Visual Dust Hazard Analysis – Understanding Threats and Assuring Controls

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Abstract

The potential harm and asset damage from a dust explosion have been known for many centuries. A wide variety of materials that are explosible in dust form exist in many industries, however knowing about an issue is not the same as properly understanding and adequately addressing the challenges.

The authors draw on their complementary experience in Dust Hazard Analysis (DHA) application (1) and BowTie implementation (2) to present a novel approach to scenario visualisation and asset management using bowties.

Just as a conventional HAZOP or Process Hazard Analysis (PHA) subdivides the process into nodes, the DHA breaks the plant into sections which are systematically challenged to determine if explosion or fire hazards exist. For dusts, this includes identification of competent ignition threats. Subsequent evaluation is conducted to determine which are prevented and/or mitigated by safeguards specific to each threat and consequence.

Risks are assigned and actions issued as per a normal hazard analysis, however the graphical presentation of the ignition scenarios and safeguards and the illustration of potential ignited particles which can travel and ignite within downstream equipment offers significant communication benefits. This can be particularly helpful in facilities or countries where English and/or Risk are not the primary language or familiar terminology. This paper will show how BowTies are an effective tool to engage less technical stakeholders and offer a robust framework to assure the health (presence and performance) of the assumed or planned human and hardware controls which must be sustained to provide the necessary risk reduction.

In summary, this novel approach evolves analysis into an operational framework to ensure that the ignition risks are better understood, and the controls are properly implemented, operated and maintained.

1 Combustible Dust Hazard Analysis

The potential harm and asset damage from a dust explosion have been known for centuries. A wide variety of materials that are explosible in dust form exist in many industries, however knowing about an issue is not the same as properly understanding and adequately addressing the challenges.

Figure 1 shows the progression from fire to flash fire to explosion for combustible dusts. These hazards exist in dust processing equipment and in building spaces where dust is escaping equipment. To prevent the realization of these unwanted events, one of the elements of the original fire triangle needs to be removed. While explosions are the most destructive, flash fires often result in fatalities, and having one of these events can trigger secondary events.

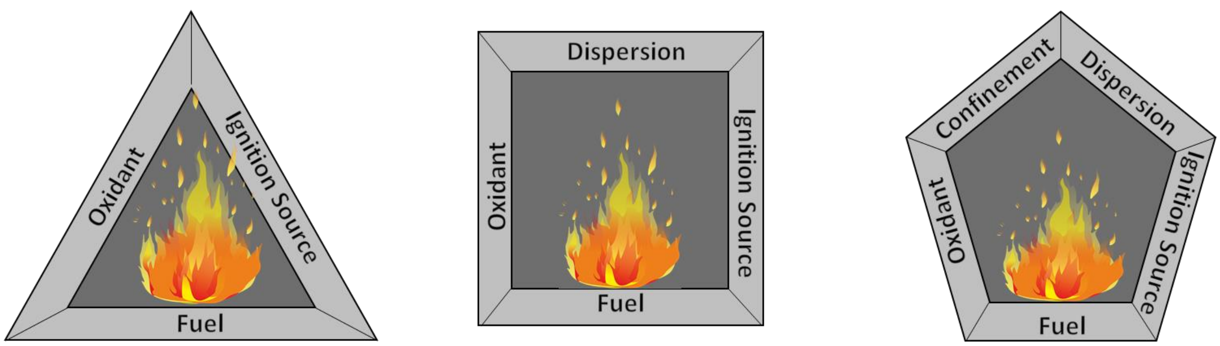

Figure 1 – Progression of combustible dust hazards from fire to flash fire to explosion

Dust hazard analyses (DHAs) are conducted to identify and assess dust flash-fire and explosion hazards in both process equipment and building spaces. Like PHAs, many methodologies are available for completing hazard identification and assessment of dust hazards. Most involve recording of the discussion in a spreadsheet format. Visual DHAs (bowties) are a novel approach to scenario visualization that can simplify communication of DHA results, elevate appreciation of safeguards (barriers), and improve the management of change (MOC) process.

At present, most applications involve development of bowties for higher hazard scenarios after a more traditional hazard analysis has been completed. This paper will present bowties as developed from traditional DHA records.

1.1 Regulations

In the US, the Occupational Health and Safety Administration (OSHA) does not have a comprehensive combustible dust standard. It relies on existing related regulations and recognized and generally accepted good engineering practices (RAGAGEPs). The most widely applied of these standards are from the National Fire Protection Association (NFPA®). Both the fundamentals standard NFPA 652 (3) and the industry-specific standards (4; 5; 6; 7), require dust hazards analysis (DHA) of dust handling operations. The NFPA does not specify a DHA technique to be adopted however one example is provided and several commonly applied hazard analysis techniques are listed in the appendix. In their recent paper, Murphy and Borene (8) detail the NFPA requirements for conducting DHAs and present a typical DHA process.

