# Visualising Risk Reduction: Utilising Weighted Bowtie Diagrams for Enhanced Risk Assessment, Management and Communication

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This paper explores the application of Weighted BowTie Diagrams (WBTDs), a method developed by researchers at the Health and Safety Executive (HSE) and presented at Hazards 33, for risk assessment and communication of its outcomes. We demonstrate the effectiveness of WBTDs in both conducting a risk assessment and communicating the results through a case study focusing on the overfilling of a bulk fuel storage tank.

Quantifying Risk Reduction with WBTDs: In a WBTD, the risk reduction achieved by a barrier can be determined by evaluating its Risk Reduction Factor (RRF), which can be thought of as the barrier's 'health'. The barrier health is determined using performance standards, which can include traditional techniques like failure rate data, Fault Tree Analysis (FTA) or Event Tree Analysis (ETA).

The barrier health can be represented either by a qualitative descriptor (known as a 'word model') or quantitively by a Probability of Failure on Demand (PFD), which indicates the likelihood of the barrier failing to perform its intended function. The qualitative descriptor or PFD essentially acts as the barrier's 'weight', hence the term 'weighted bowtie diagram'.

WBTDs build upon traditional bowtie diagrams by introducing enhancements, particularly in risk visualisation. The method employs a structured approach to identify barriers, their associated degradation factors and corresponding control measures (see the CCPS/EI concept book on 'Bow Ties in Risk Management'). Most importantly, it provides a visual representation of the cumulative risk reduction achieved by successive barriers along each threat and consequence pathway.

Benefits of Visualisation: By visualising the evolving risk reduction while traversing the WBTD from threat to top event to consequence, we can identify not only dominant threats but also the most effective barriers. This information is crucial for prioritising efforts to improve barrier health and robustness by identifying barrier escalation factors and implementing appropriate controls. Consequently, WBTDs contribute to improved decision-making. This paper analyses the functionalities of current bowtie diagram software packages, focusing on their visualisation capabilities. We then discuss how the WBTD's visualisation of cumulative risk reduction enhances the information presented to various audiences, including engineers, risk assessment specialists, managers/senior leaders or the workforce/public (depending on the risk assessment requirement).

BTDs vs. LOPA: We further explore the potential advantages of BowTie Diagram (BTD) analysis over Layer Of Protection Analysis (LOPA). HSE researchers developed a modified LOPA to aid in the assessment of the Covid-19 scenario table mirroring the bowtie diagram structure, to address the structural difference between a BTD and a traditional LOPA. The modified LOPA table separates the top event from its causes and consequences, facilitating the assessment of preventive and mitigation measures, as in the BTD approach. Additionally, the modified LOPA table accommodates multiple outcomes within one LOPA table, addressing a potential limitation of the generic LOPA approach.

Bulk fuel storage tank overfill case study: For illustration, we present a simple yet realistic scenario from the process industry – a bulk fuel storage tank overfill. We start by building and populating a traditional bowtie diagram using Enablon BowTieXP software, as an example of current software capability. It is important to note that other bowtie software tools are available and may be equally suitable for this exercise. We then produce a weighted bowtie diagram and use this to discuss the outcomes of the WBTD assessment and to demonstrate the risk communication benefits of the WBTD's enhanced visualisation.

Key words: Weighted Bowtie Diagram, risk assessment, risk communication, layer of protection analysis, risk visualisation

## Introduction

The primary aim of this paper is to demonstrate how the visualisation of a Bowtie Diagram (BTD) can be enhanced using the Weighted Bowtie Diagrams (WBTDs) method, thereby improving the BTD's effectiveness in communicating risk assessment outcomes (CCPS, 2018). By refining risk visualisation, the goal is to facilitate better understanding and decision-making for a diverse audience.

To support this aim, the paper presents the practical application of WBTDs through a real-world case study involving a bulk fuel storage overfill scenario. This case study illustrates how the WBTD method can be effectively used in both conducting risk assessments and communicating the results.

Previously, the WBTD method was applied using a qualitative approach to risk assessment, primarily due to the lack of suitable numerical data, a COVID-19 scenario, (Chambers, 2023). In this paper, we apply the WBTD method to a scenario where appropriate numerical data is available: a fuel storage tank overfill scenario.

Another key objective is to quantify and visualise risk reduction achieved by implementing various barriers. This paper provides a quantified assessment of a real-world scenario, demonstrating how the WBTD method represents the cumulative risk reduction achieved by these barriers.

Additionally, the paper explores the advantages of WBTDs over traditional Layer of Protection Analysis (LOPA). It examines how a modified LOPA table, see Figure 6, designed to mirror the Bowtie diagram structure, can be integrated with WBTDs to enhance, and record the risk assessment.

As part of this work this paper evaluates example visualisation capabilities of currently commercially available bowtie diagram software, highlighting their role in improving the communication of risk assessment outcomes and hence show how the added visualisation using WBTDs can improve risk communication.

## Enhancing Risk Visualisation with BTDs

The bowtie method can be traced back to Haddon's Hazard-Barrier-Target model, which addresses "the generic strategies for control of potentially harmful energy flows", (Haddon, 1973). This accident causation theory indicates what the risks are within the unwanted energy transfers. A bowtie shows risks through the paths, leading from causes to consequences. These paths are risk scenarios.

Barriers are implemented within risk scenarios to prevent the occurrence of unwanted events. They serve the functions of prevention, control, and mitigation of risk. Without clear risk scenarios, it is challenging to visualise how and when a barrier performs its function. The effectiveness of barriers within a scenario determines the level of control over the risk. If barriers are effective and perform as intended, the risk is managed as designed; if not, the risk may be high due to ineffective or insufficient barriers.

## The basic concepts of bowtie

Risk is commonly defined within a scenario that combines the severity of negative consequences with the likelihood of an accident pathway involving a series of unwanted events. A bowtie diagram effectively visualises these risk scenarios in a clear and structured manner.

In the bowtie diagram in Figure 1, the "hazard" represents an operation, activity, or material with the potential to cause harm. The "top event" marks the first moment when control over the hazard is lost, releasing its harmful potential. Threats, which are potential causes of the top event, are shown on the left-hand side. Consequences, the unwanted outcomes that may result from the top event and lead to damage or harm, are depicted on the right-hand side.

Barriers are measures, either physical or non-physical, designed to prevent, control, or mitigate unwanted events. Preventive barriers act against threats or the top event itself. They function by either eliminating the threat or preventing it from escalating into the top event. Recovery barriers, on the other hand, are implemented to reduce the likelihood or severity of potential consequences. They work by either preventing the consequences from occurring or by mitigating their severity.

A "degradation factor" refers to a situation, condition, defect, or error that compromises the function of a main pathway barrier, either by defeating it or reducing its effectiveness. These factors can include human errors, abnormal conditions, or the loss of critical services. Degradation factor controls are measures that help prevent the escalation factor from impairing the barrier's effectiveness.

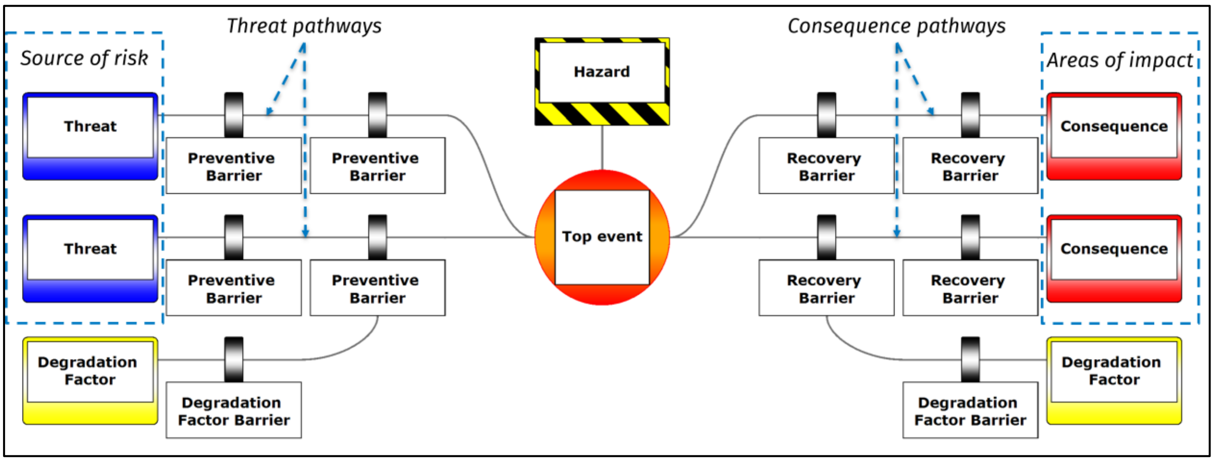


Figure 1: Typical bowtie diagram concepts

## Risk information on a bowtie diagram

By using digital tools, a bowtie diagram can display not only risk scenarios but also the results of risk assessments. This makes it easier to identify high-risk scenarios both before and after implementing barriers. For example, risk management decision-makers can focus on high-risk scenarios based on assessment results, which may include inherent and residual risk.

