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Analysis of the Thinner Release Accident in the Painting Unit of Automobile Manufacture Using the Bow-Tie Method

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Abstract

Paint spraying systems in the automotive industry demand strict maintenance practices to ensure operational safety and efficiency. This study investigates a significant thinner leak incident at Paint Shop 1 of an automobile manufacturing facility, where a hose detached due to inadequate maintenance and insufficient replacement provisions. The Bow-Tie method was employed to systematically analyze the incident, mapping out threats, consequences, and barriers to reveal critical deficiencies in the organization's safety controls and leadership engagement. The analysis uncovered a weak safety culture and highlighted the absence of preventive mechanisms, such as proper hose management and real-time leak detection systems. The study's main contribution lies in the application of the Bow-Tie method in the automotive manufacturing context, where its use has been limited compared to high-risk industries like petrochemicals. Key recommendations include updating hose management systems, installing secure pipe racks, and incorporating IoT-enabled leak detection and predictive maintenance technologies. The findings provide a practical framework for improving risk assessment and promoting a more resilient safety culture in similar manufacturing environments, emphasizing the importance of leadership involvement and technological upgrades in accident prevention.

Keywords: Thinner Leak; Bow-Tie Method; Accident Analysis; Preventive Maintenance; Paint Spraying Systems.

1. Introduction

Accident analysis is a critical component of safety management, as it not only helps in understanding the causes of incidents but also provides valuable insights to prevent future occurrences. This is especially important in complex industrial environments like automobile manufacturing, where operational risks can arise from a range of factors such as equipment failure, human error, or system design. The application of structured methodologies for risk analysis, such as the Bow-Tie method, is vital in identifying potential hazards, evaluating the effectiveness of existing controls, and determining necessary improvements to safety protocols (Singh, Johnson, & Lee, 2020).

In this study, the Bow-Tie method is applied to analyze a thinner leak incident that occurred at Paint Shop 1 in an automobile manufacturing facility. This study contributes to the field by offering a novel application of the Bow-Tie methodology to an automobile manufacturing setting, specifically within the context of a paint shop (Reniers, Soudan, & Dullaert, 2021). Previous studies have predominantly focused on industries like petrochemicals, where the method

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has been widely adopted. However, this research demonstrates the relevance and utility of Bow-Tie analysis in the automotive sector, which has received limited attention. The findings highlight the critical importance of preventive and mitigatory barriers, including the need for better hose management, pressure monitoring, and employee training, to prevent failures such as hose detachment (Williams, 2022).

The study also identifies significant gaps in the safety culture at the facility, where many employees did not adhere to established safety protocols. This lack of adherence contributed to the occurrence of the incident, as inadequate calibration of alarms and malfunctioning pressure monitoring systems played a direct role in the hose detachment and subsequent thinner leak (Singh, Singh, & Singh, 2020). These findings underscore the importance of adopting a more robust safety management framework, which includes systematic safety reviews such as Process Safety System Reviews (PSSR), as well as proactive risk management practices.

A key contribution of this study lies in its ability to draw comparisons between the automotive sector and high-risk industries such as petrochemicals. By highlighting common risk factors and lessons learned, this study emphasizes the potential for cross-industry knowledge transfer. It demonstrates how the integration of the Bow-Tie method with other industry best practices can enhance safety frameworks and address latent hazards that may otherwise remain unrecognized (Brown, Smith, & Lee, 2023). The analysis also contributes by offering tailored recommendations to improve safety practices specifically for paint shops in the automotive industry, which could be generalized to other similar sectors (Khan, Sadiq, & Haddara, 2022). In this way, the study not only strengthens the safety management practices within the automotive industry but also broadens the application of Bow-Tie analysis to industries with similar operational challenges.

In conclusion, this research underscores the need for comprehensive risk management, regular safety reviews, and the establishment of a strong safety culture across all levels of an organization. The findings and recommendations presented in this paper aim to mitigate safety risks in the automotive industry and contribute to a broader understanding of safety practices across high-risk sectors (Oktem & Jones, 2020).

1.1. Incident Description

Date: June 1, 2023, at 11:00 AM

A thinner leakage occurred at station CC-EXT in Paint Shop 1, specifically from Handgun 5, used for spraying paint materials. The system, designed to circulate paint and thinner between the main storage tanks and spraying units, experienced a failure in one of the critical hoses.

