad /8/$$

$$P_{r,\max} = 2 \cdot \frac{X_s}{r_{obs}} \cdot P_{s,\max} \qquad \text{(used when flame hits obstacle)} \qquad /9/$$

$$W_{fl,\max} = 2.5 \cdot \frac{\sqrt{10V}}{r_{obs}} \qquad \text{(used when flame hits obstacle)} \qquad /10/$$

$X_{fl,max}$ Maxiumum flame length (m)

V Vessel volume (m^3)

$W_{fl,max}$ estimate of maximum flame width (m)

$P_{s,max}$ maximum external pressure (kPa)

$P_{red,max}$ maximum overpressure inside vessel (kPa)

A	vent area (m^2)
$X_{s,up}$	distance to maximum external pressure, venting directed upwards (m)
$X_{s,up}$	distance to maximum external pressure, venting directed horizontally (m)
$P_{r,max}$	external pressure at a distance r from the vessel (kPa)
r	distance (m)
r_{obs}	distance to obstacle

Equations /3/ through /11/ have the following restrictions:

Vessel volumes:	$0.1\ m^3 \leq V \leq 1000 m^3$
Relief vent static bursting pressures:	$0.1\ bar \leq P_{stat} \leq 0.2\ bar$
Reduced maximum explosion pressure:	$0.1\ bar \leq P_{red,max} \leq 2\ bar$
Maximum material explosion pressure:	$5\ bar \leq P_{max} \leq 10\ bar$
K_{st} value of material:	$10\ bar\ m\ s^{-1} \leq P_{red,max} \leq 200\ bar\ m\ s^{-1}$

Recoil force from venting

$$F_{R_i i,\max} = \alpha \cdot A_v \cdot P_{red} \qquad /11/$$

$F_{Ri,max}$	recoil force, (kN)
A_v	vent area, (m)
P_{red}	reduced explosion pressure (bar)

Radiation calculations

The method used for radiation calculations is described in *The SFPE Handbook of Fire Protection Engineering* [51]. Equation /12/ is taken from the SFPE handbbok. The radiation from flames is assumed to come from a plane, see Figure 23 where A_2 is the flame surface and A_1 is the receiving surface or person.

The view factor is calculated using equation /12/. A_2 is ¼ of the emitting flame surface, this means that the resulting view factor is multiplied by four to get the actual view factor.

The emitted energy from the flame surface is calculated using equation /13/. The received energy at the distance from the flame that is investigated is calculated with equation /14/.[28]

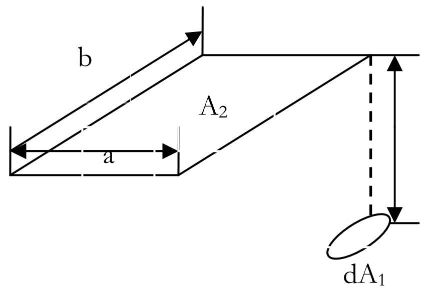


Figure 23. Radiation model

View factor formula:

$$F_{d1-2} = \frac{1}{2\pi}\left\{\frac{X}{\sqrt{1+Y^2}}\tan^{-1}\left[\frac{Y}{\sqrt{1+X^2}}\right]+\frac{Y}{\sqrt{1+Y^2}}\tan^{-1}\left[\frac{X}{\sqrt{1+Y^2}}\right]\right\} \quad /12/$$

where X and Y are:

$$X = \frac{a}{c}$$

$$Y = \frac{b}{c}$$

$E = \varepsilon \cdot \sigma \cdot T^4$ Emitted radiation energy (kW/m^2) /13/

$Q = E \cdot F_{d\,1-2}$ Received radiation energy (kW/m^2) /14/

$F_{d\,1-2}$ View factor

E Emitted radiation energy (kW/m^2)

ε Emissivity, assumed value of 0.8 is used

σ Boltzmann´s constant ($5.67 \cdot 10^{-8}$ W/m^2K^4)

T Temperature (Kelvin), assumed to be 1000K

Appendix D – Calculation values

Moulding Line Hall

Process equipment	Vessel Volume (m^3)	Flame height, length (m)	Flame width (m)	Comment
Starch separating drum	1	1.5	1	Not entierly confined
Sieve	1	8	2.8	
Surge Bin	1	1.5	1	Not entierly confined
Process Filter	7	5	8	Secondary Explosion, 8x10x5m
Powder Dryer	18	5	5	
Powder Cooler	18	5	5	
Fine Sieve	0.5	8	2.2	

Manuell Drageé

Process equipment	Vessel Volume (m^3)	Flame height, length (m)	Flame width (m)	Comment
Process Filter	6	5	5	Entire Room
Dust Deposit	-	2 (medium)	2 (medium)	Secondary explosion in entire room

Grinding and Sugar Room

Process equipment	Vessel Volume (m^3)	Flame height, length (m)	Flame width (m)	Comment
Grinder	0.2			Withstands an explosion
Hopper	2	8	3.5	Entire Room length
Main Sugar Silo	60 (assuming half full)	30	8.7	Maximum observed length on any vessel

Azo Room

Process equipment	Vessel Volume (m^3)	Flame height, length (m)	Flame width (m)	Comment
Starch Cloud in Room	-	2	3	Secondary explosion 5x5x5m
Pipe or screw under Big Bags	1.5 (Big Bag)	1.5	1	Secondary explosion 3x4x3m
Gum Arabic Tank	15	10	5	Entire Room
Foam Tank	2	10	3.5	
Aspiration Filter	1	10	2.8	

Drying Chamber

Process equipment	Room Volume (m^3)	Flame height, length (m)	Flame width (m)	Comment
New Chamber	40	2.5	2.5	Flames in half the room
Old Chamber	80	2.5	2.5	Flames in ¼ of the room

GA-Kitchen

Process equipment	Room Volume (m^3)	Flame height, length (m)	Flame width (m)	Comment
Starch tank	3	5	4	

