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Non-Chemical Process Industry Applications of Bowtie Analysis

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The current paper demonstrates the broad applicability of bowtie analysis within the scope of scenarios requiring effective hazard identification to facilitate comprehensive risk management. This work is motivated by the largely unrecognized usefulness of process hazard analysis methodologies and other process safety techniques beyond the boundaries of the chemical process industries (CPI). Examples of creative bowtie use are given by drawing on the technical literature and ongoing research involving non-CPI, high-hazard applications.

1. Introduction

An overview of the bowtie technique is first given by explaining its traditional use in CPI applications such as oil & gas and petrochemical operations. Reference is then made to bowtie analysis use in diverse areas such as food processing, water quality management, healthcare, and a specific forest industry sector. The latter two applications are discussed from the perspective of current research initiatives in which the authors are engaged (respectively): (i) bowtie analysis related to the novel coronavirus hazard leading to the risk of COVID-19 infection, and (ii) bowtie analysis in the high-hazard industry of wood pellet manufacturing, with combustible wood dust as the hazard leading to the risk of a dust explosion. In both projects, the objectives are to identify relevant threats and likelihood of hazard occurrence, evaluate the prevention and mitigation measures already in place at research partner organizations, explore additional measures based on inherently safer design and the hierarchy of controls, communicate the analysis findings in an efficient and straightforward manner, and provide guidance for making risk-based decisions on the selection of the most effective safety measures.

2. Bowtie Analysis

Bowtie Analysis (BTA) is a barrier-based process hazard analysis tool that combines a fault tree with an event tree in a single diagram to graphically demonstrate and communicate how various factors can cause loss of control of a hazard and lead to undesirable consequences. The basic elements of a bowtie diagram as shown in Figure 1 are: (i) hazard, (ii) top event, (iii) threats, (iv) consequences, (v) prevention and mitigation barriers, (vi) degradation factors, and (vii) degradation factor controls (CCPS/EI, 2018).

One of the greatest strengths of bowtie diagrams is that they are a visual tool able to communicate hazardous scenarios to a wide range of audiences (Anderson et al., 2016). Although not without limitations, bowtie analysis shows direct cause and effect lines, making it easier to understand how hazardous events and consequences can occur. In contrast to the single safeguard column used in standard HAZOP formats (which can make it challenging to understand the efficacy and criticality of safeguards), bowtie diagrams allow barrier weaknesses and degradation factors to be clearly displayed. This is a significant benefit, given that not all safety barriers have the same effectiveness or reliability (CCPS/EI, 2018).

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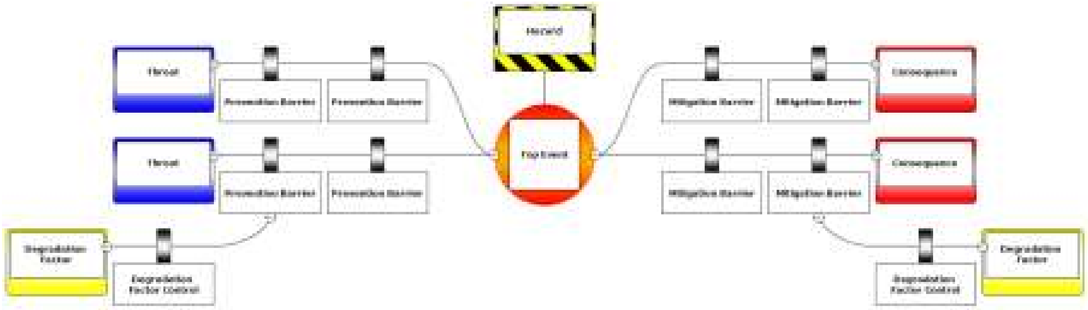

Figure 1: A standard bowtie diagram

3. BTA in the Chemical Process Industries

Bowtie analysis finds its primary and most widespread use as a process hazard analysis tool in the chemical process industries. As the aforementioned combination of the fault tree and event tree techniques, BTA is a methodology that has become increasingly familiar to CPI researchers and practitioners. Excellent resources for bowtie application in the CPI are available (for example, CCPS/EI (2018) and Vaughen & Bloch (2016)).
Application examples include the:

- 1984 release of methyl isocyanate at a pesticide manufacturing facility in Bhopal, India (Rayner Brown, 2020),
- sulphur trioxide vapour cloud formation caused by an oleum leak from a heat exchanger used in a sulphuric acid regeneration process (Rayner Brown et al., 2021a), and
- loss of containment incident involving a spent sulphuric acid storage tank at an oil refinery (Turner et al., 2021a).