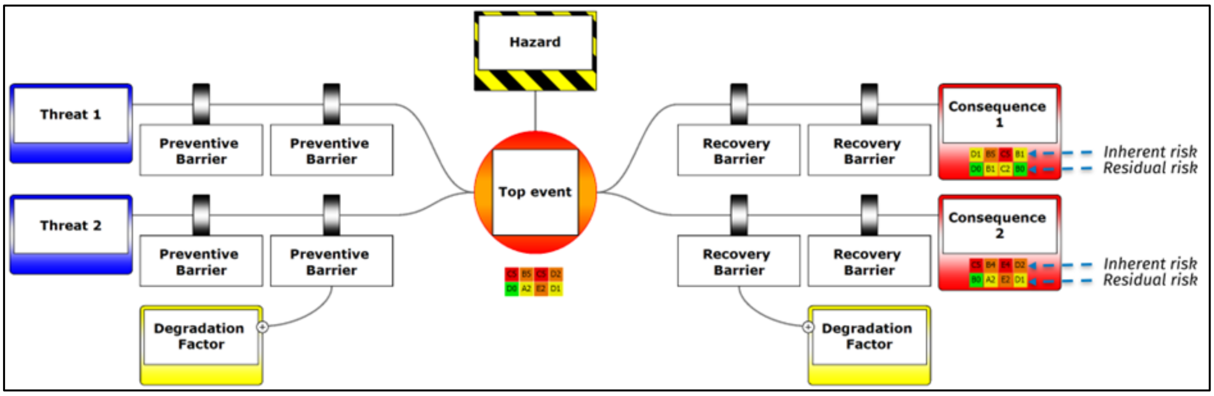


Figure 2: A bowtie diagram with risk assessment results: inherent vs residual

Figure 2 illustrates typical risk assessment results for both inherent and residual risks, displayed in the boxes beneath the consequences and top event. The different colours in the boxes represent distinct risk categories: Green for no impact, Yellow for medium, Orange for high, and Red for intolerable risk. These categories are determined by evaluating two key factors: likelihood (ranging from A – very unlikely, to E – very likely) and severity (ranging from 0 – no injury, to 5 – multiple fatalities). The combination of these two factors determines the overall risk level. For instance, E5 represents the highest risk, shown in red, while A0 represents the lowest risk, shown in green.

According to the risk assessment results in Figure 2, the second consequence scenario is riskier as it has higher overall risk levels compared to the first consequence scenario. By displaying both inherent and residual risk for the second scenario, we see that the risk level has significantly improved with the application of all barriers. Notably, in the first aspect of impact, the risk level decreased from C5 (unacceptable) to B0 (no impact). Under the top event, the general risk assessment results for the scenarios related to this top event are displayed. These risk assessment results reflect the worst-case scenario of the consequence risk assessments for this bowtie. This example demonstrates ways by which the bowtie diagram communicates risk assessment results.

Additionally, a bowtie diagram simplifies the identification of weaknesses in risk controls using the reference information within the diagram, see Figure 3 and Figure 4. Decision-makers can assess these weaknesses by considering factors such as the frequency of threats, the effectiveness of critical barriers, and the categories of consequences. Based on this reference data, it becomes easier to identify substandard barriers and determine how to efficiently improve risk management, as these barriers are positioned within different aspects of the scenarios.

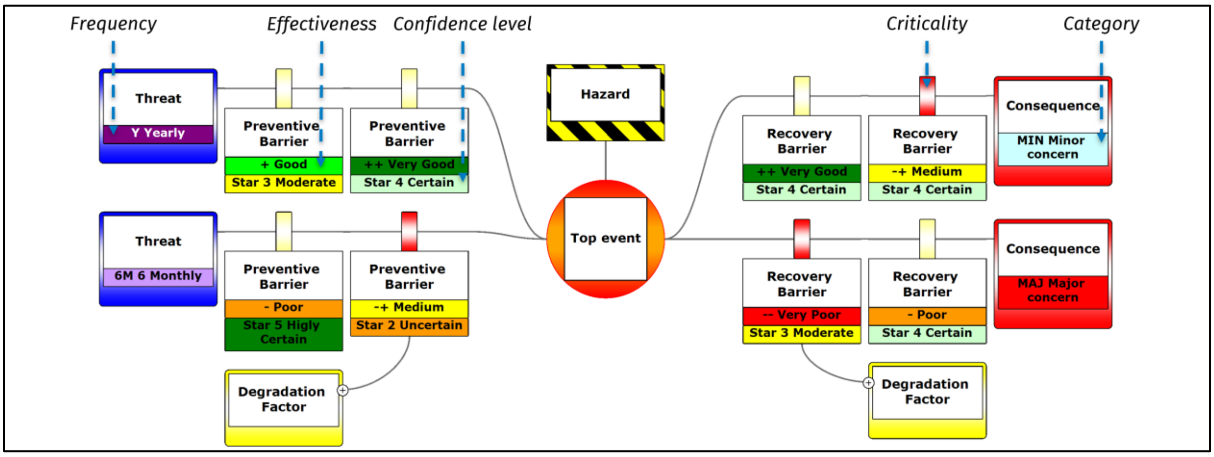


Figure 3: A bowtie diagram with reference data

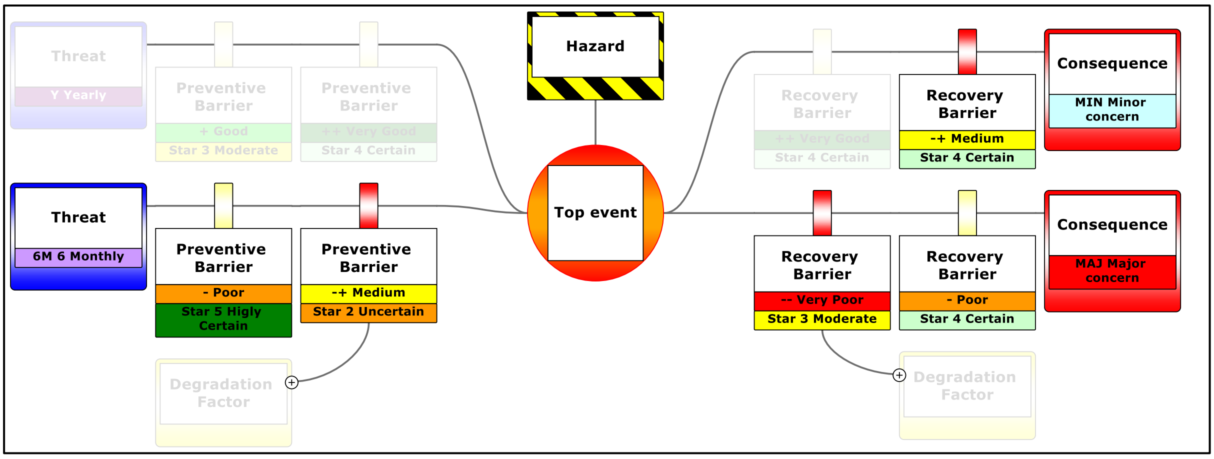


Figure 4: High-lighted substandard barriers in risk scenarios

## BTDs complement LOPA

Bowtie and Layer of Protection Analysis (LOPA) can be used in conjunction if applied correctly to support process safety management (CCPS, 2018, CCPS, 2001).

Bowtie can be used to enhance LOPA. What does building a Bowtie give you?

- It helps break down complex risk scenarios into manageable parts, making it easier to identify where additional layers of protection might be needed.
- Provides a holistic view of the risk scenario, ensuring that all potential threats and consequences are considered.
- Provides a clear, visual representation of the relationship between a hazard, its threats, and consequences.
- Helps in identifying both preventive and mitigative controls for each threat and consequence.
- Identifies degradation factors that could weaken controls.

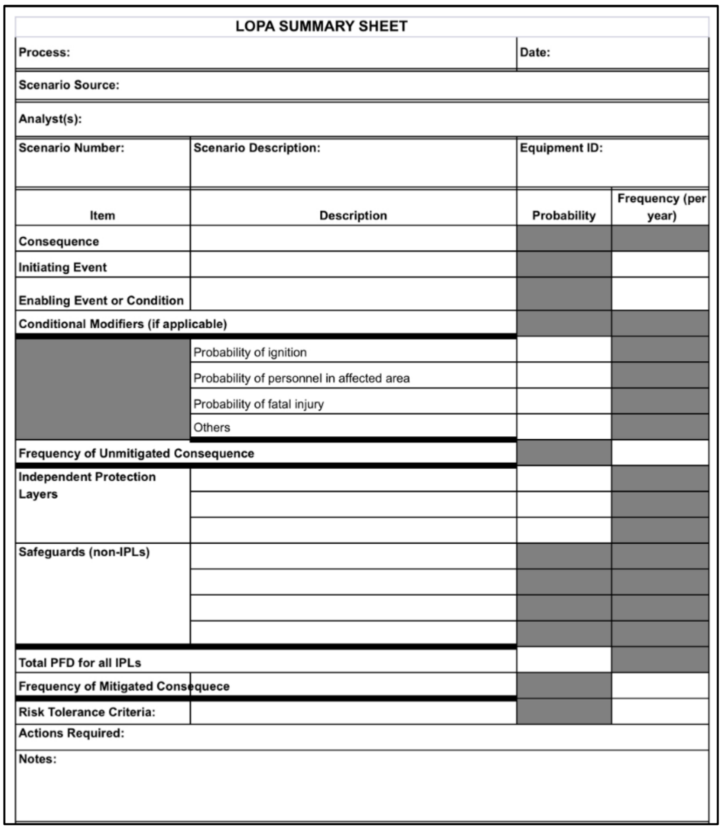
How does this help complement a LOPA study?