Appendix E – Number of ignitable dust clouds

Dust clouds in process units

Process (PHA scenario)	Duration	Quantity	Estimated number of ignitable dust clouds per year
Gum Arabic milling (**G1, G2, A4**)	6 h per day 6 days a week	0.5 kg/s	6000
Sugar filling main tank (**G7**)	15 times per day á 7 min each	2.4 kg/s	5000
Dust Cloud in Room (**A1**)	Rare	-	0.5
Screws in Azo room (**A2**)	About 3min per hour (depends on which screw)	-	3000
Foam Tank in Azo room (**A6**)	3 times per hour	-	3000
Aspiration filter in Azo room (**A7**)	Less than once a week	-	50
Starch tank in GA Kitchen (**P2**)	About 30 minutes out of every hour	0.2 kg/s	8000
Aspiration filter in Manuell Drageé (**Z2**)	Continuous	-	1000
Process filter, Nid 4 and Nid 5 (**M4**)	Nid 4: 5days a week, Nid 5: 6 days a week	-	3000
Surge bin, Nid 4 and Nid 5 (**M3**)	Nid 4: 5days a week, Nid 5: 6 days a week	-	50
Sieve, Nid 4 and Nid 5 (**M2**)	Nid 4: 5days a week, Nid 5: 6 days a week	-	2000
Fine Sive, Nid 4 and Nid 5 (**M7**)	Nid 4: 5days a week, Nid 5: 6 days a week	-	9000
Starch separating drum, Nid 4 and Nid 5 (**M1**)	Nid 4: 5days a week, Nid 5: 6 days a week	-	30
Dryer and cooler to Nid 5 (**M5-6**)	6 days a week	-	9000
Filling and emptying of new drying chambers (**D1**)	72 times a day	-	5
Filling and emptying of old drying chambers(**D2**)	36 times a day	-	2

Appendix F – Results from event tree calculations

Moulding line hall

Scenario	P_{red}, kPa)	Distance to 30 kPa (m)	Distance to 70 kPa (m)	Distance to 20 kW/m² (m)	Estimated number of injured	Estimated number of Deaths	Estimated Economic Damage (€)
1	-	-	-	-	0	0	0
2	-	-	-	1	1	0	100 000
3	-	-	-	-	0	0	1000
4	-	-	-	-	0	0	25 000
5	1 Bar	4.8	3.2	2.5	1	0	100 000
6	1 Bar	4.8	3.2	4	1	1	100 000
7	-	-	-	-	0	0	0
8	-	-	-	1	1	0	1000
9	-	-	-	-	0	0	1000
10	0.5 Bar	35 kPa at ceiling		5	1	1	1000 000
11	0.5 Bar		70 kPa at ceiling	5	2 (vad finns ovanför)	1	20000000
12	0.5 Bar		70 kPa at ceiling	6.5	2	2	20000000
13	0.3 Bar	-	-	-	0	0	1000
14	0.3 Bar	55 kPa at wall		3.5	1	0	1000 000
15	0.3 Bar		109 kPa at wall	3.5	1	1	20000000
16	0.3 Bar		109 kPa at wall	Entire Room over 20 kW/m²	1	1	20000000
17	0.3 Bar	-	-	-	0	0	1000
18	0.3 Bar	55 kPa at wall		3.5	1	0	1000 000
19	0.3 Bar		109 kPa at wall	3.5	2	0	1000 000
20	0.3 Bar		109 kPa at wall	Entire Room over 20 kW/m²	2	1	1000 000
21	-	-	-	-	0	0	1000
22	1 Bar	-	-	-	0	0	100 000
23	1 Bar	3.8	2.5	4	2	0	500 000

GA-Kitchen

Scenario	P_{red}, kPa)	Distance to 30 kPa (m)	Distance to 70 kPa (m)	Distance to 20 kW/m^2 (m)	Estimated number of injured	Estimated number of Deaths	Estimated Economic Damage
1	1 Bar	-	-	-	0	0	
2	1 Bar						
3	1 Bar	-	-	-	0	0	
4	1 Bar	6.9	4.6	beräkna			
5	1 Bar	6.9	4.6				
6	1 Bar	6.9	4.6				
7	1 Bar	6.9	4.6				
8	1 Bar	6.9	4.6				

Grinding and sugar room

Scenario	P_{red}, kPa)	Distance to 30 kPa (m)	Distance to 70 kPa (m)	Distance to 20 kW/m^2 (m)	Estimated number of injured	Estimated number of Deaths	Estimated Economic Damage
1	-	-	-	-	0	0	0
2	1 Bar	-	-	-	0	0	500 000
3	1 Bar	6	4	2.8	1	1	1000 000
4	1 Bar	-	-	-	0	0	100 000
5		-	-	-	0	0	1000
6	1 Bar	-	-	-	0	0	1000
7	1 Bar	-	-	-	0	0	500 000
8	1 Bar	-	-	-	0	0	100 000
9	1 Bar	6	4	2.8	1	1	1000 000
10	1 Bar	6	4	2.8	1	1	1000 000
11	1 Bar	-	-	-	0	0	25 000
12	1 Bar	-	-	-	0	0	1000 000
13	1 Bar	14.8	9.9	9	3	2	20000000

Azo Room

Scenario	P_{red}, kPa)	Distance to 30 kPa (m)	Distance to 70 kPa (m)	Distance to 20 kW/m^2 (m)	Estimated number of injured	Estimated number of Deaths	Estimated Economic Damage
1	-	-	-	-	0	0	0
2	-	-	-	1.9	1	1	1000

3	-	-	-	3.8	1	1	500 000
4	-	-	-	-	0	0	1000
5	-	-	-	-	0	0	1000
6	-	-	-	1	1	0	1000
7	-	-	-	1	1	0	1000
8	-	-	-	2.5	1	1	500 000
9	-	-	-	-	0	0	1000
10	-	-	-	-	0	0	1000
11	1 Bar	6.9	4.6	3.8	1	1	500 000
12	-	-	-	-	0	0	25 000
13	1 Bar	11.7	7.8	Almost Entire room	1	1	500 000
14	1 Bar	11.7	7.8	Entire room	1	1	1000 000
15	1 Bar	11.7	7.8	Entire room + 2.8	1	1	1000 000
16	1 Bar	11.7	7.8	Almost Entire Room	1	1	100 000
17	1 Bar	11.7	7.8	Entire room	1	1	500 000
18	1 Bar	-	-	-	0	0	1000
19	1 Bar	-	-	-	0	0	100 000
20	1 Bar	4	6	3.2	1	1	100 000
21	1 Bar	4	6	Entire room	1	1	500 000
22	0.5 Bar	-	-	-	0	0	0
23	0.5 Bar	-	-	1	1	0	25 000
24	0.5 Bar	-	-	-	0	0	25 000
25	0.5 Bar	4.7	3.2	2.9	1	0	25 000
26	0.5 Bar	4.7	3.2	Entire Room	1	1	100 000
27	0.5 Bar	4.7	3.2	2.9	1	0	25 000