4. BTA and Food Safety

The web site for Campden BRI (2021) illustrates the efficacy of bowtie analysis as a visual tool for risk communication with respect to food safety culture and identification of barriers for allergen management. As noted on the site: *As globalisation puts more distance between raw materials and final products, and as regulatory requirements grow in complexity, it's time for businesses in the food and drink industry to enhance their HACCP* [Hazard Analysis and Critical Control Pont] *plans with Bowtie for better risk communication* (Campden BRI, 2021).
Bilska & Kołozyn-Krajewska (2019) conducted a study aimed at developing a risk management model for dairy product losses. Just as process safety and process security share common features, so too do food safety and food security as evidenced by the authors' comment that *food losses represent a missed opportunity to improve global food security* (Bilska & Kołozyn-Krajewska, 2019). Their work utilized bowtie analysis to identify hazards occurring in a specific dairy product and the ensuing consequences in terms of three options: (i) reprocessing for human consumption, (ii) use as animal feed, and (iii) disposal.

5. BTA and Water Quality Assurance

Merrett et al. (2019a) used bowtie analysis to develop a process approach to drinking water quality risk assessment. They found that the chaining together of several bowtie diagrams provided a good visual picture of risk progression. Further, the diagrams could also be integrated with the more traditional HACCP methodology used in the food and drinking water industries (in accordance with the advice given by Campden BRI (2021)).
In another study, Merrett et al. (2019b) undertook a comparison of System-Theoretic Process Analysis (STPA) and bowtie analysis in determining hazards and safety barriers for an automated water quality management system at a small hydroponics installation. They concluded that while STPA was able to identify hazards unrelated to the BTA-identified barriers, the developed bowtie diagram afforded a clear distinction between prevention and mitigation controls.

6. BTA and the COVID-19 Pandemic

Several studies demonstrating the usefulness of bowtie analysis in enhancing various aspects of medical safety have been reported in the literature, including:

- patient safety in an intensive care unit (Abdi et al., 2016),

- surgical instrument retention (Chatzimichailidou et al., 2018),
- anesthesia risk management (Culwick et al., 2016),
- primary healthcare (McLeod & Bowie, 2018), and
- adverse drug effects caused by systematic medication errors (Wierenga et al., 2009).

The current authors have employed bowtie analysis to address the risk of individuals acquiring the novel coronavirus during the current COVID-19 pandemic (Rayner Brown et al., 2021b). An excerpt from this ongoing work in partnership with a tertiary care women's and children's healthcare facility in eastern Canada is given in Figure 2 (Turner et al., 2021b). Key objectives in this project are to evaluate existing prevention and mitigation barriers, and to identify potential new safety measures based on inherently safer design (ISD) and the hierarchy of controls (Kletz & Amyotte, 2010; CCPS, 2019). The ISD protocol developed by Rayner Brown et al. (2021a) is being used for this purpose.

Due to space limitations, Figure 2 does not show the relevant prevention and mitigation barriers for each threat and consequence, respectively; nor are the corresponding barrier degradation factors and degradation factor controls shown. Table 1 provides an illustrative example in this regard.

Table 1: Examples of degradation factors and degradation factor controls for a typical prevention barrier

Barrier	Barrier Type	Degradation Factor	Degradation Factor Category	Degradation Factor Control	Degradation Factor Control Type
Physical distancing in public areas and during assessments (when possible)	Administrative (with potential aspects of ISD)	Difficulty managing traffic	Situational violation	Decreased number of people in building	Administrative (with potential aspects of ISD)
				Locked doors	Administrative
		Not followed	Unintended violation or personal optimization	Visual cues on floor and signage	Administrative (with potential aspects of ISD)

7. BTA and Wood Pellet Manufacturing

The current authors have also employed bowtie analysis to assess and manage combustible dust hazards related to wood pellet manufacturing and medium density fibreboard (MDF) production. Top events considered include combustible wood dust fire, explosion, deflagration, and ignition. Again, the ISD protocol developed by Rayner Brown et al. (2021a) is being used to identify barrier opportunities that incorporate the principles of inherently safer design (minimization, substitution, moderation, and simplification), as well as the other levels in the hierarchy of controls (passive, active, and administrative).

Figure 3 and Figure 4 show excerpts from this work for a hammer mill used to effect size reduction of wood particles in a typical pellet production process. The threats identified in Figure 3 relate to various ignition sources given the existence of the other four elements of the dust explosion pentagon: (i) fuel – combustible wood dust in the mill, (ii) oxidant – oxygen in ambient air as evidenced by the presence of a dust concentration above the MEC (minimum explosible concentration), (iii) mixing – again, the presence of a dust concentration above the MEC, and (iv) confinement – provided by the mill itself. Figure 3 also illustrates consequences related to people, property, and the environment; other potential consequences (not shown) include business interruption and reputational damage.