- Improved starting point by using structured information from the Bowtie.
- By assessing the defined controls (or Independent Protection Layers, IPLs) for their reliability and effectiveness, ensuring that each control is robust and independent.
- Can then evaluate the impact of these degradation factors on the controls/IPLs.

By modifying the LOPA recording tool, you can directly import the structure from the bowtie in a more efficient way.

One commonly used LOPA calculation sheet is presented in Figure 5, (CCPS 2001), it does not use the structure from a bowtie as it tends to be about a single scenario, so you have multiple sheets to cover the scenarios created in a bowtie.

We could change to a modified LOPA sheet to match the layout of a bowtie and cover all the scenarios in one sheet, rather than having multiple sheets. Figure 6 presents a suggested example of what a modified LOPA sheet could look like, this was developed by the authors as part of the previous WBTD publication, (Chambers, 2023).



**LOPA SUMMARY SHEET**

| | | | |
|---|---|---|---|
| Process: | | Date: | |
| Scenario Source: | | | |
| Analyst(s): | | | |
| Scenario Number: | Scenario Description: | Equipment ID: | |
| Item | Description | Probability | Frequency (per year) |
| Consequence | | ▨ | ▨ |
| Initiating Event | | ▨ | |
| Enabling Event or Condition | | ▨ | |
| Conditional Modifiers (if applicable) | | ▨ | ▨ |
| ▨ | Probability of ignition | | ▨ |
| ▨ | Probability of personnel in affected area | | ▨ |
| ▨ | Probability of fatal injury | | ▨ |
| ▨ | Others | | ▨ |
| Frequency of Unmitigated Consequence | | ▨ | |
| Independent Protection Layers | | | ▨ |
| | | | ▨ |
| | | | ▨ |
| Safeguards (non-IPLs) | | ▨ | ▨ |
| | | ▨ | ▨ |
| | | ▨ | ▨ |
| | | ▨ | ▨ |
| Total PFD for all IPLs | | | ▨ |
| Frequency of Mitigated Consequece | | ▨ | |
| Risk Tolerance Criteria: | | ▨ | |
| Actions Required: | | | |
| Notes: | | | |

Figure 5: A LOPA calculation sheet taken from the CCPS LOPA book that requires 1 sheet per initiating event (threat)

Flowing left to right, horizontally, starting with the hazardous event, in this example ‘Bulk fuel storage tank overfill’ ( a combination of Hazard and Top Event from the bowtie), causes (Threats from the bowtie), condition modifiers from the causes, the frequency of the event occurring with no barriers, prevention barriers, frequency at the Top Event point, the mitigation barriers, leading to the frequency of the consequence with the barriers in place.

| Hazardous Event | Cause / threat Identifier | Cause Description | Cause/threat frequency of occurance without any risk reduction measures per year | frequency of event occuring with no barriers | Prevention barriers PFD | | | | | Frequency of hazardous event occurring with barriers in place per cause | Mitigation Barriers PFD | | | | | Mitigation Barrier Credit | RMF 1 probability immediate ignition occures | RMF 2 proabability of calm weather | RMF 3 probability idelayed ignition occures | RMF 4 proabability of no ignition | Probability of consequence occuring with barriers in place per cause | Total quantitative risk with barriers in place for consequence | Consequence |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Engineering Controls | | Administrative Controls | | | | - | - | - | | - | | | | | | | | |
| | | | | | IPL 1 High level alarm from the ATG system with operator response | IPL 2 Independent High level trip isolates the tank inlet & outlet | IPL 3 Ullage calculation, import planning | IPL4 operator level monitoring | IPL 5 Route setup to correct tank | | IML 1 Secondary Containment from fit for purpose bunds surrounding the tanks | IML 2 Separation of people from the tanks | IML3 Emergency Response (Medical, Crisis Management, environmental clean up etc.) | IML 4 Material released from bund contained within the site (Tertiary Containment) | IML 5 Deployment of Fire fighting system] | | | | | | | | |
| | | | | | Barrier Family | | | | | | Barrier Family | | | | | | | | | | | | |
| | | | | | Ullage calculation, import planning and operator level monitoring and alerting from the ATG system | | Ullage calculation, import planning and operator level monitoring and alerting from the ATG system | Ullage calculation, import planning and operator level monitoring and alerting from the ATG system | | | | | | | | | | | | | | | |
| Petrol in a large storage tank | C1 | Parcel too large for tank test | 1 | 1.00E+00 | 0.3 | 0.01 | 1 | 1 | 1 | 3.00E-03 | 0.1 | 0.1 | 0.8 | 1 | 0.8 | 0.0064 | 0.1 | 1 | 1 | 1 | 1.92E-06 | 3.65E-06 | Pool Fire |
| | C2 | Wrong tank filled | 0.8 | 8.00E-01 | 0.5 | 0.01 | 1 | 1 | 0.3 | 1.20E-03 | 0.1 | 0.1 | 0.8 | 1 | 0.8 | 0.0064 | 0.1 | 1 | 1 | 1 | 7.68E-07 | | |
| | C3 | Primary tank manual isolation valve failure | 0.1 | 1.00E-01 | 0.5 | 0.01 | 1 | 1 | 1 | 5.00E-04 | 0.1 | 0.1 | 0.8 | 1 | 0.8 | 0.0064 | 0.1 | 1 | 1 | 1 | 3.20E-07 | | |
| | C4 | Failure to terminate the supply | 1 | 1.00E+00 | 0.1 | 0.01 | 1 | 1 | 1 | 1.00E-03 | 0.1 | 0.1 | 0.8 | 1 | 0.8 | 0.0064 | 0.1 | 1 | 1 | 1 | 6.40E-07 | | |
| | Totals for outcome 1 | | | 2.90E+00 | | | | | | 5.70E-03 | | | | | | 0.0256 | | | | | | | |
| | C1 | Parcel too large for tank test | 1 | 1.00E+00 | 0.3 | 0.01 | 1 | 1 | 1 | 3.00E-03 | 1 | 1 | 0.8 | 1 | 1 | 0.8 | 1 | 0.03 | 0.7 | 1 | 5.04E-05 | 1.29E-04 | Unconfiened Vapour Cloud Explosion |
| | C2 | Wrong tank filled | 0.8 | 8.00E-01 | 0.5 | 0.01 | 1 | 1 | 0.3 | 1.20E-03 | 1 | 1 | 0.8 | 1 | 1 | 0.08 | 1 | 0.03 | 0.7 | 1 | 2.02E-05 | | |
| | C3 | Primary tank manual isolation valve failure | 0.1 | 1.00E-01 | 0.5 | 0.01 | 1 | 1 | 1 | 5.00E-04 | 1 | 1 | 0.8 | 1 | 1 | 0.8 | 1 | 0.03 | 0.7 | 1 | 8.40E-06 | | |
| | C4 | Failure to terminate the supply | 1 | 1.00E+00 | 0.3 | 0.01 | 1 | 1 | 1 | 3.00E-03 | 1 | 1 | 0.8 | 1 | 1 | 0.8 | 1 | 0.03 | 0.7 | 1 | 5.04E-05 | | |
| | Totals for outcome 2 | | | 2.90E+00 | | | | | | 7.70E-03 | | | | | | 2.48 | | | | | | | |
| | C1 | Parcel too large for tank test | 1 | 1.00E+00 | 0.3 | 0.01 | 1 | 1 | 1 | 3.00E-03 | 1 | 0.3 | 0.1 | 1 | 1 | 0.03 | 1 | 1 | 0.1 | 1 | 9.00E-06 | 2.31E-05 | Flash Fire |
| | C2 | Wrong tank filled | 0.8 | 8.00E-01 | 0.5 | 0.01 | 1 | 1 | 0.3 | 1.20E-03 | 1 | 0.3 | 0.1 | 1 | 1 | | 1 | 1 | 0.1 | 1 | 3.60E-06 | | |
| | C3 | Primary tank manual isolation valve failure | 0.1 | 1.00E-01 | 0.5 | 0.01 | 1 | 1 | 1 | 5.00E-04 | 1 | 0.3 | 0.1 | 1 | 1 | 0.03 | 1 | 1 | 0.1 | 1 | 1.50E-06 | | |
| | C4 | Failure to terminate the supply | 1 | 1.00E+00 | 0.3 | 0.01 | 1 | 1 | 1 | 3.00E-03 | 1 | 0.3 | 0.1 | 1 | 1 | 0.03 | 1 | 1 | 0.1 | 1 | 9.00E-06 | | |
| | Totals for outcome 3 | | | 2.90E+00 | | | | | | 7.70E-03 | | | | | | 0.09 | | | | | | | |
| | C1 | Parcel too large for tank test | 1 | 1.00E+00 | 0.3 | 0.01 | 1 | 1 | 1 | 3.00E-03 | 1 | 0.3 | 0.1 | 1 | 0.8 | 0.024 | 1 | 1 | 0.1 | 1 | 7.20E-06 | 1.85E-05 | VCE (Vapor Cloud Explosion) |
| | C2 | Wrong tank filled | 0.8 | 8.00E-01 | 0.5 | 0.01 | 1 | 1 | 0.3 | 1.20E-03 | 1 | 0.3 | 0.1 | 1 | 0.8 | 0.024 | 1 | 1 | 0.1 | 1 | 2.88E-06 | | |
| | C3 | Primary tank manual isolation valve failure | 0.1 | 1.00E-01 | 0.5 | 0.01 | 1 | 1 | 1 | 5.00E-04 | 1 | 0.3 | 0.1 | 1 | 0.8 | 0.024 | 1 | 1 | 0.1 | 1 | 1.20E-06 | | |
| | C4 | Failure to terminate the supply | 1 | 1.00E+00 | 0.3 | 0.01 | 1 | 1 | 1 | 3.00E-03 | 1 | 0.3 | 0.1 | 1 | 0.8 | 0.024 | 1 | 1 | 0.1 | 1 | 7.20E-06 | | |
| | Totals for outcome 4 | | | 2.90E+00 | | | | | | 7.70E-03 | | | | | | 0.096 | | | | | | | |
| | C1 | Parcel too large for tank test | 1 | 1.00E+00 | 0.3 | 0.01 | 1 | 1 | 1 | 3.00E-03 | 0.1 | 1 | 0.1 | 0.1 | 1 | 0.001 | 1 | 1 | 1 | 0.1 | 3.00E-07 | 7.70E-07 | No ignition, potential for an environmental spill |
| | C2 | Wrong tank filled | 0.8 | 8.00E-01 | 0.5 | 0.01 | 1 | 1 | 0.3 | 1.20E-03 | 0.1 | 1 | 0.1 | 0.1 | 1 | 0.001 | 1 | 1 | 1 | 0.1 | 1.20E-07 | | |
| | C3 | Primary tank manual isolation valve failure | 0.1 | 1.00E-01 | 0.5 | 0.01 | 1 | 1 | 1 | 5.00E-04 | 0.1 | 1 | 0.1 | 0.1 | 1 | 0.001 | 1 | 1 | 1 | 0.1 | 5.00E-08 | | |
| | C4 | Failure to terminate the supply | 1 | 1.00E+00 | 0.3 | 0.01 | 1 | 1 | 1 | 3.00E-03 | 0.1 | 1 | 0.1 | 0.1 | 1 | 0.001 | 1 | 1 | 1 | 0.1 | 3.00E-07 | | |
| | Totals for outcome 5 | | | 2.90E+00 | | | | | | 7.70E-03 | | | | | | 0.004 | | | | | | | |