Manual drageé

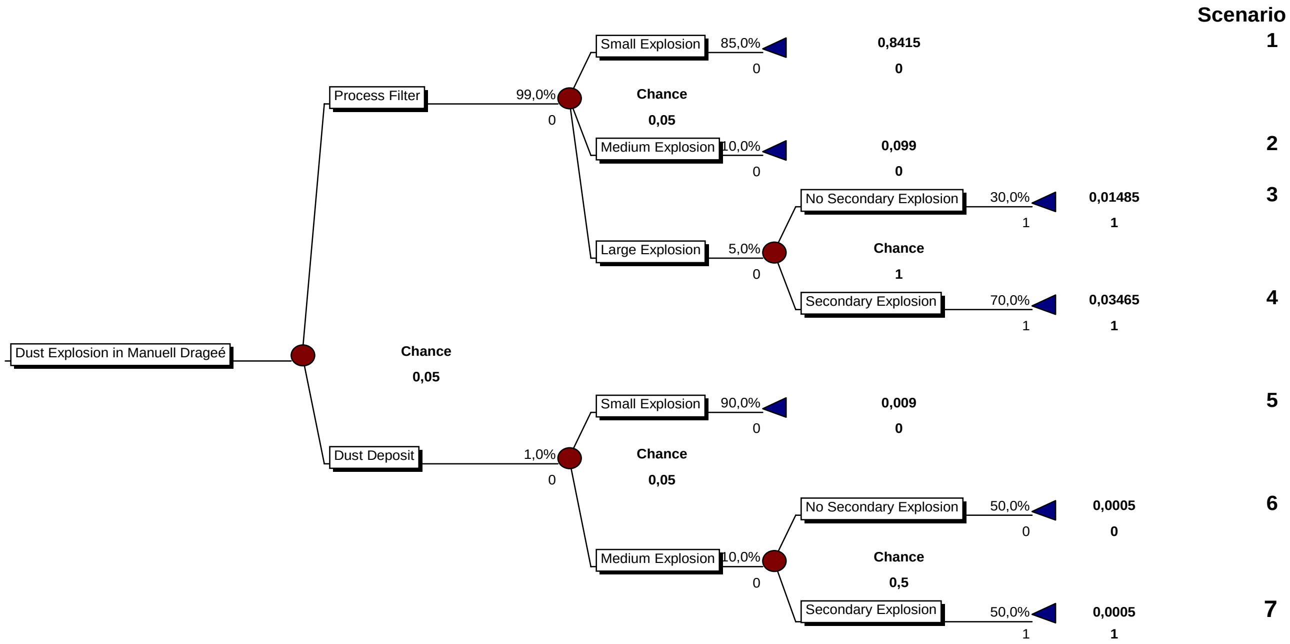
Scenario	P_{red}, kPa)	Distance to 30 kPa (m)	Distance to 70 kPa (m)	Distance to 20 kW/m² (m)	Estimated number of injured	Estimated number of Deaths	Estimated Economic Damage
1	1 Bar	-	-	-	0	0	1000
2	1 Bar	-	-	-	0	0	25 000
3	1 Bar	8.7	5.8	2.8	1	0	100 000
4	1 Bar	8.7	5.8	Entire Room	1	3	1000 000
5	-	-	-	-	0	0	0
6	-	-	-	-	0	0	25 000
7	-	beräkna		Entire Room	1	3	1000 000

Drying Chambers

Scenario	P_{red}, kPa)	Distance to 30 kPa (m)	Distance to 70 kPa (m)	Distance to 20 kW/m² (m)	Estimated number of injured	Estimated number of Deaths	Estimated Economic Damage
1	-	-	-	-	0	0	0
2	-	-	-	1	1	0	100 000
3	-	-	-	2	0	1	500 000
4	-	-	-	-	0	0	0
5	-	-	-	1	1	0	100 000
6	-	-	-	2	0	1	500 000

