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Systematic Framework for Industrial Warehouse Fire Management

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Abstract

Fire is a primary threat to property and human safety in warehouses, and risk management of warehouse fires is challenging due to potential accident causes and various safety measures. Warehouse fires are caused by many factors such as the size of the buildings and the amount of stored combustible material. The size of the buildings andthe volumes of combustible material held result in many of the fires becoming major conflagrations which pose challenges for fire and rescue services and result in significant property losses. Storage fires, like those in fuel storage facilities, can quickly spread to surrounding products, generate a number of secondary fires, resulting in conditions where accidents are uncontrollable, and severely destroy assets. The bowtie analysis approach was used in this paper for the industrial warehouse fire scenario. A generalized framework to manage warehouse fires was then developed followed by a general mitigation measure to control fires at industrial warehouses. A successful fire safety strategy is a thorough fire risk assessment that considers warehouse protection and life safety in compliance with national fire safety legislation. In the interests of developing a successful risk control program, an assessment will identify the fire threats and the potential for property losses and business interruption losses. The assessment shouldconsider the structure of the building and the flammability of the products stored and the mode of storage.

Keywords
Industrial Warehouse, Fire Hazards, Bow-Tie Analysis, Framework, and Mitigation Strategies.

Introduction
With the 20th century of the ever-growing economy and with the vast rapid global trade, the trends of Goods demands, logistics and transportation have witnessed significant increases in a global context. Consequently, storage facilities and warehouses have grown in numbers to meet the demand for goods storage across different industries. Accordingto the data obtained from the US Bureau of Labor Statistics, the number of private warehouses has grown from 15,203in 2008 to 18,182 in 2018(Bureau of Labor 2022). Furthermore, it can be also noticed that the sizes of warehouses arealso increasing as reported in the literature (NFPA na). This increase in both numbers and sizes can be explained by the growing industry demand. Generally, warehouses are defined as designated areas to store and handle materials in the most optimal and planned way according to the logistics of Bearue (18 et al. 2017). Warehouses are categorized using different approaches such as categorization per purpose or by the cargo characteristics. Some examples of warehouse by purpose include wholesale, processing, and retail warehouses. The categorization per the

characteristic of the cargo can include raw material warehouse and refrigerated warehouse. As a focused approach, industrial warehouses will be considered for the purpose of this paper. An intriguing aspect of warehouse managementis the safety of these warehouses. Warehouse safety has gained wide attention over the past decade to overcome the safety challenges that have also arsons with the increase of warehouse space demand. Some of the safety challenges that face the warehouse industry are workload changes, types of goods stored, human error and unsafe working conditions. According to the latest statistics by the Bearue of Labor, over 683 thousand employees working inwarehouse settings have suffered from injuries ranging from mild to severe. The objective of this study was to scope the research on safety wearable technology for construction workers with respect to the following research question: What are the risks associated with fires at industrial warehouses and what is the best approach to manage them?

Objectives

Conduct a suitable fire risk assessment for the industrial warehouse using a Bow-tie analysis approach
Develop a generalized framework to manage fires at the warehouse and proposed strategies.
Propose Mitigation measures to control fires at an industrial warehouse

Literature Review

Several factors and sources were evaluated in the literature as they're considered a crucial part of taking necessary steps against a warehouse fire. First, sources of warehouse fires are considered one of the essential steps in managing them. It's important to take steps to prevent fires in storage warehouses by implementing safety protocols, performing regular maintenance on electrical systems and equipment, properly storing flammable materials, and having an emergency plan in place in case a fire does occur. For that, some important sources need to be considered.

Faulty electrical systems or equipment, overloaded circuits, and electrical shorts can all result in sparks that ignite flammable materials. Deliberate acts of arson can cause fires in warehouses, particularly if the building is unoccupiedor poorly secured (Dragan Živanić 2019). If smoking is allowed on the premises or nearby, discarded cigarettes or matches have been found to be a protentional source of a fire. The presence of flammable materials, such as chemicals, fuels, or packaging materials, can create a fire hazard. This is because of storing flammable materials in an unsafe manner, which can increase the risk of fire. Heating equipment, such as furnaces or space heaters, can start fires if they malfunction or are used improperly. Warehouses with metal roofs or structures are particularly vulnerable to lightning strikes and are prone to causing fires (Dragan Živanić 2019).