In Europe, ATEX (ATmosphères EXplosives) is the name commonly given to the two European Directives for controlling explosive atmospheres:

- Directive 1999/92/EC (9) (also known as 'ATEX 137' or the 'ATEX Workplace Directive') on minimum requirements for improving the health and safety protection of workers potentially at risk from explosive atmospheres.
- Directive 2014/34/EC (10) (also known as 'ATEX 95' or 'the ATEX Equipment Directive') on the approximation of the laws of Members States concerning equipment and protective systems intended for use in potentially explosive atmospheres.

Article 8 of the ATEX Workplace Directive requires the employer to draw up (and maintain) an Explosion Protection Document (EPD) which includes:

- Identification of hazards
- Evaluation of risks
- Definition of specific measures to safeguard the health & safety of workers at risk from explosive atmospheres

In the UK, the Dangerous Substances and Explosive Atmospheres Regulations 2002 (DSEAR) regulations (11) put into effect the requirements of ATEX 137 and require employers (duty-holders) to identify dangerous substances (including flammable gases, vapours, mists and combustible dusts), evaluate the associated risks, implement controls to remove/reduce flammable atmospheres and/or ignition sources, prepare emergency plans and ensure employees are properly informed about and trained to control the risks from dangerous substances. Although DSEAR does not require an EPD (since its contents are covered by Regulation 5 *Risk Assessment* and Regulation 7 *Places where explosive atmospheres may occur*) these are often prepared by duty-holders as a clear, concise, basis of safety that can be communicated with employees and other interested parties. This approach is intended to complement and/or supplement such documents.

1.2 Regulatory Deadlines

In the US the deadline for most facilities to complete a dust hazard analysis (DHA) is 7th September 2020 (later for agricultural and food manufacturers) in accordance with NFPA Standard 652 on the Fundamentals of Combustible Dust and the associated industry-specific standards.

In the UK and Europe, the ATEX Workplace Directive and DSEAR regulations are already effective and the obligations on duty-holders are long established. This approach aims to improve the awareness and understanding of those responsible for and/or affected by flammable atmospheres.

1.3 DHA Elements

NFPA states that a dust hazard analysis is intended to identify and evaluate areas of the process or building spaces where fire, flash fire, and explosion hazards exist. Once identified, they are to be evaluated for applicable fire and deflagration scenarios, including:

1. Safe operating ranges
2. Existing safeguards
3. Additional safeguards, as needed

Like all hazard analyses, an identification method is employed to identify hazards. Once identified, causes and consequences are postulated to define scenarios. In the case of combustible dust, these would focus on fire, flash fire and explosion scenarios. Existing safeguards are identified and evaluated for their ability to manage these events and remove or limit the consequences. Where existing safeguards are deemed inadequate, additional safeguards are recommended. Finally, a plan for implementation is put together. The process is depicted in Figure 2. An implementation plan is typically completed after the hazard analysis step and is not shown in the hazard analysis flow diagram.

Figure 2 – Hazard analysis flow

1.4 Hazard Identification Methods

Many methods exist to identify dust hazards. Typical identification methods include:

- What-if/Checklist
- HAZOP
- Event Tree/Fault Tree
- Failure Modes and Effects Analysis

Due to the straightforward operation of combustible dust handling equipment, a checklist approach is often employed to identify hazards. Such a checklist can be based on specific requirements and recommendations found in several reference documents (e.g., NFPA codes and standards, CCPS Guidelines for Safe Handling of Powders and Bulk Solids (12) , CCPS Guidelines for Combustible Dust Hazard Analysis (13) and Lee's Loss Prevention in the Process Industries (14)).

CCPS Guidelines for Risk Based Process Safety (15) states “A company that uses its risk and understanding is better able to deal with the resultant risk, and subsequently, sustain long-term, accident-free, and profitable operations.” DHAs are the first step in the risk assessment process.

2 Application of Bowties

2.1 Purpose of Bowtie

A 'bowtie' is a diagram that visualizes the risk you are dealing with in just one, easy to understand picture. The diagram is shaped like a bowtie, creating a clear differentiation between proactive and reactive risk management. The power of this type of diagram is that it gives you an overview of multiple plausible scenarios, in a single picture. In short, it provides a simple, visual explanation of a risk that would be much more difficult to explain otherwise.