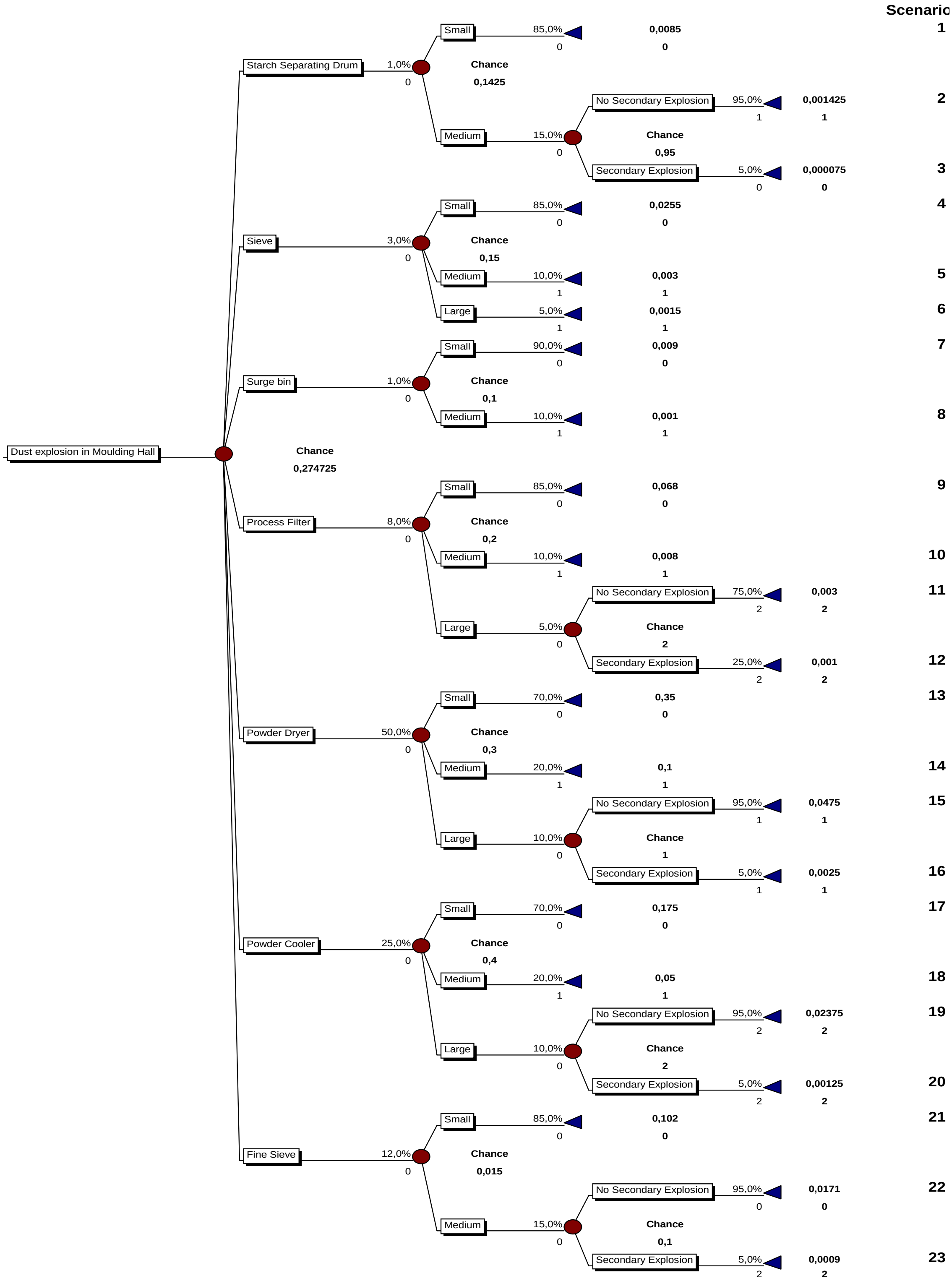
Appendix G – Event Trees

Manual Drageé



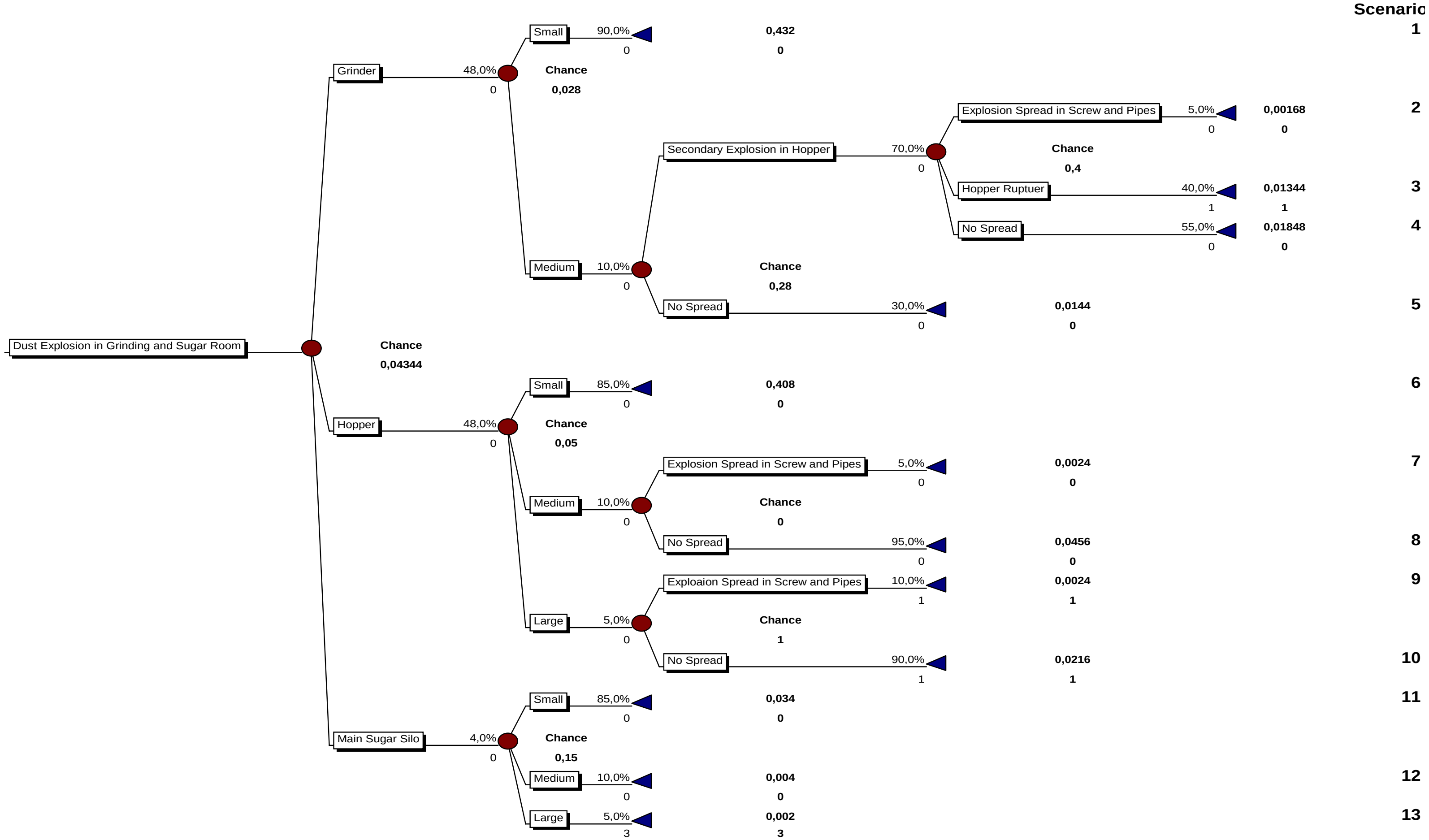
STATISTICS	Injured	Deaths	Money
Mean	0,05	0,10545	39964
Minimum	0	0	0
Maximum	1	3	1000000
Mode	0	0	1000
Std Dev	0,217944947	0,552476513	183750,9393
Skewness	4,12948321	5,048359404	5,005365305
Kurtosis	18,05263158	26,48593267	26,19319977