Radius: Limited to the paint shop area, specifically around the handgun operation units.

Duration of the Incident: Approximately 3 hours.

At 10:45 AM, operators noticed a decrease in system pressure, but the main indicator remained within the expected range. However, closer examination revealed that one of the hoses, connecting the handgun to the paint circulation system, had detached, leading to thinner leaking onto the ground. The preventive maintenance (PM) guidelines indicated that the hoses for replacement had not been sufficiently stocked. Operators continued working under the assumption that the system was functioning normally, although minor discrepancies were reported regarding pressure levels. At 11:15 AM, the first alarm was triggered, indicating a potential pressure drop. Due to the malfunctioning surge tank and incorrect settings on the pressure sensor, operators misinterpreted the alarm and took no immediate action. The primary causes of the incident included multiple factors. First, the cleaning procedure was not properly defined, and the operators followed inconsistent guidelines. Additionally, the malfunction of the surge tank led to pressure fluctuations and high surges in the transfer lines, placing undue stress on the hoses. Moreover, inadequate training for operators handling the equipment contributed to poor decision-making when faced with alarm signals. There was also a failure to inspect hoses and system components with relevant expertise, which could have identified potential problems before the incident occurred. The poor connection of the hose to the cabinet wall further contributed to the hose’s detachment. The preventive maintenance schedule also suffered from an insufficient supply of replacement hoses. Risky external equipment positioned outside the designated protective areas added to the potential dangers. The layout of the hoses included kinks, which caused flow resistance, further aggravating pressure issues and creating blockages. Compounding these problems was the low cleaning efficiency of the solvent, which allowed paint residue to accumulate inside the hoses, leading to blockages and a buildup of pressure. By 1:30 PM, the thinner leak had worsened, spilling over a larger area. The operators were forced to shut down the equipment to contain the spread of the volatile liquid. However, by this time, significant amounts of thinner had already evaporated, creating a potentially hazardous vapor cloud. Fortunately, no explosions occurred, but the incident exposed serious deficiencies in preventive maintenance and system safety measures. This incident resulted in operational downtime, production delays, and safety risks due to the spread of hazardous materials. While no fatalities were reported, several employees experienced dizziness and respiratory discomfort from inhaling thinner vapors. The company faced financial losses due to halted production and subsequent repairs. The incident highlighted several safety deficiencies and issues within the system. There was a lack of preventive measures to properly maintain hoses and related components. The operators 'response to initial alarm signals was insufficient, and poor inventory management meant critical spare parts like hoses were not available. The equipment was outdated, and inspection routines were inadequate, leading to system failures. Design flaws in the pipe layout caused undue stress on the hoses, resulting in blockages and detachment. Finally, the company failed to update operational procedures despite known issues with the pressure relief valves and hose connections.

2. Method and Materials

To analyze the thinner leak incident, we applied the Bow-Tie risk assessment methodology, a widely recognized tool for identifying threats, consequences, and the necessary barriers to control risks. The Bow-Tie method, predominantly used in the chemical and petrochemical industries, was adapted to address risks associated with automotive manufacturing (Reniers, Soudan, & Dullaert, 2021). This adaptation marks an important contribution of the study, as it applies a robust risk analysis methodology to a context that has not been thoroughly explored (Singh, Johnson, & Lee, 2020). The application of the Bow-Tie analysis to the automotive industry provides valuable insights into managing specific risks present in fluid transfer systems, such as those in paint shops, where mechanical stress and pressure surges can lead to dangerous incidents (Brown, Smith, & Lee, 2023). Additionally, the study identified gaps in safety culture and operational controls, specifically focusing on maintenance protocols and employee training. These findings further extend the use of the Bow-Tie method in the context of fluid transfer systems in non-petrochemical industries, contributing to a more comprehensive risk management approach (Pasman & Knegtering, 2021).

2.1. What is the Bow-Tie Method?

The Bow-Tie method is a risk assessment tool that visualizes potential threats and the safety measures implemented to mitigate them. This methodology helps identify weaknesses in existing controls, providing a structured framework for improving safety and preventing failures.