Bowtie diagrams are now commonplace in understanding and managing process safety risks, particularly associated with major accidents. Historically they have been applied most frequently in the chemical, petrochemical and oil & gas industries but are equally applicable in all industries, e.g., transport, mining, energy, finance or healthcare and can be used to manage all risks (effect of uncertainty on objectives) including safety, environmental impact, asset damage or loss of reputation.

Bowties demonstrate how hazards are controlled and illustrate the links between controls (barriers) and the relevant components of the safety or risk management system.

2.2 Methodology

The bowtie diagram is based on the concept of the “Swiss Cheese Model” developed by James Reason (16). This model illustrates system failures which can be addressed by controls (barriers) represented by swiss cheese slices which are intended to provide ‘defence in depth’.

Barriers have weaknesses which are either inherent i.e., always present or are active failures created during the scenario which, when aligned, allows the ‘accident trajectory’ to pass through the holes, as depicted in Figure 3.This model has evolved into the familiar and increasingly popular bowtie diagram which allows multiple trajectories (Cause-Consequence relationships) to be visualised on the same diagram.

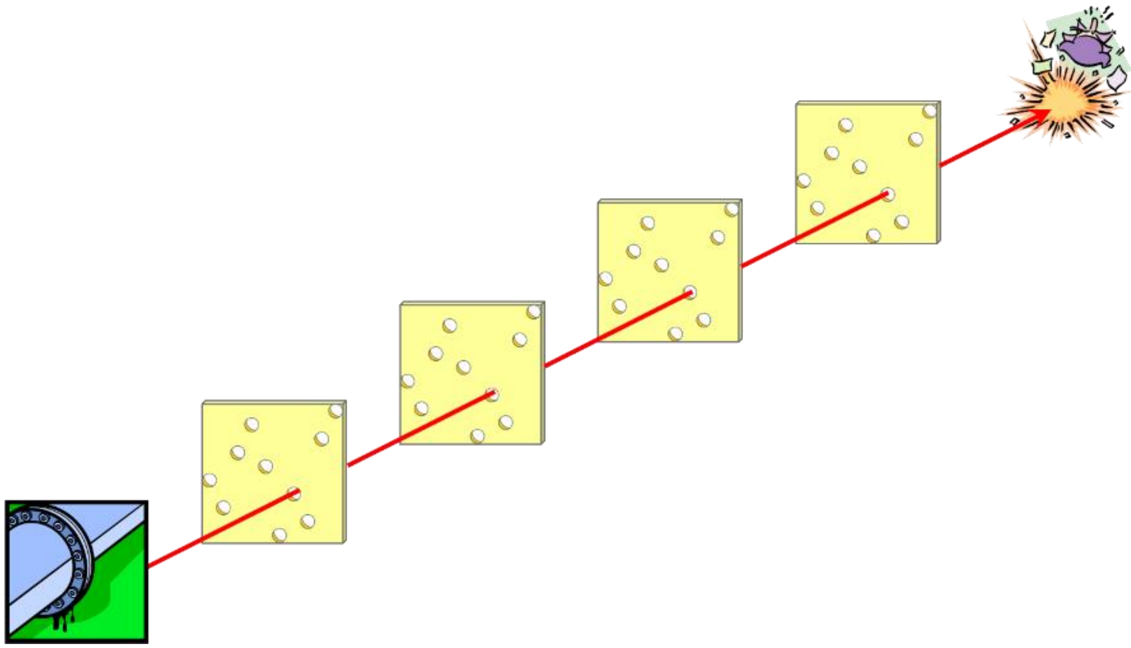

Figure 3 – Swiss Cheese Model

The components of a bowtie diagram are summarised as follows:

- Hazard = Operation, activity or material with potential to cause harm
- Top Event = Initial loss of control of Hazard
- Consequences = Negative effects (harm or damage) that could result from Top Event
- Threats = Potential reasons for loss of control of the Hazard leading to the Top Event
- Barrier = Engineering or Administrative risk reduction measure
    - Prevention
    - On its own can prevent a Threat from developing into a Top Event
        - Eliminate the Threat
        - Prevent the Top Event
    - Mitigation
    - On its own can mitigate the Consequences of the Top Event once it has occurred
        - Prevent consequence (likelihood)
        - Reduce impact (severity)

Barriers can either be hardware, human, or combinations of both which are implemented and operate as follows:

- Passive hardware
    - Always present e.g. structural or containment
- Active hardware