Moulding Line Hall



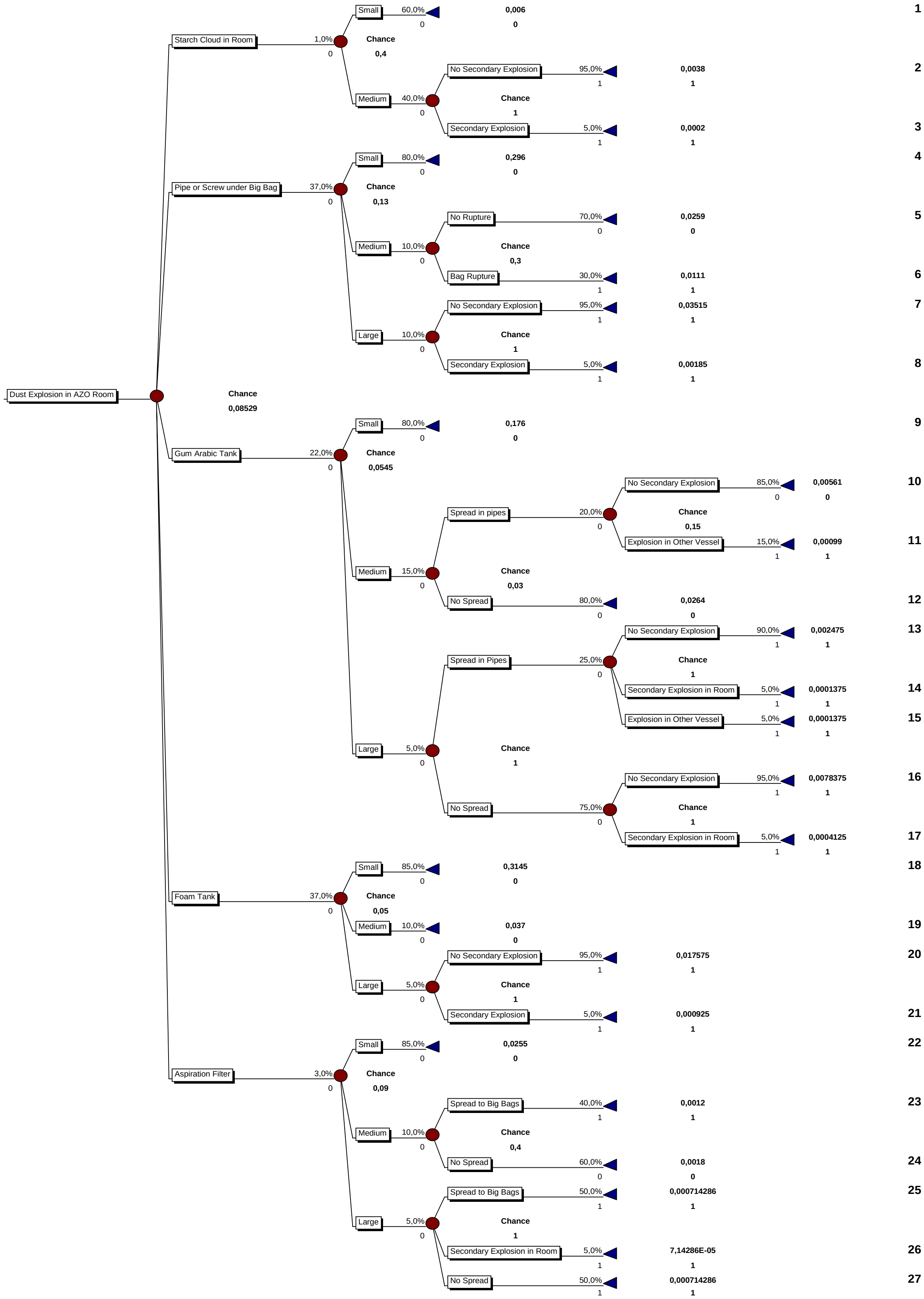
STATISTICS	Injured	Deaths	Money
Mean	0,274725	0,06575	1267086,075
Minimum	0	0	0
Maximum	2	2	20000000
Mode	0	0	1000
Std Dev	0,508970701	0,251847052	4491988,954
Skewness	1,667712217	3,690698102	3,899495868
Kurtosis	4,897893349	15,55589744	16,33755128

Grinding and Sugar Room



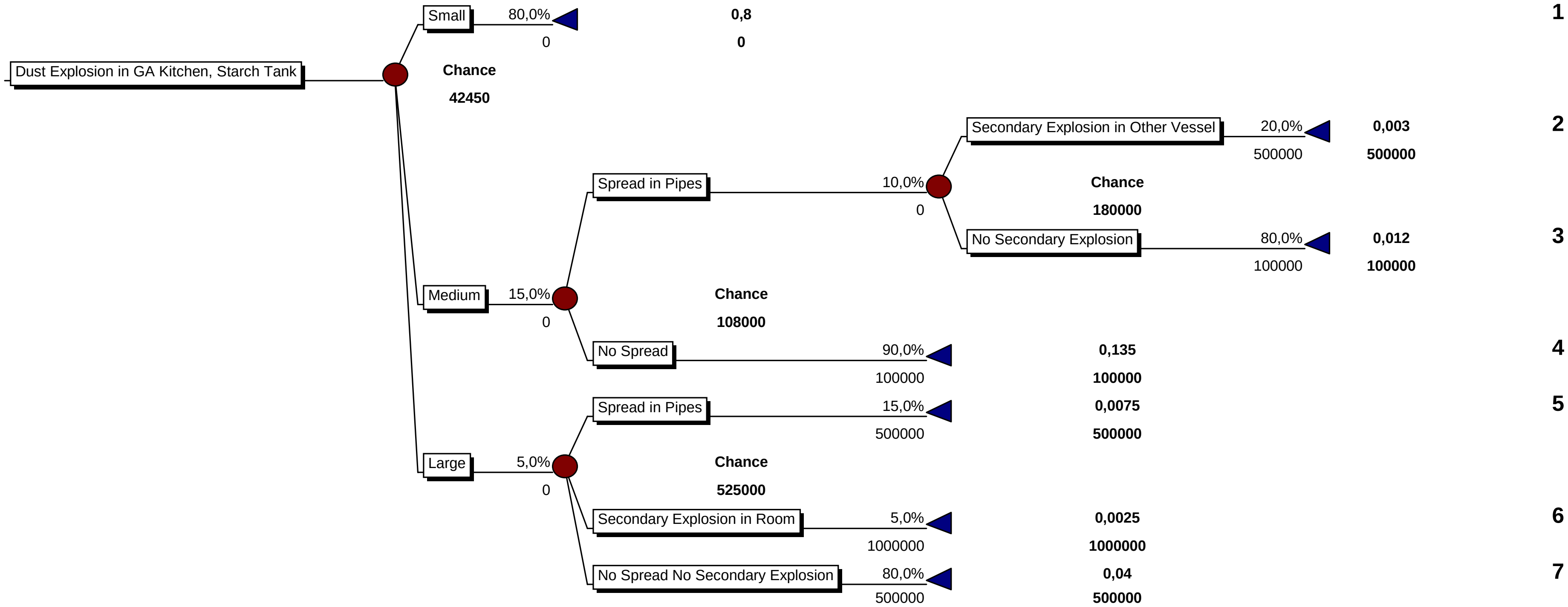
STATISTICS	Injured	Deaths	Money
Mean	0,04344	0,04144	91160,4
Minimum	0	0	0
Maximum	3	2	20000000
Mode	0	0	0
Std Dev	0,231415139	0,2090998	913680,6082
Skewness	6,808620058	5,242951177	20,73145191
Kurtosis	64,21671186	31,93067775	450,8950533