Along with, external sources, many internal factors contribute to warehouses, especially the ones meant for storage. The more densely packed the storage area, the greater the potential for a fire to spread quickly and intensely. Ignition sources such as electrical equipment, smoking, and sparks from machinery can all start a fire (Ju 2016). The type of materials stored in the warehouse can greatly impact the occurrence and severity risk of fire. Flammable and combustible materials such as chemicals, fuels, and solvents are particularly hazardous. Moreover, according to the warehouse fire cases reported, poor ventilation can allow heat and smoke to build up, which can make it difficult for firefighters to access and extinguish the fire (Dragan Živanić 2019).

Properly functioning fire detection and suppression systems can help to prevent fires from spreading and minimize damage. The construction and layout of the warehouse can impact the spread of fire, with features such as fire-resistant walls, ceilings, and doors providing additional protection (Dragan Živanić 2019).

The impact of a warehouse fire on a business's profit and loss depends on several factors, including the extent of the damage, insurance coverage, and the business's ability to quickly recover and resume operations (Ju, 2016). If the fire damages or destroys the business's inventory, equipment, or property, the business may suffer a significant financial loss. The cost of repairs, replacement, and cleanup can add up quickly, and the business may need to halt operations until the damage is repaired. If the fire causes the business to temporarily shut down, the business may lose revenue during the downtime. Additionally, the business may have ongoing expenses such as rent, utilities, and payroll that must still be paid during the shutdown. If the business has insurance coverage for fire damage, the impact on the profit and loss may be less severe. However, it's important to note that insurance policies may have deductibles or limits that can impact the amount of compensation the business receives. The massive explosion in the Port of Beirut which is considered one of the biggest non-nuclear explosions to have been recorded, significant damage worth $4.6 billion in material damage. NFPA investigation revealed that the fire that ultimately triggered the explosion was reportedly

sparked by a worker carrying out unpermitted hot work. The case reported of the nightmare warehouse fire that arose in Brooklyn contained damage to the entire property, materials, and vehicles with a suspected cause of smoke near the storage compartments (The New York Times 2022).

A warehouse fire can have a significant impact on the human factor of a business, which refers to the people involved in or affected by the business operations, such as employee morale, customers, suppliers, and the community. A warehouse fire can be a traumatic event for employees, especially if it causes injury or loss of life. Even if no one is hurt, employees may feel shaken by the experience and concerned about their job security. This can lead to decreased morale and productivity, which can impact the business's bottom line. A warehouse fire can pose health and safety risks for employees and the surrounding community. Smoke inhalation, burns, and other injuries can have long-term impacts on individuals' health and well-being. Additionally, the release of hazardous materials can cause environmental damage and pose a risk to public health. A warehouse fire can disrupt the supply chain and cause delays or cancellations of orders, which can impact the business's relationships with customers and suppliers. This can lead to a loss of revenue and damage to the business's reputation (Dragan Živanić 2019)s.

NFPA has created a downloadable warehouse fire safety sheet that provides statistics, safety benchmarks, and best practices for keeping storage structures, contents and occupants safe from harm. The piece was developed following last month's popular NFPA consideration for a warehouse fire webinar for contractors, installers, engineers, facility managers, and code officials.

2. Methods

The methodology approach followed in this paper consists of first using a qualitative risk assessment approach called Bow tie analysis. Followed by a developed generalized framework of warehouse fire management and ending up with generalized mitigation measures for industrial warehouses.

Risk assessment approaches in the workplace have gained widespread attention over the past decades due to the crucial role they play in identifying and eliminating work hazards in the industry. Bow tie analysis is a qualitative risk assessment approach that simplifies complex risk scenarios in an effective way through a graphical representation. The diagram can be divided into two parts, the left part of the diagram draws a clear relationship between the causes of an undesired event and potential preventative measures, and the right side of the diagram represents the consequences and measures to reduce their impact. The bow tie analysis is a combination of the fault tree analysis that focuses on the causes of the event and the left side of the bow tie represents an event analysis that had a more focused approachon the results of the undesired event. The importance of the bow tie analysis in risk analysis lies within its ability to provide a holistic approach in the identification process of the all-risk associated with the event and draws a clear vision ofthe relationship between them.