- Automated response to detection e.g. control action or trip
- Active hardware + human
  - Human response prompted by hardware detection e.g. alarms
  - Hardware response prompted by human detection e.g. manual call point
- Active human
  - Human response prompted by observation e.g. walk around & intervention
- Continuous hardware
  - Always operating e.g. ventilation

These components are assembled into scenarios which are read from left to right as shown in the overview in Figure 4 below (with good practice guidance from the CCPS Bowtie book (17)):

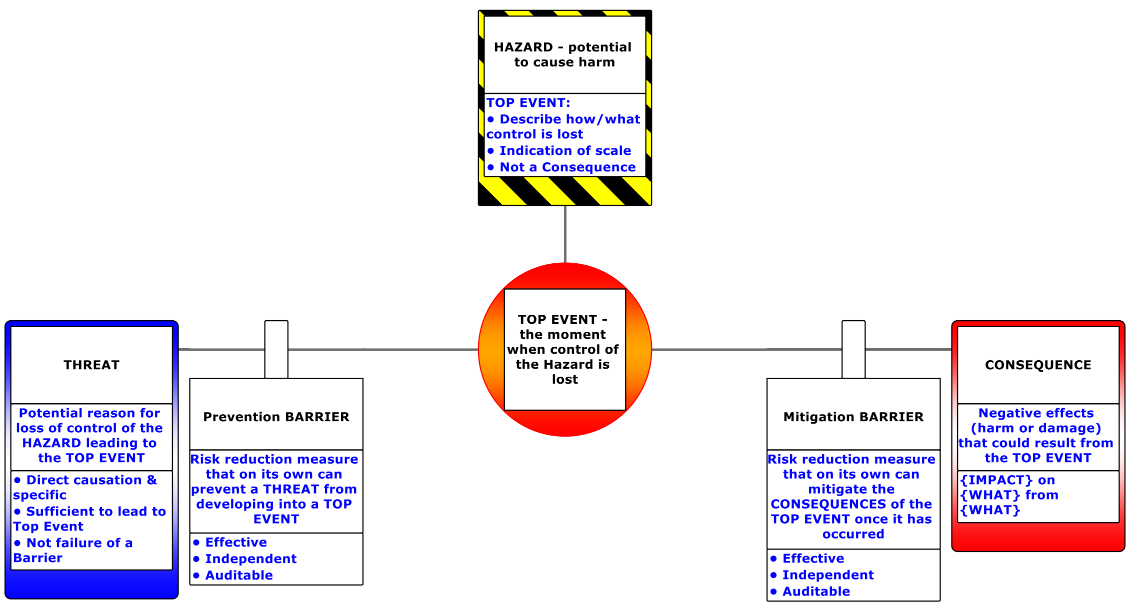

Figure 4 – Bowtie Model

A Top Event may have several Consequences (safety, environmental, asset, etc.) that result from it and several Threats (e.g., equipment failures, environmental influences or operational issues) that could cause it.

2.3 Application to Dust Hazard Analysis

Just as a conventional HAZOP or PHA subdivides the process into nodes, the DHA breaks the plant into systems which are systematically challenged to determine if explosion or fire hazards exist. For dusts, this includes identification of competent ignition threats. Subsequent evaluation is conducted to determine which are prevented and/or mitigated by safeguards specific to each threat and consequence.

Annex B of NFPA 652 (3) provides an example DHA of a wood milling process. Wood chips are brought in via rail car and trailer truck, unloaded and pneumatically conveyed into a storage silo, transported through a screw conveyer to a size reduction mill, and further processed for product delivery. The DHA is applied to each process component and is documented in paragraph format. Figure 5 shows how the results of the evaluation of the first node, offload duct to offload fan, would look in a simple bowtie representation.

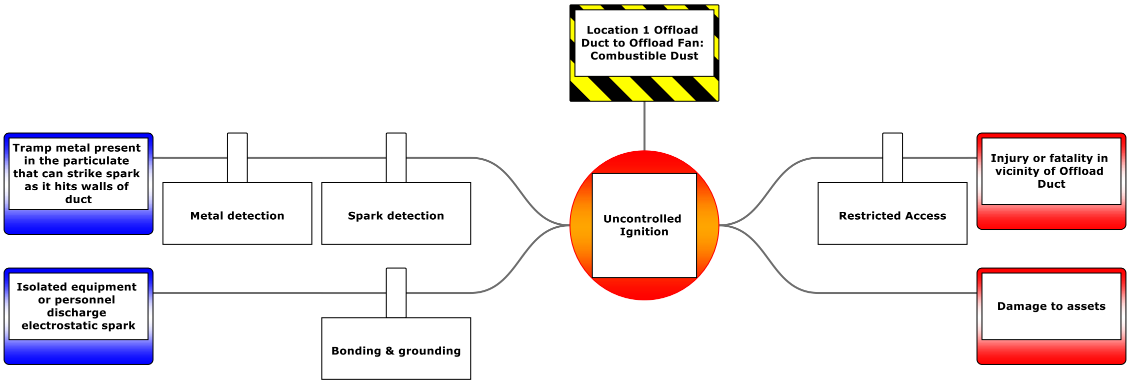

Figure 5 – Basic DHA of a process unit

A more detailed example is discussed later in this paper.