As shown in Figure 4, several prevention barriers can be used to attempt to deal with the threat of ignition by sparks generated by rocks entering the hammer mill – for example, administrative measures such as visual inspection of the feedstream and active measures such as spark detection and alarm notification. Figure 4 gives three factors (e.g., regular wear and tear) that act to degrade the efficacy of the mechanical scalping roll barrier, along with the use of a preventive maintenance (PM) program as a control for this particular example.

A critical feature of bowtie analysis is the need to identify degradation factors and controls for each prevention and mitigation barrier claimed. As previously discussed, it is also important to note that risk reduction barriers and their associated degradation control factors are not equal in terms of effectiveness.

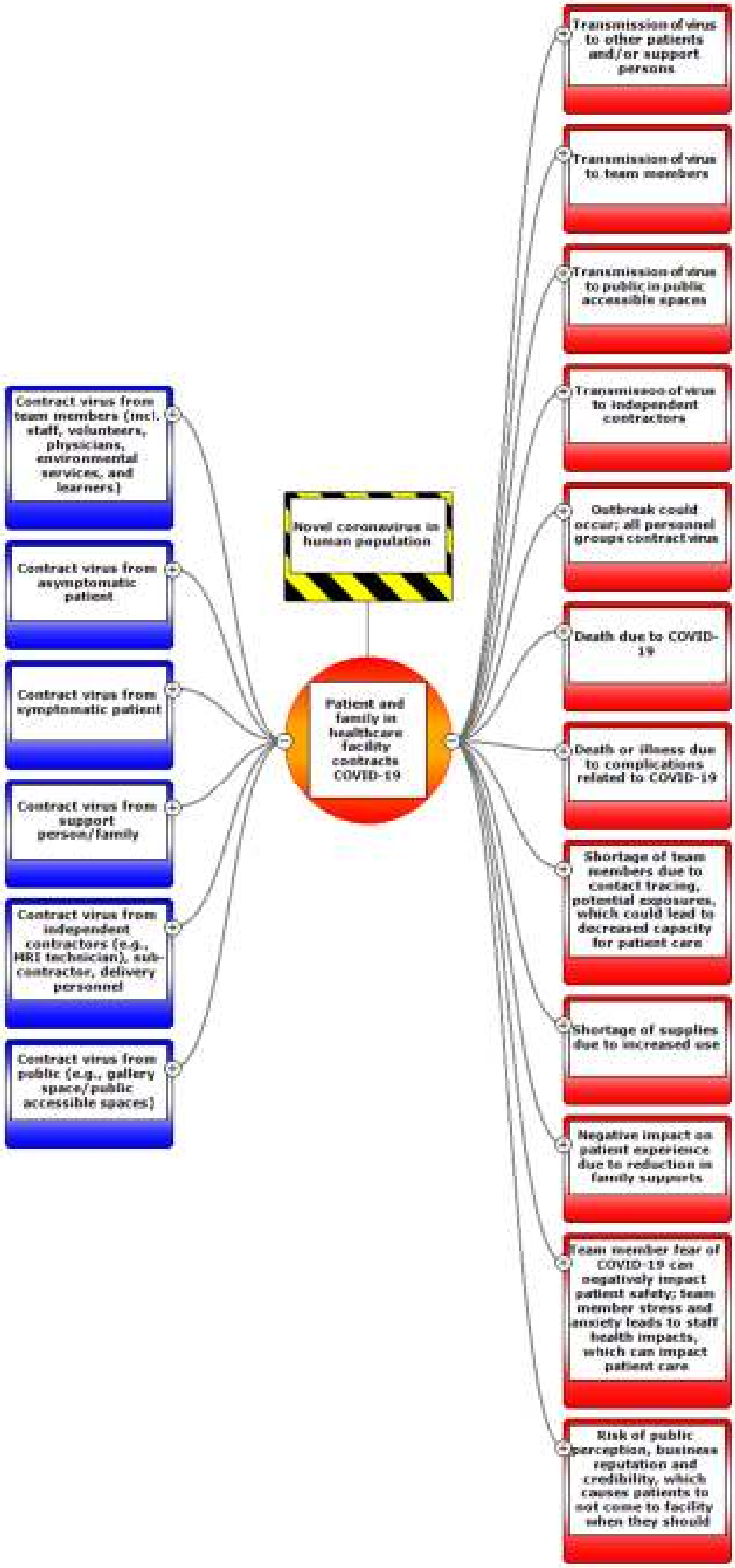

Figure 2: Excerpt of bowtie diagram representing a patient or family member at the healthcare partner facility contracting COVID-19