Furthermore, this approach also draws a connection between the management system that supports the proposed controls. This section of the paper discusses the elements of the bow tie analysis: First the analysis starts by identifying a hazard which is defined as a source that may possibly cause damage or harm to a person, property, or environment. Followed by identifying an element called a top event which is located at the center of the diagram andis defined as an undesirable event such as loss of control of a vessel or collapse of structural design. At the left side of the bow tie, the causality of the top event will be further discussed where the threat is identified at this stage. Threats arethe element that causes the top event to occur. Then preventative barriers are identified to prevent the threat from occurring. In the right side of the bow tie, where it's based on the assumption that the top event has occurred, here consequences are identified which are the chain of events that took place as a result of a release of the top event.
Then recovery mitigation barriers are identified to eliminate and reduced the impact of a possible consequence.
Figure1 shows the schematic flow of the proposed methodology.

Figure 1 . Schematic flow of the proposed methodology

5. Results and Discussion

5.1 Warehouse fire management bow tie analysis

The generated bow tie analysis for this paper was developed using the Salus Bow tie master tool. The hazard identified is Industrial warehouses as indicated in Figure 2 and the top event or the undesirable event is the occurrence of fire at the industrial warehouse identified at the center of the bow in Figure 2. The bow tie analysis is divided into two parts the right and left sides each will be further discussed in detail in reference to Figure 2 Bow tie analysis of the fire scenario at a warehouse.

5.1.1 Threats and Preventative Barriers

The left side of the generated bow tie discusses in detail some of the anticipated threats and the preventative measures.

Table 1 below summarizes some of the major high probability threats that have been found related tothe occurrenc of fire at the warehouse and their preventative Barriers as follows:

Table 1. Summary of the preventative barriers

Threat	**Preventative Barrier #1**	**Preventative Barrier #2**	**Preventative Barrier#3**
Electrical equipment failure	Design of proper insulation as per standards and codes	electrical equipment are in good conditions	Regular maintenance of electrical equipment
Heating issue	Regular maintenance of electrical equipment and AC units	Invest in heat insulators	Use of electrical lights type that doesn't generate heat
Mechanical failure	Trained personnel are authorized to start machines and operations	Regular inspection of mechanical equipment	Proper housekeeping to prevent machinery from malfunctioning

5.1.2 Consequences and Mitigation Barriers

The right side of the generated bow tie discusses in detail some of the consequences and the mitigation measures to reduce the impact of the hazard. Table 2 below summarizes some of the major high probability consequences that have been found related to the occurrence of fire at the warehouse and their mitigation Barriers as follows:

Table 2. Summary of the mitigation barrier

Threat	**Mitigation Barrier #1**	**Mitigation Barrier #2**	**Mitigation Barrier #3**
Electrical equipment failure	Design of proper insulation as per standards and codes	electrical equipment are in good conditions	Regular maintenance of electrical equipment
Heating issue	Regular maintenance of electrical equipment and AC units	Invest in heat insulators	Use of electrical lights type that doesn't generate heat
Mechanical failure	Trained personnel are authorized to start machines and operations	Regular inspection of mechanical equipment	Proper housekeeping to prevent machinery from malfunctioning

Escalating factors and Escalating factors control

In some cases, barriers may have weakness in implantation and hence may reduce the effectiveness of the prevention. Therefore, not only constructing barriers is important, but also understanding points at which theymight fail is also important. This concept is more profoundly known as the escalating factors which basically

serves the purpose of understanding how might the barrier fail. Once escalating factors are identified, escalating factors controls are then established to propose a measure to the failure point of the barrier.
In addition to that, there are two types of barriers which are human behavior and hardware or a combination ofany of the two. This classification provides a more profound and deeper understanding of the barrier's effectiveness. Barriers types include: Human behavior, socio-technical, active hardware, continuous hardware and human behavior.

In addition to that, the Bow-tie tool enables drawing a link between the barriers and the responsible personnel.This enables a more systemic and proactive scheme in terms of criticality and safety measures. Table 3 below shows the escalating factor and escalating factor control alongside the barrier type of the mechanical failure example from the developed bow tie.