Figure 6: Modified LOPA table that better models the risk assessment in the same way that the hazards would be presented in a BTD. These numbers are based on A review of Layers of Protection Analysis (LOPA) analyses of overfill of fuel storage tanks, (HSEb, 2009).

By combining the visual and qualitative strengths of bowtie with the quantitative rigour of LOPA, organisations can achieve a more comprehensive and effective risk management strategy, (Chambers, 2023).

Limitations of bowtie:

1. Qualitative Nature: Bowtie Analysis is primarily qualitative, which means it may not provide precise numerical risk assessments.
2. Complexity: For very complex systems, the bowtie diagram can become cluttered and difficult to interpret.
3. Subjectivity: The identification of threats, controls, and consequences can be subjective, depending on the expertise and perspective of the analysts.

Limitations of LOPA:

1. Semi-Quantitative: While LOPA provides a more quantitative approach than Bowtie Analysis, it is still semi-quantitative and relies on estimated probabilities and effectiveness of controls.
2. Data Quality: The accuracy of LOPA depends on the quality and availability of data for failure rates and effectiveness of controls.
3. Simplification: LOPA can oversimplify complex scenarios by focusing on single initiating events and independent protection layers, potentially overlooking interactions between different layers.

Combined Limitations:

1. Resource Intensive: Integrating both methods can be resource-intensive in terms of time, expertise, and data requirements.
2. Consistency: Ensuring consistency between the qualitative insights from Bowtie Analysis and the quantitative assessments from LOPA can be challenging.
3. Over-Reliance on Controls: Both methods focus heavily on controls, which might lead to an over-reliance on existing measures without considering broader systemic changes or inherent safety improvements.

Despite these limitations, the integration of Bowtie Analysis with LOPA can provide a comprehensive risk management approach when used judiciously. It combines the strengths of visual, qualitative analysis with quantitative risk assessment, offering a balanced view of potential hazards and controls.

Addressing the limitations of integrating Bowtie Analysis and Layer of Protection Analysis (LOPA) involves a combination of best practices, continuous improvement, and leveraging additional tools and techniques. Here are some practical steps:

Enhancing Bowtie Analysis:

1. Use Software Tools: Utilise specialised software to create and manage bowtie diagrams, which can help in handling complexity and ensuring clarity.
2. Expert Involvement: Involve multidisciplinary teams to reduce subjectivity and ensure comprehensive identification of threats and controls.
3. Regular Updates: Keep the bowtie diagrams updated with new information and insights from incident investigations and equipment/operational changes.

Improving LOPA:

1. Data Quality: Invest in collecting high-quality data for failure rates and effectiveness of controls. Use industry databases and historical data to improve accuracy.
2. Training: Provide thorough training for personnel involved in LOPA to ensure consistent and accurate assessments.
3. Detailed Documentation: Maintain detailed documentation of assumptions, data sources, and calculations to enhance transparency and reproducibility.
4. Ensure sufficient sensitivity studies have been done to validate/ justify assumptions made.

Addressing Combined Limitations:

1. Resource Allocation**:** Ensure sufficient resources, including time and expertise, are allocated for thorough analyses. Take into account the cost-benefit ratio of the assessments.
2. Integration with Other Method**s**: Enhance Bowtie and LOPA by incorporating other risk assessment techniques, such as HAZOP (Hazard and Operability Study) or FMEA (Failure Modes and Effects Analysis), to cover a wider range of risks and interactions.
3. Focus on Inherent Safety: Prioritise inherent safety measures that eliminate hazards at the source, rather than relying solely on control systems. This could involve design changes, process modifications, or the use of safer materials.

4. Continuous Improvement: Foster a culture of continuous improvement where lessons learned from incidents and near-misses are regularly incorporated into the risk management process.
5. Capturing Management of Change: Ensure that the management of change processes are effectively documented and integrated into the risk assessment framework.

### Brief summary of traditional bowtie diagrams potential limitations

Traditional risk assessment methods in process industries can gauge the likelihood of specific consequences linked to hazardous events. While some techniques focus on individual consequences, others evaluate multiple potential outcomes and their associated probabilities. One such technique, the bowtie diagram, provides a comprehensive visual representation of a hazardous event, encompassing its causes, consequences, risk control measures, and their failure and recovery mechanisms. Often used to illustrate the hazardous event landscape, bowtie diagrams aid in communicating risk control strategies.

However, traditional bowtie diagrams have potential limitations. When dealing with multiple hazard causes, risk control measures, and escalation events, the visual clarity can diminish. Moreover, they do not provide a visual or numerical measure of the risk associated with the hazard and its causes, nor do they explicitly show the risk reduction achieved by the implemented risk control measures.

Recent advancements have addressed some of these shortcomings by introducing bowtie diagrams with numerical risk analysis and more informative visual outputs. While some BTD software can present data on factors like the Probability of Failure Demand (PFD) of a barrier, the visual representation may be unclear, making it difficult to understand the impact of each barrier on risk reduction. The WBTD aims to address this by visually displaying the risk level before and after each successive barrier.

## Introduction of the Weighted BowTie Diagrams (WBTDs) methodology and its potential benefits

The WBTD methodology, first developed by HSE's Science Division's researchers, (Chambers, 2023), offers a comprehensive and visually appealing approach to risk assessment. It can be used to assess and communicate risks associated with a wide range of hazardous events and evaluate the effectiveness of prevention or mitigation measures.

A distinctive feature of the WBTD method is its use of varying line thicknesses along threat and consequence pathways. These lines visually represent the relative risk reduction provided by different barriers with a known failure probability (PFD). Thicker lines indicate higher risk, while thinner lines signify lower risk, making the effectiveness of each barrier instantly apparent. This approach introduces a quantitative analysis element to traditionally qualitative BowTie diagrams, enhancing overall risk assessment and communication.

Unlike traditional BowTie diagrams, which often lack qualitative or quantitative analysis, the WBTD method uses established risk assessment techniques to identify and evaluate barriers, determine their degradation factors and associated controls. These supporting techniques, when used judiciously and combined with expert judgment, enable a comprehensive analysis that includes the detailed assessment of individual barriers, their failure modes (degradation factor), and potential recovery mechanisms (controls).

The WBTD also integrates risk modification factors (RMFs)—elements that contribute to the top event risk without being explicit barriers—into the risk landscape. This provides a holistic view of the risk landscape, covering both threats and consequences, and offers a detailed analysis of risk control strategies.

The WBTD's comprehensive approach, combined with its visual clarity and inclusion of RMFs, enhances its utility in risk communication, facilitating better understanding and decision-making among stakeholders.

### WBTD process

The WBTD process, as depicted in Figure 7 begins by identifying a top event (a critical incident or failure) and its possible consequences. These are central to the WBTD, which models the pathway from threats leading to the top event and the subsequent potential consequences. Various threats that could lead to the top event are identified and analysed. For each threat, preventive barriers are designed to stop the threat from triggering the top event, whilst mitigative barriers are identified to reduce the severity of the consequences should the top event occur.

The failure probability (PFD) of each barrier is assessed, considering potential degradation factors that could impair its performance. These degradation factors are controlled to maintain barrier effectiveness by designing specific controls for each one. This information is used to construct a traditional boetie diagram (BTD), which is central to the risk assessment. The data used to evaluate the WBTD, such as the estimated frequency of threat occurrence, failure probabilities and RMF probabilities, are stored in a modified LOPA table (see Figure 6). A simplified version of the BTD is produced, where information not required to communicate the key factors of interest to the target audience is abstracted away.