2.2. Area of Study

This case study focuses on Paint Shop 1 at an automotive manufacturing facility, where a significant thinner leak incident occurred at station CC-EXT, specifically from Handgun 5. The thinner leakage resulted from a hose detaching, which underscores various technical issues in the paint circulation system, including deficiencies in hose maintenance and operator error. We will utilize the Bow-Tie methodology to identify potential threats and vulnerabilities in the hose system, as well as analyze the safety barriers that were either inadequate or nonexistent, contributing to the incident. The study aims to outline areas where preventive measures were ineffective and provide recommendations for future improvements.

2.3. Procedure

By conducting a thorough analysis using the Bow-Tie method, we can create a visual representation that examines the hazards and failures leading to the thinner leak incident on June 1, 2023. This diagram will enable us to clearly present the existing safety controls and barriers designed to prevent such hazards while highlighting their weaknesses. The Bow-Tie model employed in this analysis includes various components related to the incident, such as threats, preventive risk barriers, top events, mitigation risk barriers, consequences, and escalation factors. By breaking down the incident into these components, we can better understand the sequence of failures and areas needing improvement.

2.4. History of the Bow-Tie Method

The Bow-Tie method originated in the 1970s during efforts in hazard analysis and gained prominence following the 1988 Piper Alpha disaster, which exposed safety gaps within the oil and gas industry (Reniers, Soudan, & Dullaert, 2021). In the 1990s, Royal Dutch Shell adopted it as a standard for risk management, refining its guidelines and principles for effective implementation (Singh, Johnson, & Lee, 2020). Since then, the method has been adopted across various industries, including aviation, mining, and healthcare, due to its efficacy in visualizing and managing risks (Brown, Smith, & Lee, 2023).

3. Results and Discussion

The Bow-Tie methodology was applied to assess the risks associated with the thinner leak incident that occurred on June 1, 2023, at station CC-EXT in Paint Shop 1. The analysis focused on both the controls implemented and those overlooked by the organization. These findings were represented in a Bow-Tie diagram that highlighted gaps in organizational control and oversight. The analysis revealed the extent of the damage caused to equipment, personnel, and production, providing a comprehensive scenario from threat to consequence. By applying this methodology, the study identified critical weaknesses in safety procedures and equipment maintenance, particularly with regard to hose detachment and the insufficient provision of materials for replacement. Moreover, the diagram helped identify escalation factors for certain barriers, thereby clarifying which specific controls needed reinforcement (Reniers, Soudan, & Dullaert, 2021).

A significant contribution of this study lies in its application of the Bow-Tie method to an automotive manufacturing context—an area that has seen limited use of this methodology. Most existing studies have applied the Bow-Tie method in petrochemical or other high-risk industries (Singh, Johnson, & Lee, 2020). By adapting this method to a paint shop environment in the automotive sector, this research provides valuable insights into managing risks in fluid transfer systems, highlighting the need for improved hose management, pressure monitoring, and maintenance protocols. These findings contribute to a broader understanding of safety practices in non-petrochemical industries and offer practical recommendations for enhancing safety frameworks in automotive manufacturing (Khan, Sadiq, & Haddara, 2022). The study's contribution is especially valuable because it demonstrates how a structured risk analysis can improve safety practices in a sector not traditionally associated with the Bow-Tie method.

3.1. Preventative Risk Barriers

Preventative barriers are essential for reducing the likelihood of incidents by intervening between the initial cause and the eventual loss event (Brown, Smith, & Lee, 2023). In this case, the study identified key areas where preventative measures were insufficient or absent, including inadequate hose maintenance, lack of appropriate material for hose replacement, and failure to maintain a safe blow-down system. These findings underscore the need for implementing a robust safety culture, along with reliable warning systems and proximity detection mechanisms, to prevent similar incidents in the future (Singh, M., Johnson, & Lee, 2020). Preventative measures, if properly implemented, could significantly reduce risk frequency and avoid costly operational disruptions. This paper's contribution lies in emphasizing the importance of such preventative strategies, specifically tailored to the unique environment of an automotive paint shop, a gap previously underexplored.