Table 3 . The escalating factor and escalating factor control alongside the barrier type of the mechanical failure example from the developed bow tie

Barrier	Barrier Category	Barrier Type	Escalating Factor	Safeguards (escalating factor control	Owner / Responsible personnel
Housekeeping and inspection of mechanical equipment	Preventative	Behavioral Barrier	Failure to perform regular maintenance	Install tracking and monitoring devices on equipment	Warehouse manager

5.2 Graphical Representation

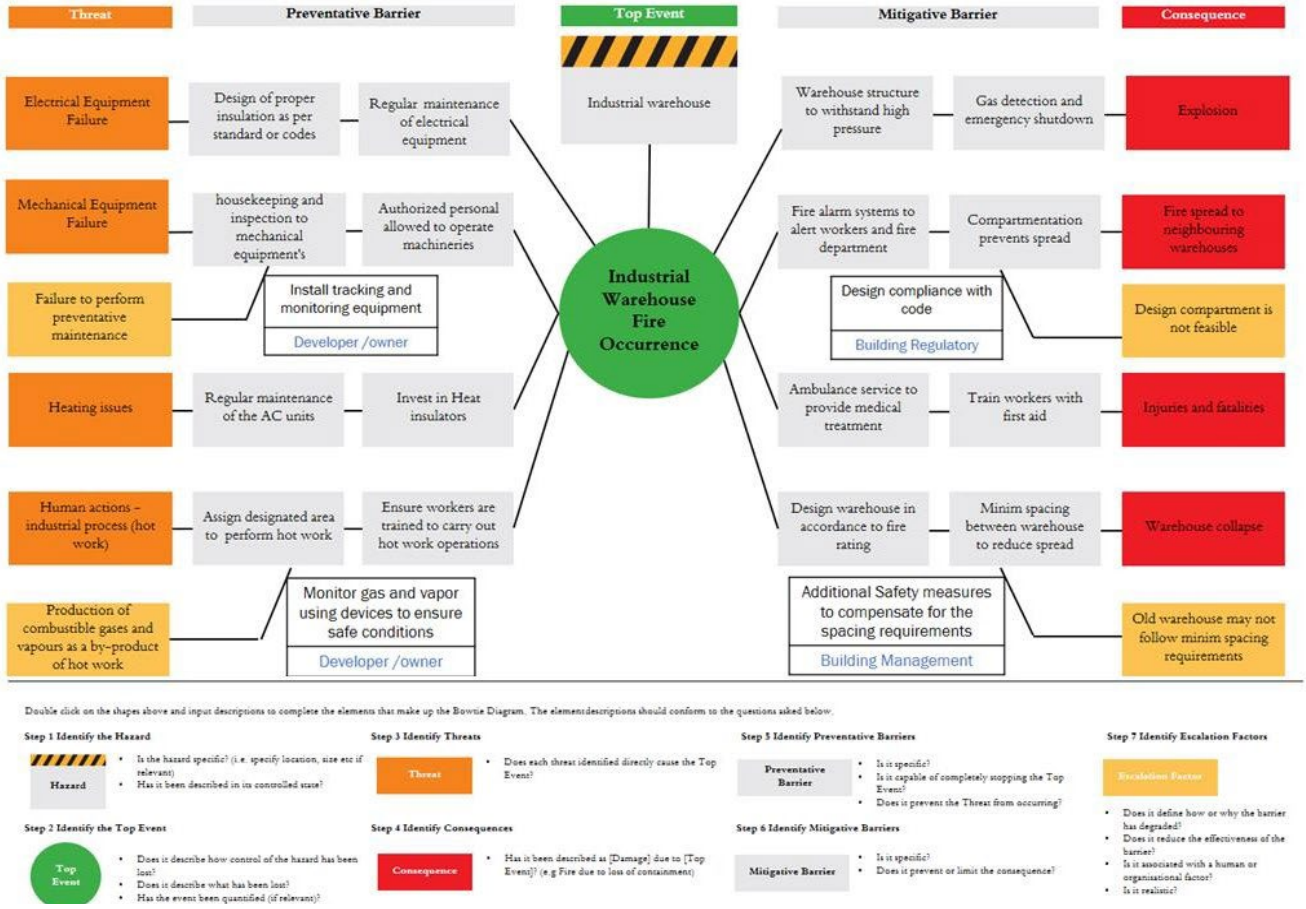

Figure 2 . The developed bow-tie analysis for fire at industrial

5.3 Generalized framework

Developing a comprehensive generalized framework to manage fire hazards was a crucial step in this paper. Figure 3 below shows the developed framework that was generated using the bow-tie analysis approach in an attempt to control fire hazards. The structure of the framework starts from the identification of potential fire hazards at the warehouse. This is considered essential and the ground of the framework as the structure of the framework aims to manage hazards. This framework is designed to systematically identify, assess, analyze and mitigate potentialhazards allowing warehouse owners to proactively protect the assets, operations and workers. Bow-tie analysis provides a more robust approach to anticipating threats and controlling them using