The simplified BTD can be converted to a weighted BTD to enable the visual communication of the risk assessment outcomes. The conversion is achieved by modifying the threat and consequence pathway line thickness and colour to represent the level of risk before and after each barrier, using the barrier's PFD or weighting factor to determine the amount of relative risk reduction it implements.

The WBTD uses visual techniques, such as colour coding and line thickness of the threat and consequence pathways, to illustrate the effectiveness of each barrier (see Figure 8).

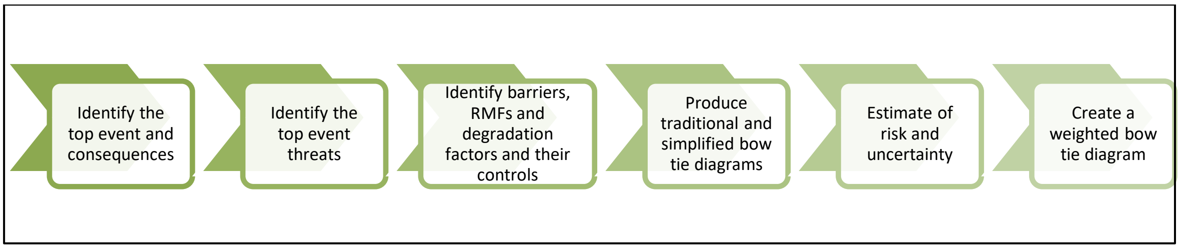


Figure 7: Weighted BTD method (WBTD) method simplified process flow.

Figure 8: Showing how the relative risk reduction implemented by each barrier is presented visually.

## WBTD supporting tools

The WBTD method utilises supporting tools to facilitate the risk assessment of the top event. Such techniques include, but are not limited to, Event Tree Analysis (ETA), the Demand Tree technique, and Fault Tree Analysis (FTA). Each of these tools can be utilised to enhance the assessment of relevant factors to be included in the WBTD.

ETA can evaluate the effectiveness of control strategies, whereby a control strategy is defined here as the combination of barriers implementing risk reduction in any given threat or consequent pathway, by modelling the modelling the effects of utilising the different combinations of barriers and either their use or omission within a control. ETA can start with a specific threat and map out possible subsequent paths, depending on the success or failure of various control strategies. For example, by modelling the effect of implementing different combinations of possible barriers and evaluating the outcomes. Insights from ETA used in this way can be used to determine which barriers are used in the WBTD, providing a clear visual representation of how control measures influence the likelihood and impact of potential outcomes, helping to prioritise strategies that offer significant risk reduction.

Figure 9 present an example event tree that evaluates the ‘parcel too big for tank’ threat control strategy, in this case we have evaluated the outcomes of different combinations of barriers using our qualitative representation of the risk of the top event occurring. What we can see here is that if each of the barriers, namely ullage calculation, Automatic Tank Guage (ATG) and operator response and high-level trip are implemented and performed to the stated barrier PFD the risk of overfill due to the ‘parcel too big for the recipient tank would be ‘very low’. Whereas, if the ullage determination and check were not performed, the lowest risk we can achieve is “low”.

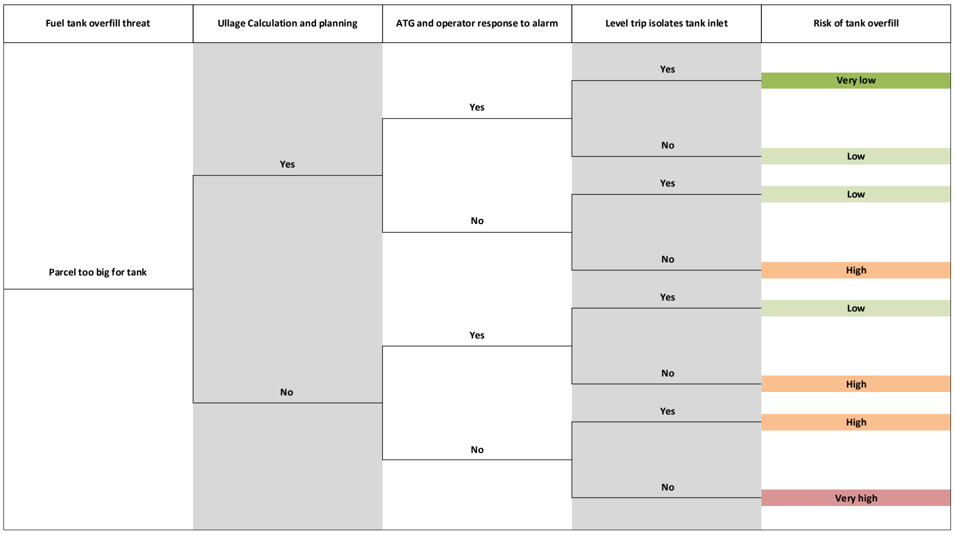


Figure 9: Example event tree showing the effect of implemented some or all of the stated barriers

## Demand Tree Analysis for Risk Assessment

A bowtie diagram visually represents and manages risks associated with a potential hazardous event, known as the "top event". Within the WBTD method, a demand tree can serve as a systematic approach to identify possible threats that could lead to the top event, see Figure 10.

The demand tree's primary purpose is to identify threats by asking how a top event could occur. This involves examining various operational modes, such as normal operation, start-up and shutdown, to detect any potential failure causes. Initially, the analysis does not consider existing protective measures like alarms, trips or interlocks to ensure a clear understanding of all possible threats.

Once the demand tree is used to identify these threats, the next step is to determine the preventive and mitigative barriers that could be deployed to stop these threats from causing the top event. The process involves asking questions such as "How can we prevent these threats?" and "What measures can be deployed?" to identify and implement appropriate barriers.

## Demand Tree Analysis for Fuel Storage Tank Overfill

One of many established techniques can be used to identity the top event threats; however, it should be noted that consideration of the consequences can also help identify relevant threats. The demand tree technique was used to identify the top event threats for this example scenario, see Figure 10. The demand tree is a systematic technique that can be used to identify top event threats and is analogous to a fault tree comprising solely of logical ‘OR’ gates, see (HSEa, 2009).

Note that in this work, we have implemented rules normally associated with LOPA, (CCPS, 2001), to help ensure consistency in how risk and, hence, risk reduction are dealt with in the WBTD. One notable difference is that the WBTD can account for multiple outcomes; how this is accounted for is discussed later in this paper. For example, in this case, a threat is only assessed in the WBTD if it results in the top event occurring if left unchecked.

The selected threats carried forward to the assessment are highlighted in Figure 10 and include: ‘parcel too large for tank’, ‘wrong tank filled’, ‘primary tank isolation fails’ and ‘failure to terminate supply pipeline flow when required’. The potential threat ‘wrong product sent’ was considered and not taken forward to assessment because this was considered unlikely to occur when compared with other threats.

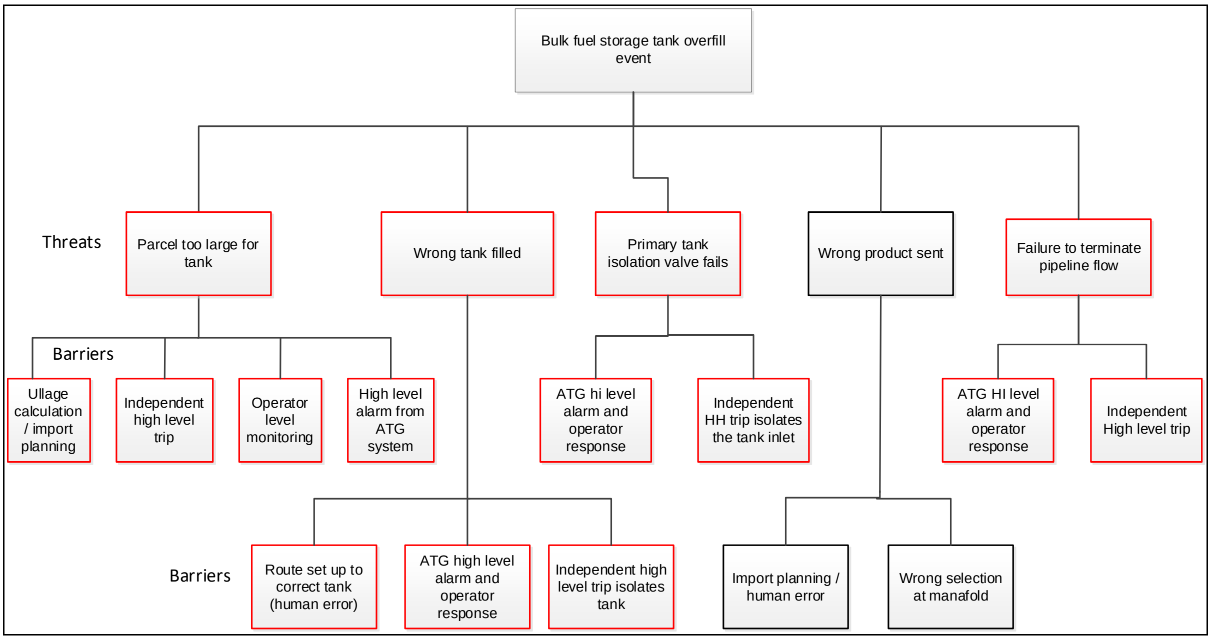


Figure 10: Demand tree showing the threats considered in the example assessment.