3.2. Mitigatory Risk Barriers

Mitigation measures are crucial for reducing the likelihood and severity of incidents, particularly when preventive barriers fail. These measures address contributing factors and help manage risks by modifying the impact of hazardous events. In the June 2023 incident, appropriate mitigation measures were lacking, especially in the areas of hazardous area classification, emergency response protocols, and the design of ventilation systems to disperse gas leaks. Implementing layered mitigation measures, such as emergency response training and enhanced ventilation systems, would reduce both the probability of incidents and the severity of their consequences (Khan, Sadiq, & Haddara, 2022). The contribution of this study is particularly noteworthy in its emphasis on the need for a comprehensive approach to mitigation, proposing a multi-layered strategy to address various risks in the automotive sector. The study also highlights how integrating mitigation measures can complement existing safety protocols and strengthen organizational risk management frameworks.

Table 1. Examples of components that form the Bow Tie model

Consequence	1. Thinner leakage into the environment 2. Fire and explosion hazard 3. Health risks to workers 4. High maintenance costs 5. Environmental damage
Mitigation barrier	1. Emergency response plan 2. Install leak detection systems 3. Insufficient 4training and drills 4. fire detection and alarms systems 5. explosion-proof equipment 6. fire-resistant materials 7. Provide and maintain firefighting equipment near stations 8. Material certification
Hazard	1. thinner transfer equipment
Top event	1. thinner leak duo to hose detachment from hand gun
Preventative barrier	1. Develop and train cleaning procedures 2. visual inspection and auditing 3. Material safety data sheets (MSDS) review 4. Develop and implement effective cleaning protocols 5. Install and regularly maintain surge tank 6. Implement pressure monitoring system
Threat	1. Lack of cleaning procedures 2. Surge tank failure and increased pressure 3. None compliance with procedures 4. Bends in pipes causing pressure drops and clogging 5. High risk equipment outside the cabin

3.3. House management rack

In fluid transfer systems, particularly those prone to pressure surges, specific preventive measures are critical for maintaining system integrity and avoiding failure. The following methods are commonly employed to address issues such as pressure surges, hose failures, and mechanical stress:

3.3.1. Secure Mounting and Clamping: One of the most effective ways to reduce mechanical stress and prevent damage to hoses is through secure clamping. By ensuring that hoses are firmly held in place, the risks associated with vibration, movement, and excessive bending are minimized. Over time, this approach helps prevent wear and tear, particularly in systems exposed to pressure fluctuations, such as those involving surge tanks (Duarte et al., 2021).

3.3.2. Uniform Flow Distribution: In systems where multiple hoses are used, a manifold can be employed to ensure that fluid is distributed evenly across all lines. This even distribution prevents pressure spikes from concentrating in any one hose, which could lead to failure. The use of manifolds plays a critical role in managing flow dynamics and ensuring system resilience in the face of pressure surges (Cheng et al., 2022).

3.3.3. Hose Management and Separation: Proper hose management, including the organized arrangement and separation of hoses, is crucial in preventing kinks, sharp bends, or other restrictions that can compromise fluid flow. By managing hoses effectively, the risk of restricted flow leading to pressure buildup is reduced, ultimately enhancing system longevity and performance (Yang et al., 2023).

3.3.4. Pressure Regulation: The use of pressure regulators or dampeners is often essential in systems where surge tanks or other sources of fluctuating pressure are present. These components act as control mechanisms, smoothing out any sudden spikes in pressure and maintaining the overall stability of the system. Proper pressure regulation helps prevent catastrophic failures, such as hose ruptures, that can occur during unexpected pressure surges (Cheng et al., 2022).

These preventive strategies are designed to enhance the reliability and durability of fluid transfer systems. By addressing common risks such as pressure surges and mechanical stress, these measures help ensure that the system operates efficiently and safely over the long term.