preventative and mitigated solutions.The framework in Figure 3 starts first by identifying fire hazards and then moves to construct a bow tie analysis by identifying the two pillars of causes and consequences. Furthermore, evaluating the existing preventative and mitigatedmeasures are considered essential to eliminate any gaps in the system that might result from the current barriers. Forinstance, adding new flammable liquids which can potentially cause a fire if not handled and stored properly, if the preventative barrier was not updated to include this category of chemicals then a gap exists meaning the barrier havevulnerability hence a controlling factor is required to prevent this barrier from occurring. The framework then moves to control measures and ends up with review and monitoring and repeating the process each time a hazard is identified. With this developed framework organizations are able to draw a clear connection between hazards, causes,and consequences and hence enable them to make informed decisions and protect the resources safely.

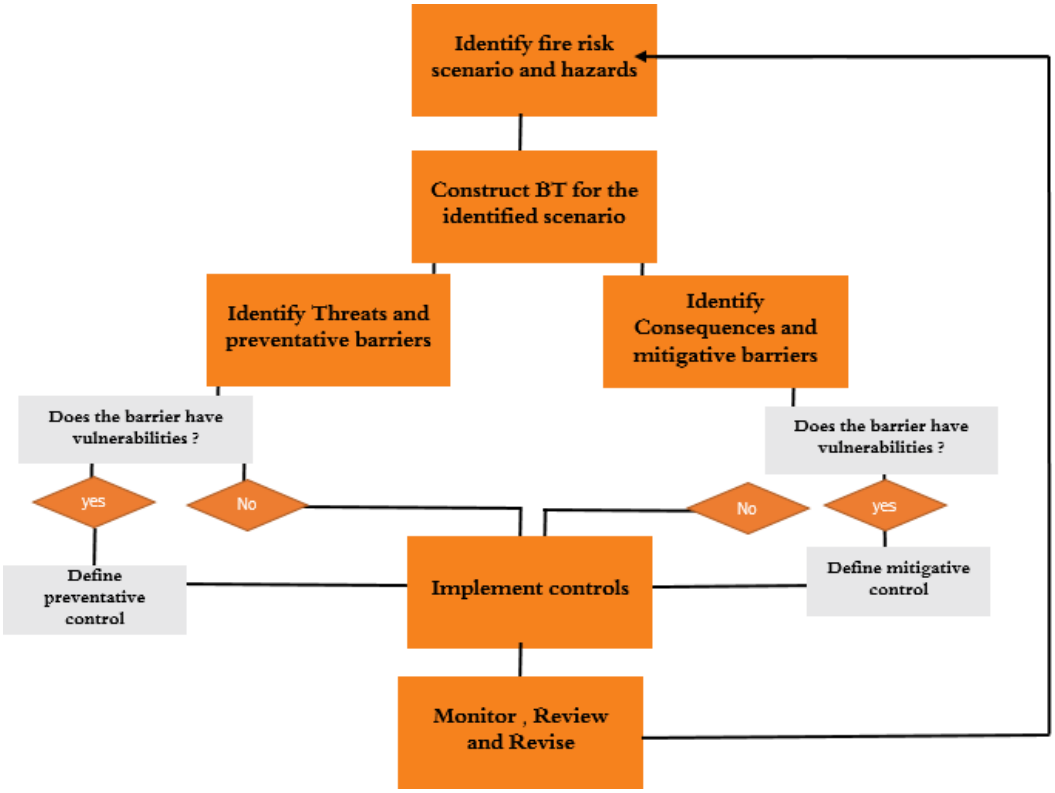

Figure 3. The developed framework that was generated using the bow-tie analysis

6. Discussion

The Bow tie analysis is a qualitative risk assessment methodology that provides a way to effectively communicate complex risk scenarios in an easy-to-understand graphic format and shows the