AZO room



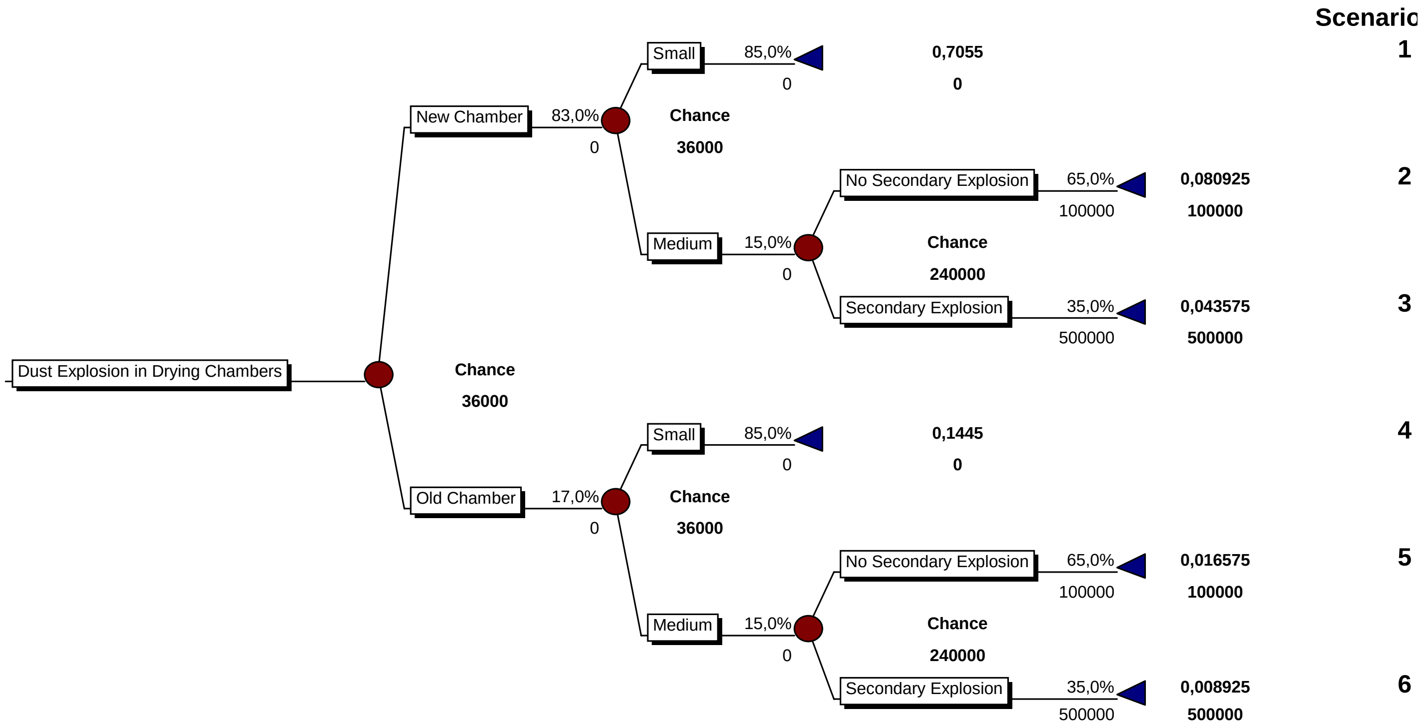
STATISTICS	Injured	Deaths	Money
Mean	0,08529	0,036411429	10954,81714
Minimum	0	0	0
Maximum	1	1	1000000
Mode	0	0	1000
Std Dev	0,279312756	0,187311603	49966,1744
Skewness	2,969502756	4,949918373	8,904073742
Kurtosis	9,817946618	25,5016919	105,7333417

GA kitchen



STATISTICS	Injured	Deaths	Money
Mean	0,053	0,0025	42450
Minimum	0	0	0
Maximum	1	1	1000000
Mode	0	0	0
Std Dev	0,22403348	0,049937461	121626,4671
Skewness	3,990475001	19,92492174	3,890083853
Kurtosis	16,92389074	398,0025063	19,73795127

Drying chambers



STATISTICS	Injured	Deaths	Money
Mean	0,0975	0,0525	36000
Minimum	0	0	0
Maximum	1	1	500000
Mode	0	0	0
Std Dev	0,296637405	0,223033069	113154,7613
Skewness	2,713750817	4,012857837	3,610153804
Kurtosis	8,364443497	17,10302802	14,86230843

Appendix H - Survey

Frågeformulär om brand och risk till anställda på Leaf i Gävle

Jag läser till Civilingenjör i Riskhantering i Lund. Som en avslutande del på utbildningen genomför jag nu ett examensarbete i samarbete med Leaf i Gävle. En del i detta arbete är att göra en riskanalys på fabriken i Gävle med avseende på dammexplosioner.

Arbetet skall förhoppningsvis leda till att er arbetsplats skall bli säkrare. För att kunna genomföra detta arbete behöver jag nu din hjälp för att besvara en del frågor! Jag är väldigt tacksam om ni kan hjälpa mig, genom att ta er tid att svara på denna enkät så ärligt som möjligt.

Du har blivit slumpmässigt utvald att besvara detta frågeformulär. För den statistiska säkerheten är det viktigt att just du svarar på denna enkät.

Lämna den ifyllda enkäten till din koordinator senast torsdagen den 30 juni 2005.

Enkäten besvaras helt anonymt!

Tack för din hjälp!

Tobias Dahl Hansson

Allmän information

Svara genom att skriva på linjen eller kryssa i rutan framför det alternativ som stämmer bäst!

1. Kön: ☐ Man ☐ Kvinna

2. Vad har du för position/positioner på Leaf?

Operatör
Koordinator
Op/rep
Reparatör
El/styr

3. Hur länge har du arbetat på företaget?_____________år.

4. Ingår någon eller några av följande arbetsuppgifter i ditt arbete?

☐ Underhållsarbete
☐ Städning ☐
Dammsugning ☐
Svetsning

Brand och dammexplosioner

Nu kommer några frågor om brand och säkerhet!

5. Har du hört talas om fenomenet dammexplosion?

☐ Ja ☐ Nej

6. Hur väl känner du till under vilka omständigheter en dammexplosion kan ske?

☐ Mycket bra Bra Ganska bra Dåligt Inte alls

7. Känner du till någon dammexplosion som har inträffat?

☐ Ja ☐ Nej

8. Hur mycket information har du fått från Leaf om dammexplosioner?

Mycket Ganska mycket Lite Väldigt lite Ingen alls

---

9. Vilka pulver här på Leaf i Gävle tror du skulle kunna orsaka en explosion?

☐ Socker ☐ Salt Gelatin ☐ Stärkelse Salmiak
Gummi ☐ Xylitol ☐ Maltodextrin Vet ej

---

10. Vad tror du skulle kunna starta en dammexplosion?

☐ Glöd från Cigarett
☐ Statisk elektricitet
☐ Svetsning ☐
Varm glödlampa
☐ Stearinljus
Vet ej

---

11. Hur skulle du släcka en brand i pulver, till exempel om gjutpudret skulle börja brinna?

____

____

---

12. Har du fått någon utbildning i brandbekämpning? I fall du svarar ja på denna fråga, ungefär hur längesedan fick du denna utbildning?