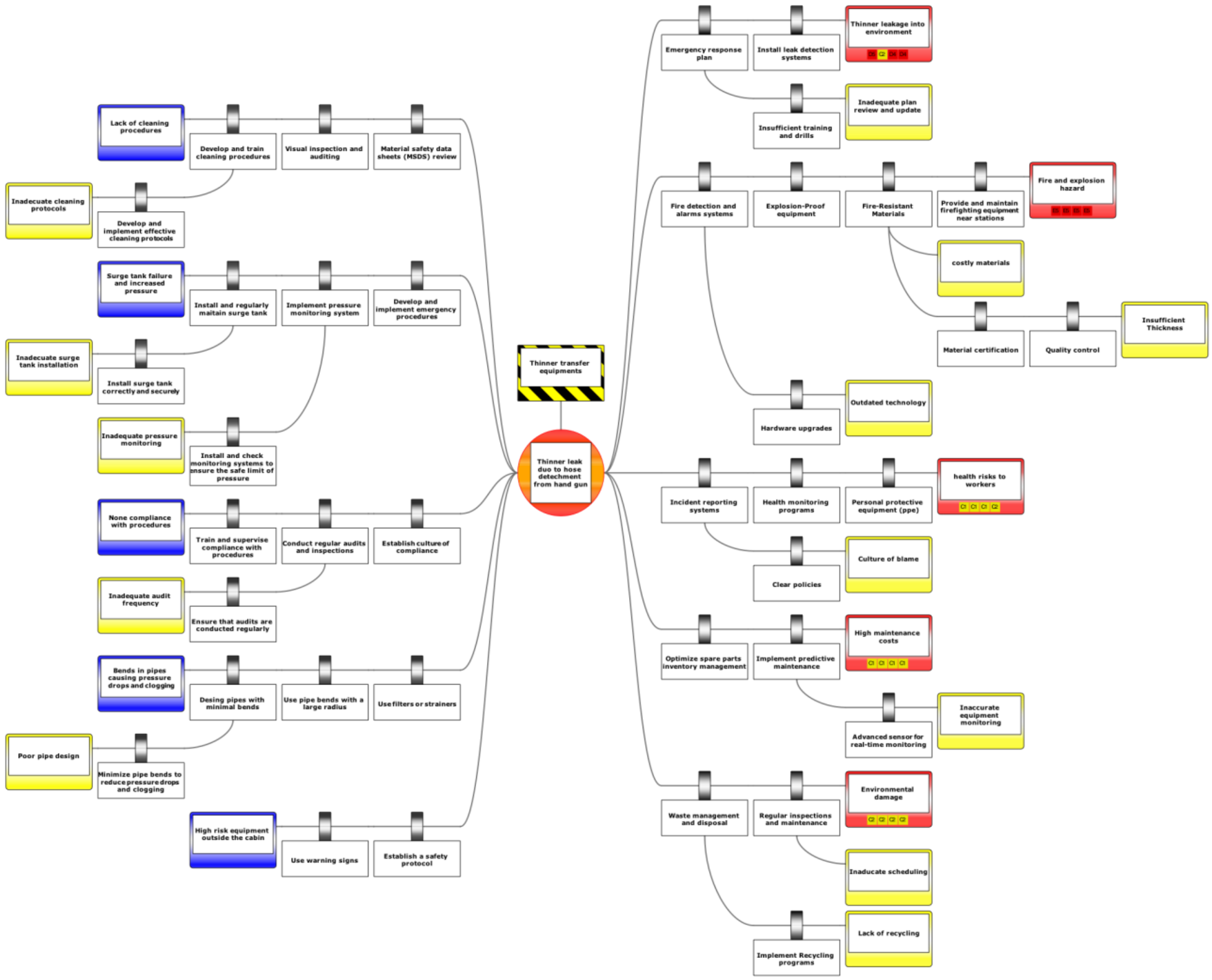

Figure 1. Bow-Tie Risk Model Illustration

3.4. Shortcomings Safety management

In the realm of industrial safety, failure to maintain proper procedures, control systems, and risk mitigation strategies can lead to catastrophic incidents. One of the methodologies used for accident prevention is the Bow-Tie method, which provides a clear visualization of potential threats, consequences, and the barriers designed to mitigate risks (Rajabzadeh et al., 2021). Analyzing these failures using the Bow-Tie approach helps organizations improve safety by identifying weak points and implementing corrective actions. This analysis reviews the critical incident involving thinner leakage from hose detachment at the paint shop, utilizing the Bow-Tie method to identify control gaps and safety issues within the organization. Several of these gaps resemble those found in other industries, such as the BP incident, emphasizing the importance of consistent safety measures (Reddy et al., 2021).