## Fault Tree Analysis

FTA can be used to assess the effectiveness of barriers by identifying their degradation factors and associated controls, (Chambers, 2023). FTA breaks down each barrier into its component parts and analyses potential factors that could cause these components to fail or degrade over time. This provides a more detailed understanding of vulnerabilities within each barrier and their potential impact on overall risk control. FTA also helps in developing controls to address these degradation factors, ensuring that barriers maintain their effectiveness. In the WBTD method, FTA results can inform the weighting of barriers, as those more susceptible to degradation may be less effective in the long term and may require additional controls or reinforcement. This process ensures the WBTD method provides a realistic and robust risk assessment, considering the dynamic nature of barrier effectiveness over time.

A degradation factor can be considered a barrier failure mode, and degradation controls can be seen as the failure mode recovery mechanisms. Barrier efficacy is defined here as the theoretical likelihood that it will achieve the identified risk reduction, without considering the negative impact of any degradation factors. Barrier effectiveness is defined as the likelihood of achieving the identified risk reduction, having accounted for the potential negative impact of degradation factors, along with the relevant degradation controls.

Each barrier can have multiple degradation factors. However, their total number should ideally be rationalised by screening and/or combining them, so that only significant degradation factors and controls are included in the risk assessment.

Figure 11 illustrates the use of FTA to identify degradation factors and their controls, applied to a tank overfill scenario. In this example, we focus on the 'ATG level alarm with operator response' barrier. For the level detection component of this barrier, two degradation factors were identified: sensor wear and tear, and calibration drift. To mitigate sensor wear and tear, two control measures were proposed: regular inspection and maintenance, as well as careful material selection. For calibration drift, potential controls include scheduled calibration activities, auto-calibration systems, and effective calibration verification procedures.

FTA applied this way, were used to identify other degradation factors and their controls associated with other aspects of the identified barriers associated with the example fuel storage tank overfill scenario.

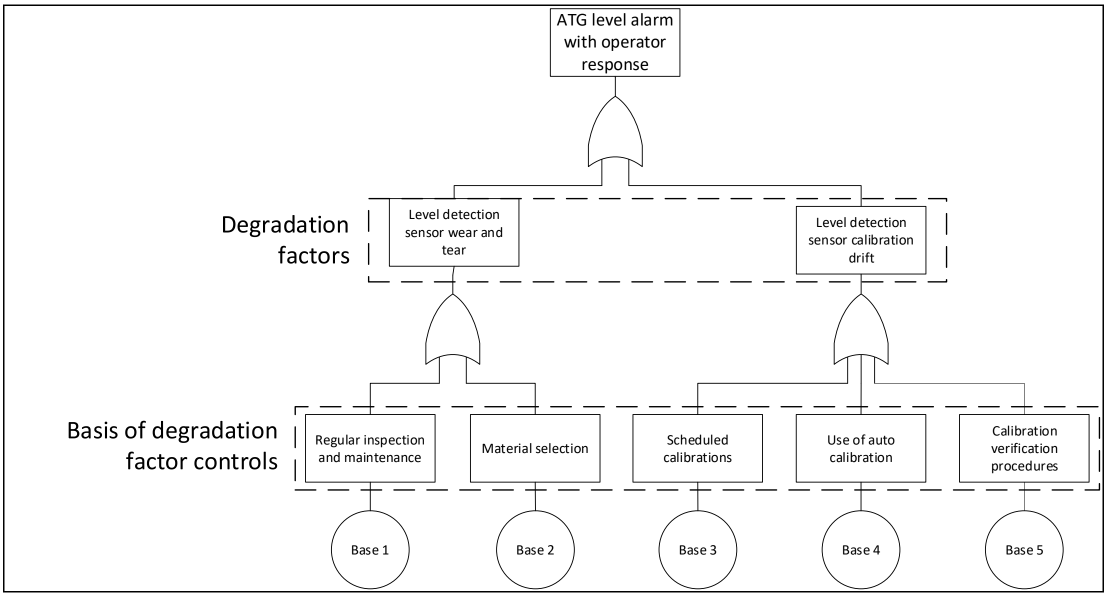


Figure 11: FTA used to identify preventative barrier degradation factors and their controls associated with the level detection element of the ATG level and with operator response.

Together, ETA, the Demand Tree, and FTA provide a comprehensive approach to risk assessment, (Chambers, 2023).

## Quantifying Risk Reduction with WBTDs

The WBTD method begins with the creation of a traditional BowTie diagram focused on a specific top event. A simplified diagram can be produced if this helps to communicates specific aspects of the risk assessment that the assessor wishes to present to the target audience.

In the WBTD method, risk is represented by the thickness or weight of each threat or consequence pathway line. The initial or unmitigated risk (frequency) is shown by the line thickness immediately to the right-hand side of the threat, which also serves as the starting risk for the first barrier.

The effectiveness of a barrier modifies the initial risk, which is represented by the barrier's probability of failure on demand (PFD) for demand-based barriers. In this paper, we refer to the barrier's PFD as the 'barrier weighting factor,' because it directly influences the line weight immediately following the barrier.

The reduction in threat pathway line thickness is proportional to the barrier weighting factor but not necessarily equivalent. For example, if a barrier has a weight (PFD) associated with it of 0.5, this will reduce the risk level before that barrier by 50%. However, this approach may become visually problematic after evaluating several barriers, because changes in line thickness might become imperceptible to the risk assessment audience, hence this would diminish from the communication of the effectiveness of some risk reduction strategies, which is contradictory to our central aim of communication of the risk assessment outcome visually.

To address this issue, the authors suggest defining multiple distinguishable line thicknesses and assigning them to a range of probabilities covering the risk assessment spectrum. A 7-point qualitative scale can be used (see Table 1 and Figure 12) was chosen because the research team could easily differentiate between each line thickness visually.

Table 1: Possible qualitative line thickness description and equivalent barrier risk (frequency of threat occurrence)

| **Line thickness qualitative descriptor** | **Extremely high** | **Very high** | **High** | **Moderate** | **Low** | **Very low** | **Extremely low** |
|---|---|---|---|---|---|---|---|
| **Frequency per year range** | >=1 | <1 to 0.1 | <0.1 to 0.01 | <0.1to .001 | <0.001 to 0.0001 | <0.0001 to 0.00001 | <0.0000 to 0.000001 |
| | | | | | | | |

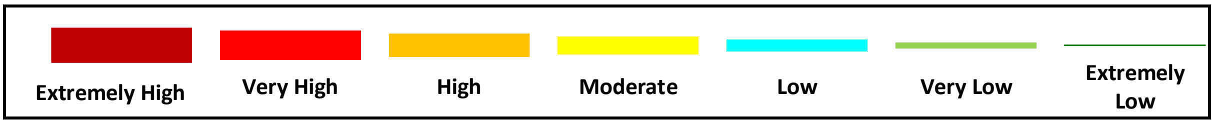


Figure 12: suggested line thickness and coulure associated with Table 1

The total frequency of the top event occurring is the sum of individual threat frequencies leading to that event. This sum serves as the starting frequency for each top event consequence evaluated in the WBTD, see Figure 13.

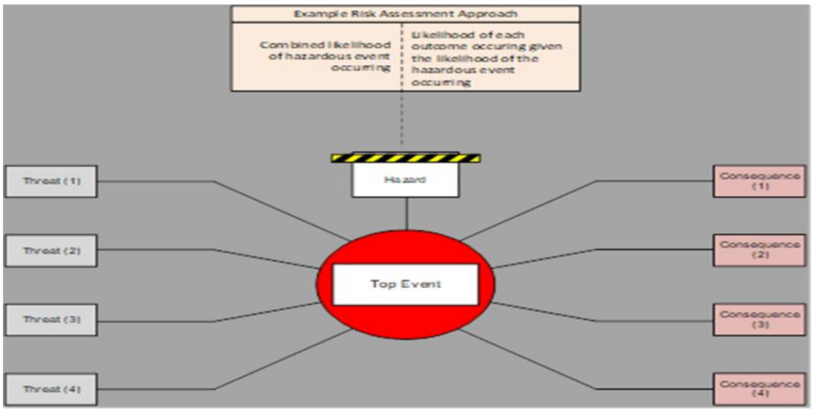


Figure 13: Depicts how the determination of cumulative risk is determined in the WBTD

## Risk Modification Factors

It is proposed that Risk Modification Factors (RMFs) be utilised in the WBTD methodology to account for inherent factors that are not necessarily intended to control risks, i.e., they are not barriers. RMFs can be considered analogous to LOPA Conditional Modifiers (CM) (CCPS, 2001). However, RMFs are more flexible than their LOPA counterparts, because they can account for a broader range of factors, some of which may negatively impact the risk assessment outcome, while others may have a positive influence.

To account for factors that can either positively or negatively affect the residual risk, it is suggested that RMFs take values either less than or greater than one. For example, the probability of ignition occurring would be represented as a value between 0 and 1, where zero indicates that ignition cannot occur, and one suggests ignition would certainly occur. In this case, a reduction in risk would represent a positive impact on the risk assessment outcome.

However, RMFs could also account for factors where there could be a negative impact (i.e., increased risk) on the risk assessment outcome and they could be represented by a multiplier (number greater than 1).