☐ Ja ☐ Nej Tid sedan utbildning: År_____Månader_____

---

13. Vet du vem du skall vända dig till om du har frågor om brand och säkerhetsfrågor?

☐ Ja ☐ Nej

---

14. Vet du vad du skall göra om du upptäcker en brand?

☐ Ja ☐ Nej

---

15. Vet du vem du skall vända dig till om du misstänker att något verkar vara fel på en maskin eller annan del av anläggningen?

☐ Ja ☐ Nej

16. Vilka risker upplever du som störst i ditt arbete?

____

____

Vad tycker du?

Nu kommer ett antal frågor om vad du tycker om olika saker, kryssa för det alternativ som stämmer bäst!

17. Hur upplever du säkerheten på din arbetsplats?

Mycket bra Bra Ganska bra Dålig Väldigt dålig

18. Hur upplever du risken att du skulle kunna skada dig på din arbetsplats?

Mycket liten Liten Ganska liten Stor Väldigt stor

19. Tycker du att du uppmuntras av dina chefer att hålla ordning och reda och städa din arbetsplats?

Väldigt mycket Mycket Ganska mycket Lite Väldigt lite

20. Hur tycker du att bortstädningen av damm och pulver sköts i fabrikslokalerna?

Mycket bra Bra Ganska bra Dåligt Väldigt dåligt

21. Hur mycket personligt ansvar känner du för säkerheten på företaget?

Väldigt mycket Mycket Ganska mycket Lite Väldigt lite

Hur skulle du handla?

Nu kommer några frågor om hur du skulle handla i några olika situationer!

22. Skulle du rapportera en händelse som var nära att bli en olycka men som inte blev det?

☐ Ja, alltid ☐ Ja, förmodligen ☐ Kanske ☐ Förmodligen inte ☐ Nej, aldrig

23. Om du ser att en maskin eller annan utrustning på fabriken är skadad men ändå fungerar bra, skulle du rapportera detta?

Ja, alltid Ja, förmodligen ☐ Kanske ☐ Förmodligen inte Nej, aldrig

24. Om en kollega skulle begå ett misstag som skulle kunna ha resulterat i en olycka men som inte gjorde det, skulle du då rapportera det?

Ja, alltid Ja, förmodligen ☐ Kanske ☐ Förmodligen inte Nej, aldrig

Tack för din medverkan! Har du något ytterligare du vill tillägga kan du göra det på raderna nedan!

Appendix I – Survey results for operators

a.e	available extinguishing equipment
w	water
We	Welding
F	foam
p	powder
c	cleaning
m	maintenance
v	vacuuming

Survey results for operators and general staff, Leaf Gävle
Answers: 24/39

Question number

	1. Sex	2. Position	3.Y. at Leaf	4. Tasks	5	6	7	8	9	10
1	f	Op	24	c, v	n	1	n	1	0	0
2	m	Op	4.5	c, v	n	1	n	1	0	2/5
3	m	Op	17	-	j	2	n	1	0	1/5
4	f	Co	16	c	j	3	n	3	3/6	2/5
5	f	Op	5	m,c,v	n	1	n	1	0	1/5
6	m	Co	8	m,c,v	j	4	n	2	4/6	4/5
7	m	Co	10	m,c,v	j	3	n	1	0	3/5
8	m	Op	8	c	j	2	n	2	0	0
9	m	Op	3	c, v	j	2	n	3	0	1/5
10	m	Op	1	m, c	j	2	n	1	0	4/5
11	f	Op	6	c, v	n	1	n	1	0	0
12	m	Op	4	c, v	j	2	j	1	0	2/5
13	f	Op	4	c, v	j	2	n	1	0	5/5
14	m	Op	8	c, v	n	1	n	1	0	1/5
15	m	Op	10	m, c, v	j	1	n	1	1/6	0
16	m	Op	8	m, c	j	3	n	1	1/6	1/5
17	f	Co	16	c, v	j	1	n	1	0	1/5
18	m	Op	4	c, v	n	1	n	1	0	0
19	m	Co	9	c, v	j	2	n	1	0	3/5
20	m	Op	9	m, c, v	j	2	n	2	0	1/5
21	m	Op	2	m, c, v	n	1	n	1	1/6	1/5
22	m	Op	3	c	j	2	n	1	0	1/5
23	f	Op	6	m, c, v	n	2	n	1	0	2/5
24	m	Op	10	c, v	-	2	n	1	1/6	1/5
25	m	Co	13	c, v	j	2	n	1	0	2/5
26	f	Op	27	c	n	1	n	1	2/6	3/5
average:			**8.7**		**3.6**	**1.8**	**1.2**	**1.3**	**0.5/6**	**1.6/5**

Survey results for operators, Leaf Gävle

Question number

	11	12	13	14	15	16	17	18	19	20
1	don't know	n	n	-	j	-	3	3	1, never	1
2	f	n	n	j	j	squeeze, burn	3	3	4	4
3	a.e	n	n	n	n	fire and expl. In aroma	3	2	4	3
4	don't know	8	n	j	j	-	3	3	4	3
5	water	n	n	j	j	-	4	4	1	4
6	f	9.5	n	j	j	fork lift	2	2	3	3
7	f	n	j	j	j	-	3	3	4	3
8	water	12.5	n	j	j	fingers in machine	3	3	5	4
9	a,e [no idea]	n	j	n	j	jet lag, back pain hearing damage		3	4	4
	3									
10	a.e, not dry powder	n	n	n	j	oxidizing product, hearing	3	3	3	3
11	water?, don't know	n	n	j	j	change f.lift battery, noise, powder	2	2	4	2
12	dry powder	n	n	-	j	heavy lifting	3	3	4	4
13	suffocating	8	n	j	j	burn, forklift, squeeze	3	2	2	3
14	don't know	n	j	j	j	squeeze	4	4	4	4
15	water	n	n	j	j	chemicals	2	2	1	2
16	suffocating	n	n	j	j	chemicals	2	3	3	1
17	water?	14	n	j	j	no special	3	3	5	3
18	powder	2.5	n	j	j	squeeze, powder in air	2	2	4	2
19	don't know	n	n	n	j	heavy lifts	2	2	5	4
20	don't know	n	n	j	j	forklift	3	2	4	3
21	a.e	n	j	j	j	squeeze	3	4	3	2
22	foam	n	n	j	j	back and neck	3	3	4	3
23	a.e	n	n	j	j	ear damage, stress	3	3	3	3
24	water	4	n	j	n	squeeze, burn	4	3	2	2
25	foam	n	j	j	j	dust	2	3	3	3
26	-	15	j	j	j	electrical error	4	3	3	4
average			**2.0**	**4.0**	**4.7**		**2.9**	**2.8**	**3.2**	**3.0**