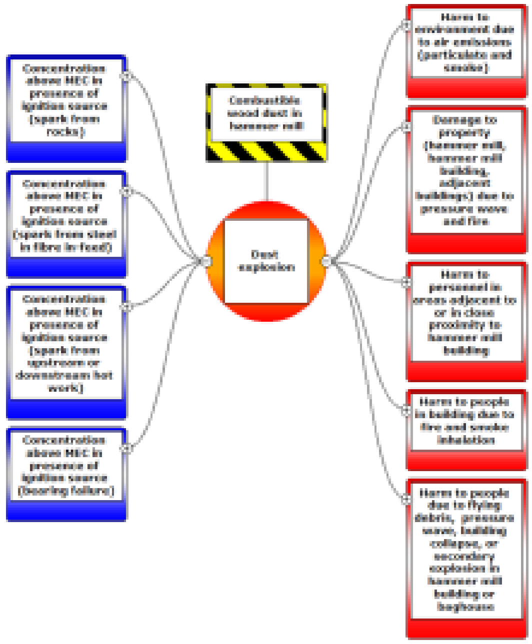

Figure 3: Excerpt of threats and consequences in bowtie for combustible wood dust in a hammer mill

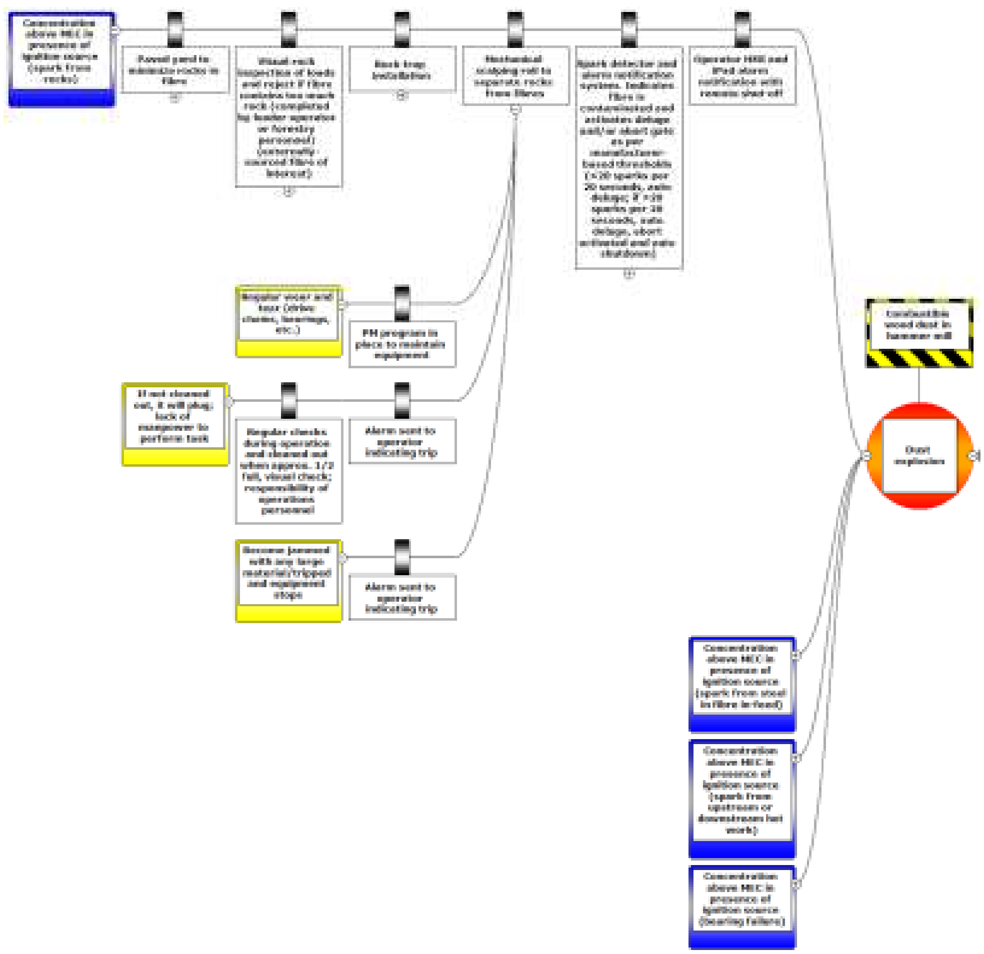

Figure 4: Excerpt of degradation factors and controls in bowtie for combustible wood dust in a hammer mill

8. Conclusion

Bowtie analysis is a proven methodology for process hazard analysis in the traditional chemical process industries. The technique can also be effectively applied in other industries and hazardous scenarios where consideration of additional process safety concepts such as inherently safer design and the hierarchy of controls can also have significant benefits.

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