In the manner presented in Figure 5, each DHA node (major asset or sub-system) is represented by a separate bowtie with the credible/competent ignition sources represented as threats e.g. from EN 1127-1 (18) . To simplify the documentation of ignition sources, these can be coded to make the diagrams concise:

- AC Adiabatic compression and shock waves
- EA Electrical apparatus
- EC Stray electric currents, cathodic corrosion protection
- EW Electromagnetic waves
- EX Exothermic reactions, including self-ignition of dusts
- FL Flames and hot gases (including hot particles)
- HS Hot surfaces
- IR Ionizing radiation
- LT Lightning
- MS Mechanically generated sparks
- RF Radio Frequency (RF) Electromagnetic waves
- SE Static electricity

- US Ultrasonics

Hazard data can be added to the diagram including:

- Material and properties
- Safe Operating Range
- Deflagrable (Yes/No)
- Suspended in Air (Yes/No)
- Above Minimum Explosive Concentration (Yes/No)

The potential effects of an uncontrolled ignition (some processes involve controlled ignition e.g., biomass fuel) include fire, flash fire, or explosion that result in fatality, injury, and/or property damage (including business interruption). These can occur in the node/asset/system under review or in connected nodes/assets/systems e.g., ignited or smouldering particles passing downstream. Figure 6 shows the connection of consequences (upstream) that become threats (downstream). In the figure, uncontrolled ignition in the offload duct propagates to the offload fan. These have become threats to the downstream system.

NFPA specifically calls out the evaluation of potential deflagration propagation between parts of the process. The bowtie simplifies the application and visualization of this critical part of the analysis.

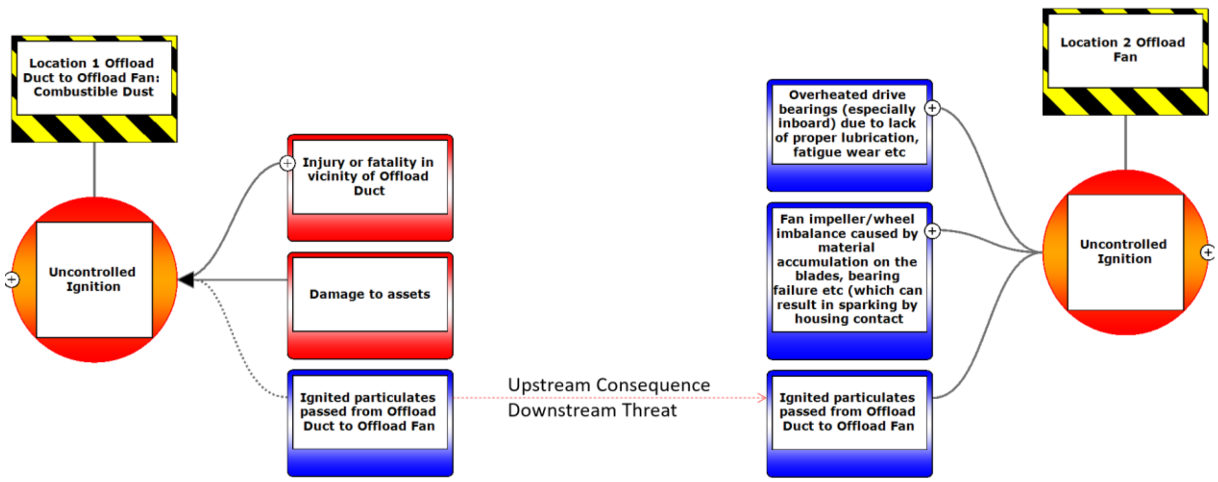

Figure 6 – Indirect Consequences (chained bowties)

Risks are evaluated based on the likelihood of a coincident flammable dust atmosphere (in ATEX, this is defined in hazardous area classification) and an ignition source (based on threat frequency or potential) and the severity of the fire or explosion impact. These are assigned and actions issued as per a normal hazard analysis. The graphical presentation of the ignition scenarios and safeguards and the illustration of potential ignited particles which can travel and ignite within downstream equipment offers significant communication benefits. This can be particularly helpful in facilities or countries where English and/or Risk are not the primary language or familiar terminology.