Examples of factors that could result in a negative impact include:

- Ageing infrastructure: Older equipment and facilities may be more prone to failure due to wear and tear, corrosion, or outdated design.
- High-pressure systems: Equipment operating under high pressure carries an inherent risk of rupture or explosion.
- Extreme temperatures: Processes involving very high or low temperatures can cause equipment stress or failure.

This is an area that would benefit from further research.

## Case Study: Bulk Fuel Storage Tank overflow

This case study is fictitious but is largely based on lessons learnt from past incidents. Additionally, in this paper data for the barrier PFDs in this example case study was based on data collected as part of this work, (HSEb, 2009).

The tank overfill event described in this paper occurs during the import of petrol from a third-party pipeline to a bulk storage tank at an oil storage facility. The storage tank is 6 metres high with a diameter of 60 metres, and the petrol is imported at a rate of 300 $m^3$/hour. The site is bounded by railway tracks, roads, and industrial units.

The scenario under evaluation considers the potential hazard of overfilling the tank. If left unchecked, the tank could overtop, leading to either the formation of a large vapour cloud or the spillage of petrol into the bunded area. Three outcomes were considered for the purposes of the case study: namely, a flash fire, an open unconfined flammable cloud explosion, and the loss of unignited petrol to the ground.

Immediate ignition could result in a contained pool or flash fire with the severity of up to two fatalities. Delayed ignition of a significant vapour cloud, on the other hand, could cause an open flammable cloud explosion or extended fire, leading to a much more severe outcome, with the potential for up to 50 fatalities.

The environmental risk involves the unignited release of petrol, which could form a pool within the bunded area. Should the bund fail, this could result in the release of petrol to the ground, which could contaminate aquifers or nearby rivers, posing a significant environmental hazard.

The operation of the petrol import process involves a SCADA system, automatic tank gauges (ATG), safety instrumented systems (SIS), and emergency shutdown (ESD) mechanisms. However, there is reliance on the ATG for all alerts and alarms, making it a potential critical point of failure. Other initiating events include incorrect routing of petrol, incorrect ullage calculations, valve failures, and failure to stop the flow when required. Safety procedures such as pre-transfer checks, tank selection based on available ullage, and manual level checks are in place, but the scenario highlights the risks associated with these operations if any part of the system fails.

## Case study assessment

Following a simplified assessment process, see Figure 14, using the LOPA details from Figure 6.

A full bowtie was created for the case study, focus on a large storage tank containing petrol with the potential for a tank overflow.

Figure 15 shows the complete bowtie, Figure 16 shows a simplified version of the bowtie with the degradation layer hidden.

For the case study, we are focussing on ‘Open Flammable Cloud Explosion’ consequence, see Figure 17.

The frequency and PFD values come from Figure 6 and applied on the bowtie in Figure 16.

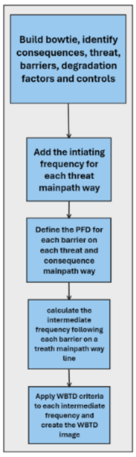


Figure 14: Assessment process applied to the tank overfill case study.

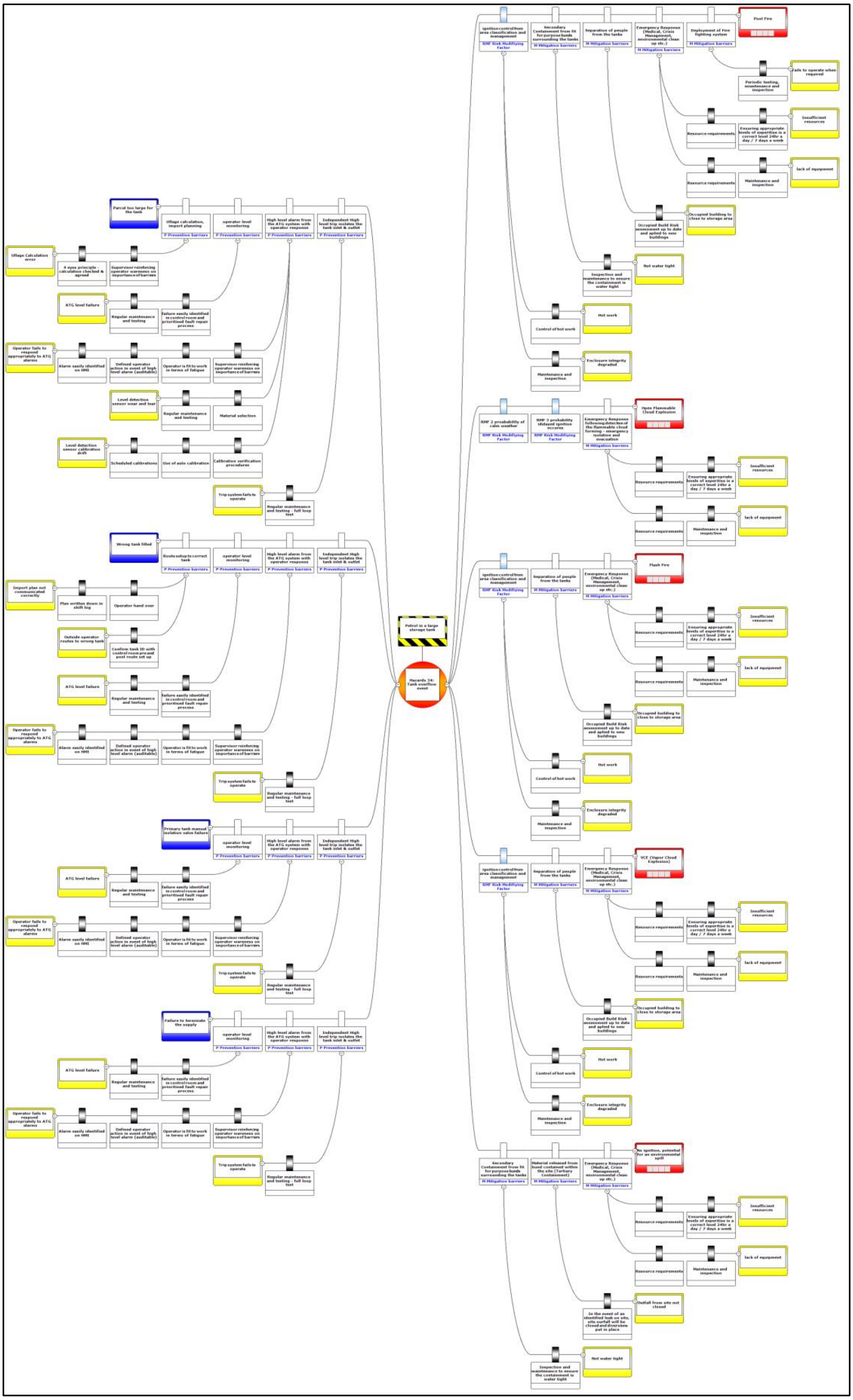


Figure 15: Full BTD for the fuel tank overfill case study showing degradation factors and controls

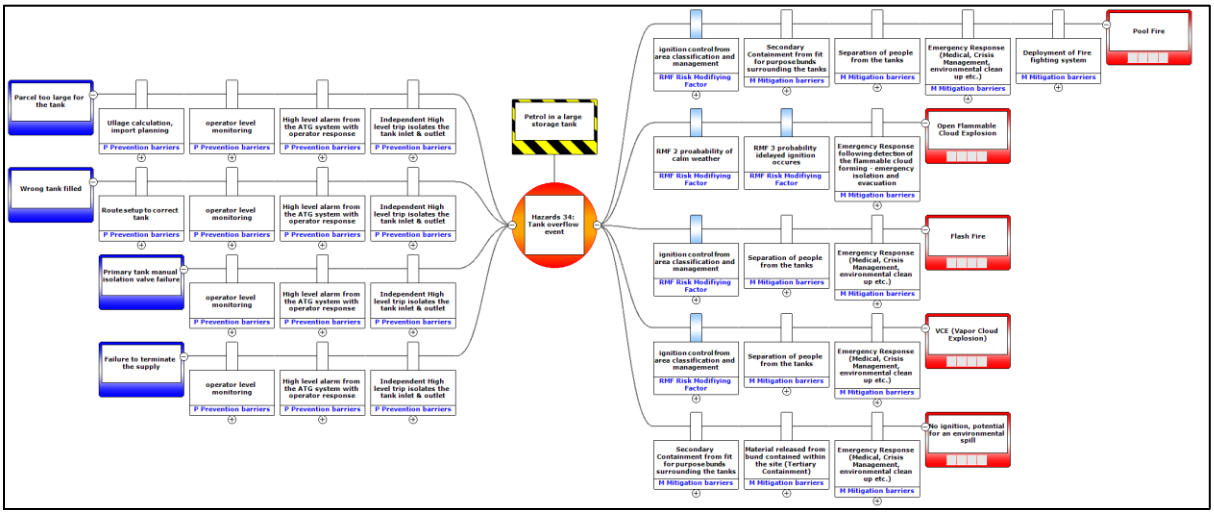


Figure 16: Simplified BTD for the fuel tank overfill case study with degradation factors removed for clarity