Survey results for operators crew, Leaf Gävle

Question number

	21	22	23	24	Comments
1	-	3	4	2	
2	4	5	5	4	
3	4	5	5	5	
4	4	5	4	4	
5	3	4	4	5	
6	3	4	4	4	
7	4	4	5	4	
8	4	4	4	3	
9	2	3	4	3	Good luck!
10	3	3	4	3	
11	3	5	5	5	
12	2	4	4	3	
13	3	4	5	3	
14	4	5	5	5	
15	2	5	5	4	Never heard any managers discuss dust explosions during my ten years.
16	2	4	4	4	
17	4	4	5	4	It would be good with [dust explosion] education here at the company
18	1	5	5	4	Good Luck!
19	1	2	5	2	
20	3	4	5	4	
21	4	3	3	2	
22	2	2	2	2	
23	3	5	5	5	Good Luck
24	3	3	5	2	
25	4	5	5	2	
26	4	5	5	4	
average	**3.1**	**4.1**	**4.4**	**3.6**	

Appendix J – Survey results for maintenance crew

a.e	available extinguishing equipment
w	water
We	Welding
F	foam
p	powder
c	cleaning
m	maintenance
v	vacuuming

Survey results for maintenence crew, Leaf Gävle
Answers: 17/19

Question number

	1. Sex	2. Position	3.Y. at Leaf	4. Tasks	5	6	7	8	9	10
1	m	maintenance	32	m,c	j	2	n	2	2/6	3/5
2	m	mai, storage	0.4	-	j	4	n	1	3/6	5/5
3	m	maintenance	29	c	j	2	n	1	3/6	1/5
4	m	maintenance	40	m,we	j	4	n	4	1/6	3/5
5	m	maintenance	6	m, we	j	4	n	1	2/6	2/5
6	m	mai, coordinator	3.5	m	j	3	n	2	0	1/5
7	m	mai, coordinator	5	m	j	2	n	1	1/6	4/5
8	m	maintenance	3	m	j	2	n	1	0	2/5
9	m	maintenance several	m, we	j	3	j	1	2/6	2/5	
10	m	mai, el/sty	5	m	j	3	j	1	0	3/5
11	m	maintenance	9	m, c, v, we	j	3	j	1	3/6	3/5
12	m	maintenance	3.5	m, we	j	3	n	2	1/6	5/5
13	m	maintenance	7	m, we	j	3	n	1	-	1/5
14	m	mai, el/sty	1.5	m	j	2	n	1	0	5/5
15	m	mai, coordinator	2	m, we	j	2	n	1	0	5/5
16	m	mai, el/sty	10	m, we	j	2	n	1	3/6	1/5
17	m	maintenance	22	m	j	2	n	1	1/6	1/5
average:			**11**			**2.7**	**1.7**	**1.4**	**1.3/6**	**2.8/5**

Survey results for maintenence crew, Leaf Gävle

Question number

	11	12	13	14	15	16	17	18	19	20
1	a.e	2.3	j	j	j	-	4	4	3	2
2	w, a.e,	6	n	j	j	-	4	4	2	3
3	w, a.e	0.6	j	j	j	fall, squeeze	3 4	2	2	
4	w	04	j	j	j	welding, grinding	5	5	3	3
5	f	2.5	j	j	j	electrical, pumps, engine	4	4	1	3
6	a.e	n	n	j	j	-	4	3	5	3
7	p	3	j	j	j	squeeze	3	3	4	3
8	a.e	n	n	j	j	risk for personal injury	3	2	4	2
9	CO_2	1.5	j	j	j	everything	2	2	3	2
10	a.e	1	n	j	j	squeeze	4	3	3	1
11	w, a.e	4	n	j	j	squeeze, cut injuries	2	3	3	1
12	w	14	n	j	j	fall, cut, burn	3	3	2	3
13	w	9.5	j	j	j	fall, cut, burn	3	1	3	2
14	w	8	n	j	j	-	3	3	3	2
15	w	n	n	j	n	squeeze + [unreadable]	4	2	4	3
16	-	2	j	j	j	squeeze, fire	2	2	1	1
17	-	4	j	j	j	-	4	4	2	3
average:		**3.4** **3: n**	**3.1**	**5**	**4.8**		**3.1**	**3.1**	**2.8**	**2.3**

Survey results for maintenence crew, Leaf Gävle

	Question number				
	21	22	23	24	Comments
1	4	4	5	4	
2	4	4	5	3	work part time in the storage, spend limited time in the factory
3	2	3	4	3	
4	5	5	5	2	
5	5	5	5	5	
6	4	5	5	5	
7	2	4	5	4	
8	5	5	5	4	
9	2	3	4	4	
10	4	4	4	2	
11	3	5	5	4	
12	3	2	5	3	
13	3	4	4	2	
14	4	3	4	3	
15	3	2	4	3	
16	2	3	3	3	
17	5	5	5	4	
average:	**3.5**	**3.9**	**4.5**	**3.4**	

Appendix K – Example of Goal list for mills

Gum mill Goal List	Compliance
1. Remove ferrous materials from the feed	Yes
2. Remove non ferrous metals and materials with pneumatic separator	No
3. Ensure separators are regularly maintained and emptied	Yes
4. Control feed input rate	No
5. Install overload monitor on drive motor	No
6. Maintain and lubricate bearings regularly	Yes/No
7. Check and maintain the alignment of mechanical components and tolerances regularly	Yes/No
8. Periodically check for excessive heating of mechanical components	No
9. Regularly maintain drive chains and lubrication. Maintain correct tension	Yes/No
10. Ensure correct number of V-belt drives, and maintained at correct tension. They should be fire resistant and anti static.	Yes/No
11. Open mesh metal machinery-guards should be fitted to prevent dust accumulation and prevent dust accumulation and aid ventilation	No
12. Check all components for earth connection regularly. Earth resistance should be less than 10 ohms	No
13. Feedstock should not be kept within the size reduction enclosure.	No

Appendix L – Example of Check list for mills

Check list gum Mill

	Date/Sign	Comment	Date/Sign	Comment	Date/Sign	Comment	Date/Sign	Comment
Magnet emptied								
Maintenance of separator								
Maintenance and lubrication of bearings								
Alignment of mechanical components								
Check for excessive heating								
Tension and lubrication of drive chains								
Earth connection								