The visual nature of the bowtie helps confirm existing control measures (prevention & mitigation barriers) e.g. explosion vents, temperature sensors, etc. and identify where additional measures to meet risk target are needed.

2.4 Risk Management

Effective risk management requires an understanding of hazard scenarios and an appreciation (and respect) of the measures to prevent loss of control and mitigate the consequences. Bowtie diagrams provide clear, consistent information to a wide audience compared to detailed analyses which are limited to specialist interpretation.

Once barriers have been identified, a barrier-management program is necessary to ensure that controls are implemented and continue to operate and perform as required to provide ongoing risk reduction. This program involves monitoring the presence and measuring the effectiveness of hardware (technical) and human (organisational) barriers and repairing, replacing or refreshing them as and when appropriate in advance of any demands to act, i.e., before the scenarios occur. The visual nature of bowties can simplify the identification of barriers for program development.

3 Example

The approach of converting from a traditional spreadsheet format is presented in an example of a filter receiver (Figure 7). Filter receivers are one type of air material separator and are often found in dust handling operations as part of the pneumatic transport system. In this example, material is transferred from a silo to a day bin, through a filter receiver. The receiver has a rotary air lock before discharging by gravity into the bin. The material properties and safe operating ranges would also be documented for the DHA. The example employs the risk-ranking presented in the paper by Murphy & Borene (8), wherein C, L, and R represent a ranking of consequence, likelihood, and risk. The rank is determined from the consequence and likelihood assigned by the DHA team. The resultant rank is color-coded to depict a prioritization of risk, moving from green (acceptable) to red (highest priority).

Table 1 shows the results of an analysis of ignition sources, as part of an overall checklist review of the filter receiver. Note that the example is provided for demonstration purposes only and is not intended to represent a complete DHA.

The same record is presented in a bowtie format in Figure . The first impression is one of simplicity. The information is presented clearly and concisely, allowing a quick review of the barriers that are imperative to preventing the fatality. This allows for further discussion on the availability/reliability of the barriers. For example:

1. Equipment material is fixed so very effective barrier
2. Overload trip needs to be regularly tested

3. Ignition energy is a robust barrier as long as material doesn't change i.e., analysis only fit for specific dust
4. Explosion vent needs to be regularly inspected
5. Explosion vent size/capacity needs to match dust (explosion) properties i.e., if material changes vent may not be adequate.

The visual design can be used as a communication tool for design, operation, and maintenance to understand the importance of specific activities and the role they play in preventing and mitigating the event of an explosion in the receiver resulting in a fatality. Additionally, during the MOC process, it will be straightforward to see what changes will impact the barriers (here change of material, change of rotary valve speed, removal of explosion vent, for example).

In this example, the following bowtie features are exploited:

1. Threat types categorised from EN 1127-1
2. Barrier (safeguard) types
3. Consequence risk for 4 types of receptors:
    a. Safety = D
    b. Environment = not determined (grey box)
    c. Asset = not determined (grey box)
    d. Reputation = not determined (grey box)

It is also possible to show individual Threat likelihoods (with or without safeguards or Barriers) and the individual Barrier effectiveness to appreciate the risk reduction contribution that each makes.

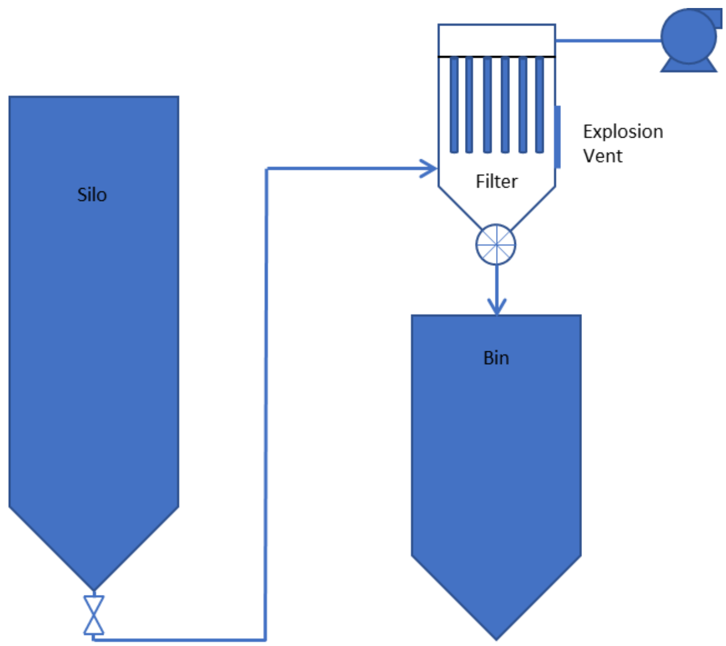

Figure 7 – Example receiving system

Table 1 – Excerpt of a traditional recording of a checklist DHA on a filter receiver