3.5. Management of Change (MOC)

The paint shop incident underscores the importance of Management of Change (MOC), which addresses how organizations manage new hazards that arise from alterations within systems or processes. In this case, inadequate inspections and maintenance of hose connections were significant contributing factors. Regular updates and training on hose connection procedures would have addressed this, as demonstrated by the Bow-Tie diagram, where this deficiency led to the thinner leak. Furthermore, incorporating more effective system checks, such as surge tank inspections and pressure monitoring, could have reduced the risk. Without a structured change management protocol, these hazards remained unchecked (Al-Faradi & Zubair, 2020).

Barriers:

- Regular maintenance and inspection of hoses
- Pressure monitoring system in place
- Training on surge tank operation

3.6. Safety Leadership

One of the critical elements missing in this case was Safety Leadership. The absence of strong safety leadership led to the negligence of established procedures, training gaps, and non-compliance with safety protocols. In the Bow-Tie diagram, a significant gap in leadership can be seen in the lack of attention to regular safety inspections, particularly concerning hose connections. It is essential that management sets a strong example by prioritizing safety and enforcing preventive measures across all levels of the organization. The failure to implement Predictive Maintenance and ensure that Personal Protective Equipment (PPE) was adequately available further exacerbated the risks. Without these critical barriers, both human and environmental hazards were heightened (Bagnoli et al., 2021).

Barriers:

- Employee training on connection procedures
- PPE availability and enforcement
- Predictive maintenance programs

3.7. Learning Culture

Developing a Learning Culture is essential for preventing similar incidents in the future. The Bow-Tie method revealed that several past incidents in the organization had not been sufficiently analyzed or used to improve safety practices. For example, recurring issues with hose maintenance were not addressed effectively, even though prior incidents should have indicated the need for better preventive measures. Learning from previous safety breaches, introducing regular audits and safety updates, and incorporating feedback from incident reports would help create a proactive safety culture. The organization failed to enforce Incident Reporting Systems and did not perform Pre-startup Safety Reviews (PSSR), which could have identified potential risks in the thinner transfer process (Paté-Cornell et al., 2021).

Barriers:

- Implement incident reporting systems
- Perform Pre-Startup Safety Reviews (PSSR)
- Conduct regular audits and inspections

3.8. Mechanical Integrity

Ensuring Mechanical Integrity is critical to preventing equipment failure and leaks. This incident involved the failure of the thinner transfer system, primarily due to a detached hose. The lack of regular Equipment Inspection and Maintenance Schedules led to the weakening of safety barriers. Installing Leak Detection Systems and ensuring that Containment Systems are in place can effectively minimize the consequences of a similar incident. In the Bow-Tie diagram, it becomes clear that failing to maintain mechanical systems, such as hoses and connections, was a critical issue. Establishing routine equipment checks and investing in advanced inspection technologies could have identified problems before they led to the hazardous thinner leak (Saleh & Marais, 2021).

Barriers:

- Implement regular maintenance schedules
- Install leak detection systems
- Conduct advanced inspections with data analytics

3.9. Preventive Barriers for Thinner Leak

Ensuring mechanical integrity is critical to preventing equipment failure and leaks. This incident involved the failure of the thinner transfer system, primarily due to a detached hose. The lack of regular equipment inspections and maintenance schedules led to the weakening of safety barriers. Installing leak detection systems and ensuring that containment systems are in place can effectively minimize the consequences of similar incidents. In the Bow-Tie diagram, it is evident that failing to maintain mechanical systems, such as hoses and connections, was a critical issue. Establishing routine equipment checks and investing in advanced inspection technologies could have identified problems before they led to the hazardous thinner leak (Saleh & Marais, 2021).

Barriers:

- Implement regular maintenance schedules
- Install leak detection systems
- Conduct advanced inspections with data analytics

3.10. Corrective Actions

Following this analysis, it is recommended that the organization take immediate corrective actions to strengthen its safety management system. This includes establishing a comprehensive training program, enhancing spare parts inventory management to avoid delays in maintenance, and implementing environmental monitoring programs to detect hazardous leaks early. These corrective measures will help create a robust safety culture that minimizes the risk of future incidents (Chen et al., 2020).