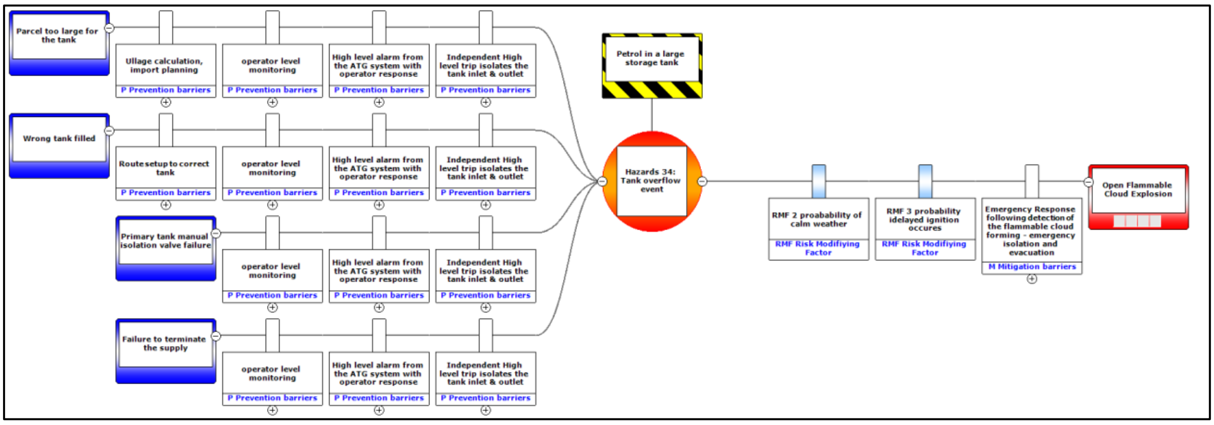


Figure 17: BTD for the assessment to be communicated in this case study

Calculating the intermediate frequencies for each threat main pathway and applying the line colour and size from Table 1 and Figure 12, we obtain the following results.

Table 2: Calculations for the 'parcel too large' threat

| | | Intermediate Frequency | | Intermediate Frequency | | Intermediate Frequency | | Intermediate Frequency | |
|---|---|---|---|---|---|---|---|---|---|
| Parcel too large for the tank | Ullage calculation, import planning | 1.00E+00 | operator level monitoring | 1.00E+00 | High level alarm from the ATG system with operator response | 0.300 | Independent High level trip isolates the tank inlet & outlet | 0.003 | Tank overflow event |
| 1.00E+00 | 1 | | 1 | | 0.3 | | 0.01 | | |

Table 3: Calculation for threat 'wrong tank selected'

| | | Intermediate Frequency | | Intermediate Frequency | | Intermediate Frequency | |
|---|---|---|---|---|---|---|---|
| Wrong tank filled | Route setup to correct tank | 0.240 | High level alarm from the ATG system with operator response | 0.120 | Independent High level trip isolates the tank inlet & outlet | 0.001 | Tank overflow event |
| 8.00E-01 | 0.3 | | 0.5 | | 0.01 | | |

Table 4: calculation for primary tank manual isolation valve failure threat

| | | Intermediate Frequency | | Intermediate Frequency | |
|---|---|---|---|---|---|
| Primary tank manual isolation valve failure | High level alarm from the ATG system with operator response | 0.050 | Independent High level trip isolates the tank inlet & outlet | 0.00050 | Tank overflow event |
| 1.00E-01 | 0.5 | | 0.01 | | |

Table 5: calculation for the failure to terminate flow threat

| | | Intermediate Frequency | | Intermediate Frequency | |
|---|---|---|---|---|---|
| Failure to terminate the supply | High level alarm from the ATG system with operator response | 0.300 | Independent High level trip isolates the tank inlet & outlet | 0.00300 | Tank overflow event |
| 1.00E+00 | 0.3 | | 0.01 | | |

Combining the threat frequencies and applying the risk modifying factors along with the barrier PFD on the consequence side for the 'Unconfined Vapour Cloud Explosion' consequence (PSLG, 2009).

Table 6: calculation for open flammable cloud explosion consequence

| Top Event Frequency | | Intermediate Frequency | | Intermediate Frequency | | Intermediate Frequency | |
|---|---|---|---|---|---|---|---|
| 0.0077 | RMF 2 proabability of calm weather | 0.00023100 | RMF 3 probability idelayed ignition occures | 0.0001617 | Emergency Response following detection of the flammable cloud forming - emergency isolation and evacuation | 0.000129 | Open Flammable Cloud Explosion |
| | 0.03 | | 0.7 | | 0.8 | | |

Then visualising this back on the assessment bowtie to create the WBTD for the case study

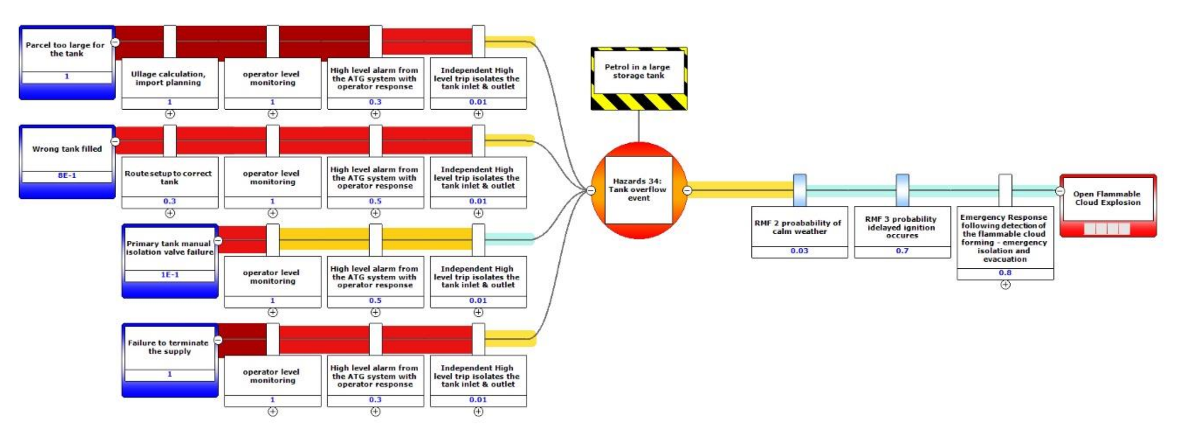


Figure 18: Weighted BTD presenting the assessment results.

## Analysis of Results

Visually inspecting the weighted Bowtie Diagram (BTD) in Figure 18 provides valuable insights into the assessment outcomes of the fuel storage tank overfill scenario. One of the most notable findings is that the most significant threat arises from the issue of the 'parcel too large for the tank.' This threat dominates the risk profile, suggesting that this aspect of the operation requires particular attention. In contrast, the least dominant threat identified is the primary tank side manual isolation, indicating that this factor plays a smaller role in contributing to the risk of an overfill event.

When examining the effectiveness of the prevention barriers, the independent high-level trip emerges as the most effective measure. This barrier provides the greatest reduction in risk, acting as a critical control in preventing the top event. On the other hand, the ATG high-level alarm, which relies on operator response, is identified as the least effective prevention barrier for which credit has been claimed. Its limited impact on reducing the risk highlights the potential for human error or delays in response, making it less reliable in critical situations.

Another key finding is the role of the Risk Modification Factor (RMF) associated with calm weather. This factor significantly increases the likelihood of the Unconfined Vapour Cloud Explosion (UVCE) occurring. Without the calm weather RMF, the residual risk of the top event would be intolerable, underlining the importance of this external factor in maintaining safety. The current risk level is dependent on this RMF and the existing mitigation barrier, which together help bring the risk to a tolerable if ALARP level. However, this reliance suggests that further preventive measures would be highly beneficial in reducing the residual risk without depending so heavily on favourable weather conditions.

It is noted that credit has not been claimed for the operator level check barrier, primarily due to a lack of rigour and supporting evidence. This omission points to a missed opportunity in the risk assessment, because addressing the shortcomings of this barrier could lead to a more robust risk control strategy for this case study. If improvements were made, and the operator level check barrier was properly validated, the residual risk would likely be reduced further by claiming a PFD of 0.1 for this barrier.

In summary, the analysis of Figure 18 visually highlights both the strengths and vulnerabilities in the current risk management approach. While certain barriers, such as the independent trip, are highly effective, others, such as the ATG high-level alarm and operator response, are less reliable. Addressing this apparent weakness by enhancing the operator level check to a level where it could be claimed as a prevention barrier and claiming a PFD of 0.1 could significantly reduce the residual risk and improve the overall safety of the system.

## Conclusions

The application of the WBTD method to a process industry case study in this paper aims to demonstrate their potential to enhance both risk assessment and communication. By incorporating RMF and visualising the cumulative impact of barriers, WBTDs build upon traditional bowtie diagrams and introduce a structured, more intuitive means of evaluating and improving barrier health. This improved visualisation of risk, particularly in highlighting dominant threats and the most effective barriers, provides critical insights for prioritising control measures and enhancing decision-making processes.

The case study of the bulk fuel storage tank overfill scenario serves as a practical example of how WBTDs can be effectively applied in the process industry. In this case, WBTDs were shown to aid in both the assessment and communication of risk, particularly through the visual representation of barrier performance. The benefits of this method extend beyond technical risk assessment to improve the clarity of risk communication for a wide audience, including engineers, risk specialists, managers, and the general public.

In comparing WBTDs with LOPA, the paper highlights the complementary nature of these tools, with the modified LOPA table offering an approach that mirrors the BTD structure and accommodates multiple outcomes. This suggests that WBTDs, with their enhanced visualisation and structured approach to risk evaluation, can serve as a valuable supplement to traditional risk analysis methods.

Overall, the integration of WBTDs into risk management practices offers a promising avenue for improving the understanding, communication, and mitigation of risks across various sectors.

### Disclaimer

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