Item No.	Question	Answer	Cause	Consequence	Safeguards	C	L	R	Recommendation
1.1	Are competent sources of ignition present?	Bearings	Bearings cause ignition - N/A as bearings are outboard						
		Electrical spark	Electrical spark causes ignition - N/A as no electrical equipment in receiver						
		Impact spark	Impact spark caused by tramp material	Explosion in receiver, one fatality	Material of construction is stainless steel, explosion venting on receiver	1	1	D	
		Frictional spark	Frictional spark caused by tramp material getting caught in rotary valve	Explosion in receiver, one fatality	Rotary valve is low rpm, valve has an overload trip, explosion venting on receiver	1	1	D	
		Electrostatic spark	Electrostatic spark from unbonded flex boot causes ignition	Explosion in receiver, one fatality	MIE 100-300 mJ, explosion venting on receiver to safe location	1	1	D	1.1.1 Update grounding/bonding program to assure bonding is maintained across flex boots.
1.2	Do AMS with explosion hazards have isolation devices?	Yes, rotary valve on outlet of receiver	Electrostatic spark causes ignition in filter receiver and propagates forward to day bin	Explosion in day bin, one fatality	Rotary valve designed for material blocking deflagration isolation downstream	1	1	D	1.2.1 See Recommendation [1.1.1] to update grounding/bonding program.
		No isolation back to the silo	Electrostatic spark causes ignition in filter receiver and propagates back to the silo	Explosion in silo, one fatality		4	3	B	1.2.2 Add an isolation device (in accordance with NFPA 69) upstream of the filter receiver to prevent propagation back to the silo.
									1.2.3 See Recommendation [1.1.1] to update grounding/bonding program.