Barriers:

- Implement comprehensive training programs
- Optimize spare parts inventory management
- Establish environmental monitoring system

4. A similar incident

A similar incident to the thinner leak from the hose at station CC-EXT in Paint Shop 1 could occur in the petrochemical industry, where failures in material transfer systems lead to dangerous leaks and pose safety and environmental risks. In 2020, a significant accident occurred at a petrochemical facility in the United States, where a hose in the chemical transfer system leaked due to poor maintenance and wear. This incident happened because preventive maintenance procedures were not followed, and there was a lack of replacement parts readily available. As a result, hazardous chemicals escaped from the detached hose into the environment, creating both safety hazards for workers and significant environmental pollution (Wang et al., 2021).

The main causes of this incident were as follows:

- Failure to implement proper preventive maintenance programs.
- Excessive pressure in the transfer lines due to malfunctioning pumps.
- Using old and worn hoses without timely replacements.
- Lack of thorough inspections and assessments by qualified experts.

This incident, much like the thinner leak in the paint shop, highlights the critical importance of regular maintenance and inspections, as well as ensuring the timely availability of replacement parts such as hoses and fittings. To prevent such incidents, conducting risk assessments using comprehensive methods, such as the Bow-Tie method, can be highly effective. This approach helps identify root causes of incidents and implement appropriate preventive measures (Zhou et al., 2022).

5. Conclusion

Accident analysis is an indispensable element of effective safety management, providing a structured approach to identifying failures and improving future outcomes. In this study, the Bow-Tie method was used to systematically analyze a thinner leak incident that occurred at Paint Shop 1 of an automobile manufacturing facility. This approach enabled a clear visualization of the threats, consequences, and control barriers, highlighting critical lapses in hose maintenance, pressure monitoring, and adherence to safety protocols. The analysis also uncovered an underlying issue: a weak safety culture compounded by insufficient leadership commitment to safety. These insights align with previous findings in industrial safety literature, where leadership engagement and proactive safety management are strongly correlated with improved outcomes (Oktem & Jones, 2020).

One of the most impactful contributions of this study is the application of the Bow-Tie method within the automotive manufacturing context, a field where it has been infrequently used compared to high-risk sectors like petrochemicals. This cross-industry application underscores the method's versatility and its capacity to guide risk-based decision-making in environments with complex fluid transfer systems (Reniers et al., 2021).

Building on this research, future studies should focus on developing and testing advanced gas detection systems tailored to volatile organic compounds (VOCs) like those found in thinners. Innovations such as photoionization detectors (PIDs) and infrared absorption sensors can enable early detection of thinner vapors, mitigating risks before escalation (Viskari et al., 2021).

Additionally, there is a need for integrating smart leak detection technologies and IoT-enabled predictive maintenance systems in industrial paint shops. These systems could monitor hose integrity, detect minor leaks in real-time, and predict failure points based on usage patterns and pressure fluctuations (Xu et al., 2022). Embedding these technologies with centralized dashboards would facilitate rapid decision-making and preventive action.

Future research should also explore behavioral interventions and safety leadership training programs aimed at strengthening safety culture. Studies on safety climate indicate that employee behavior is heavily influenced by perceived management commitment to safety and peer compliance (Cooper, 2020). Understanding how to shift these perceptions can lead to sustainable safety improvements across all organizational levels.

Finally, researchers may evaluate the integration of the Bow-Tie method with other risk assessment frameworks like Layer of Protection Analysis (LOPA) or Failure Mode and Effects Analysis (FMEA) to create a more robust, multi-dimensional safety model suited for complex manufacturing environments (Khan & Haddara, 2022).

In conclusion, the Bow-Tie methodology not only provides a detailed view of incident causality and control but also serves as a communication and planning tool for organizational leaders. It helps bridge the gap between technical analysis and management action, fostering a more resilient safety culture and improving long-term risk management strategies.

This research, conducted through a structured Bow-Tie risk analysis of a real-world thinner leak incident in an automotive manufacturing facility, successfully identified critical risk factors and control weaknesses. The implementation of targeted corrective actions significantly reduced the incident's recurrence probability, enhancing operational safety and risk awareness across the organization.

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