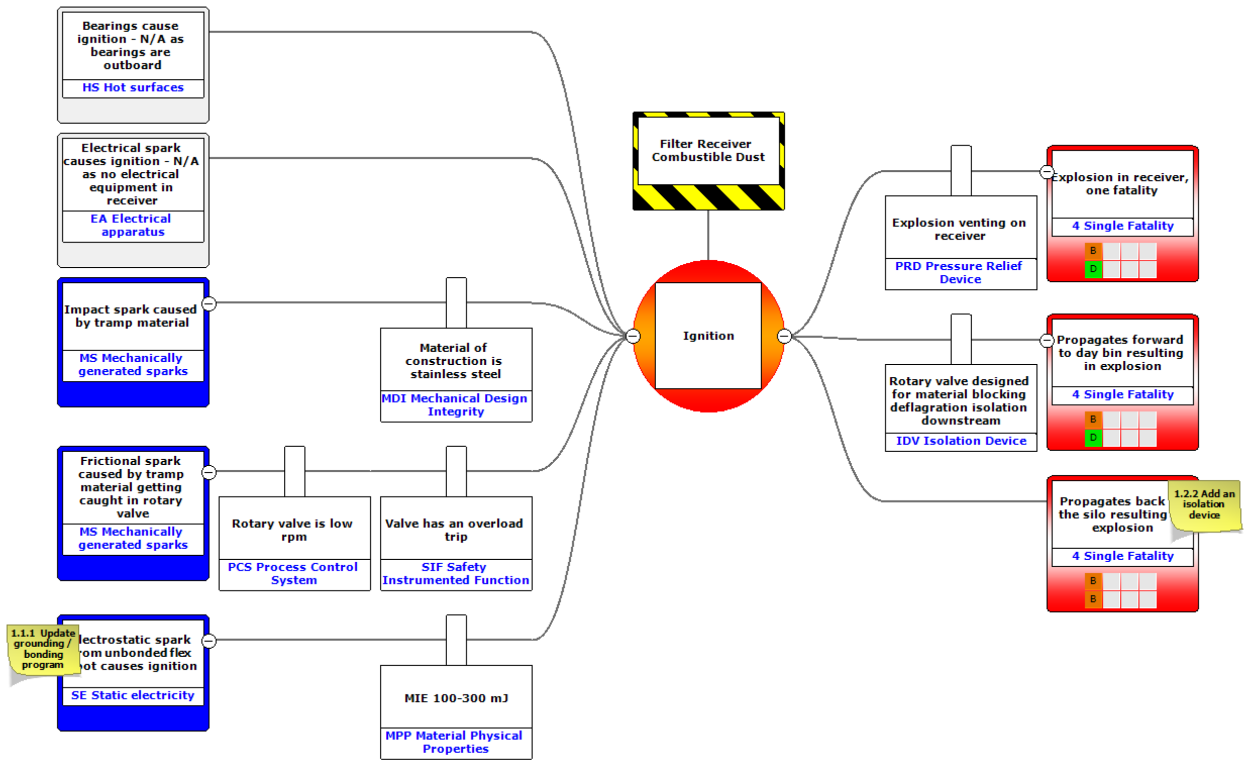

Figure 8 - Traditional DHA in bowtie format with ignition as the top event

4 Conclusion

4.1 Challenges of traditional hazard identification methods

The consequences and risks of a dust explosion have been known for many years and assessments have been conducted to address these. A traditional hazard analysis format (e.g., Checklist, HAZOP) is often applied which may have the following weaknesses:

1. Controls wrongly assigned to causes/threats/ignition sources
2. Controls missing from appropriate causes/threats/ignition sources
3. Failure to distinguish between prevention and mitigation/recovery measures
4. Failure to identify and evaluate connections between nodes/equipment where smouldering particles can ignite downstream dust

Furthermore, the presence (availability) and performance (reliability) of barriers is not part of the assessment and therefore a static snapshot of assumed or planned controls.

4.2 Benefits over traditional hazard identification methods

There are a number of identification methods ranging from simple checklists to more rigorous, systematic techniques which are well publicised (19) and employed. Bowties provide context to the explosion scenarios in a simple but effective visualisation of the relationships between:

- Causes of uncontrolled ignition;
- Consequences of those events, and;
- Barriers that prevent the event and/or mitigate the effects

A graphical representation offers a language that facilitates a common understanding of hazards, unwanted events, their risks, and controls to help direct or deploy resources appropriately and proportionately.

Classification of barriers, either by type or owner, allows dependencies or common mode vulnerabilities to be evaluated and addressed. A common mode failure occurs when a single event causes multiple barriers to fail (either within the same bowtie or across multiple bowties) and therefore barriers should be independent of the threat that they prevent and of other barriers on the same threat to top event or top event to consequence pathway.

4.3 Communication

The aim is not just to make existing assessments more engaging i.e. to involve all stakeholders but also to provide a life-long dynamic framework where threats (competent ignition sources) and barriers (control measures) are monitored, evaluated and actions taken to ensure that protection is sustained and risk targets are maintained. Visualisation enables duty holders not only to analyse their dust hazards but also to communicate the analyses to front line personnel to ensure that they understand the risks they are responsible for managing and sustain the protection measures for which they are accountable.

The current aim is to enhance not replace traditional methods.

4.4 Operational vs design focus

Bowties are not a static snapshot of assumed/planned controls but a live asset/risk management platform that can be updated (manually or automatically) to show the current state of health (presence and performance) of controls and the current risk exposure.

Barriers degrade over time and their performance must be monitored, measured and sustained at the required level to achieve the necessary risk reduction.

4.5 Better management of change implementation

Identification of barrier criticality and ownership makes management of change (MOC) more robust since the potential impact of defeating, degrading or deleting barriers within a single or across multiple scenarios (bowties) is more apparent. Suitable bowtie software with a barrier database can be filtered/sorted to focus on the deployment of barriers. This allows proper addressing in all scenarios where an affected barrier or barriers is/are implemented. Because barriers can be hardware, human or a combination of both, technical and organisational changes can be evaluated to ensure that the risk reduction is not unduly compromised.

The authors believe this approach highlights and addresses existing deficiencies whilst providing the same risk assessment functionality expected or required e.g., consideration of probability of flammable atmosphere (using ATEX (20), NFPA classification of dust flash-fire or explosion hazard area (3), or NFPA classification as a hazardous location for electrical installations (21)), probability of competent ignition source and severity of fire, flash fire, or explosion consequences.

The goal is to operationalise scenarios and demonstrate that duty-holders are and remain in control through ongoing barrier maintenance and robust change management.

An initial step for duty-holders would be to migrate their existing tabular (worksheet) assessments into bowties to expose and address weaknesses. Visual DHA is designed to be different (evolution rather than revolution) with a format where existing information is not lost but knowledge is gained.

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