relationships between the causes of unwanted events and the escalation potential for loss and damage. Bowtie can display the commands, which prevent the Top event from happening primarily, specific to each threat and also the recovery measures that are ready to limit possible effects once the Top event has been accomplished, specific for each credible result.

6.1 Mitigation strategies and fire prevention

Source Control

In the context of a warehouse, there are several mitigation strategies that can be employed to implement source control measures. fire prevention plan should be established and implemented for the warehouse. The plan should identify thefire hazards in the warehouse, the sources of ignition, and the measures to prevent fires from occurring. This can include regular maintenance of electrical equipment, proper storage of flammable materials, and ensuring smoking isprohibited in the warehouse (Lewellyn, 2019). Additionally, the warehouse should be equipped with adequate fire suppression systems, such as automatic sprinklers, fire extinguishers, and smoke detectors. The systems should be regularly inspected, tested, and maintained to ensure their effectiveness.

Proper Ventilation and air distribution

Proper ventilation and air distribution can help prevent the build-up of flammable gases and dust, reduce the risk of spontaneous combustion, and provide a means of escape for occupants in the event of a fire. Many materials stored in warehouses can release flammable gases. Proper ventilation can remove these gases and prevent their build-up, reducing the risk of a fire or explosion. Ventilation can be achieved through natural ventilation, such as open doors and windows, or through mechanical ventilation systems. Some materials stored in warehouses can spontaneously combust due to heat build-up (Manescau, 2020). Proper ventilation can help prevent heat build-up and reduce the risk of spontaneous combustion. Air distribution systems can also be used to circulate cool air throughout the warehouse to prevent the accumulation of heat. In the event of a fire, proper ventilation and air distribution can help control the spread of smoke. Smoke can reduce visibility and hinder evacuation efforts. By directing smoke towards exhaust vents, ventilation systems can help minimize smoke damage and improve the safety of occupants.

Filtration

Filtration can play an important role in warehouse fire prevention by reducing the risk of fire caused by combustible dust. Combustible dust is a fine particulate material that can accumulate on surfaces and can be ignited by a heat source, causing a fire or explosion. Filtration systems can be used to collect and remove dust particles from the air. This can be achieved through the use of air filtration systems that use filters to trap and remove dust particles from theair. Dust collection systems can also be used to capture dust particles at the source of generation, such as during material handling or processing. Filtration systems can help improve air quality by removing pollutants and contaminants from the air. This can help reduce the risk of respiratory illnesses and other health issues associated withpoor air quality.

Air Cleaning Technologies

There are several air cleaning technologies that can be used to prevent warehouse including (Kadribegovic, 2008):
High-Efficiency Particulate Air (HEPA) Filters which can capture fine particles that are typically released during material handling and processing.

Secondly, Electrostatic Precipitators (ESPs) are a prominent technology that can remove fine particles fromthe air using an electrostatic charge. The charged particles are attracted to plates in the system, where they are collected and removed. ESPs can be used in conjunction with other air cleaning technologies to reduce the accumulation of combustible dust.

Ultraviolet Germicidal Irradiation (UVGI) can be used to disinfect air and surfaces by exposing them to UVlight. This can help prevent the growth of bacteria, viruses, and other microorganisms that can contribute tothe accumulation of combustible dust.

Carbon filters can be used to remove volatile organic compounds (VOCs) and other gases from the air. VOCscan be released during material handling and processing and can contribute to the accumulation of combustible dust.

Maintenance and Cleaning

By implementing regular maintenance and cleaning practices, warehouse operators can help reduce the risk of a fire and improve the overall safety of the facility. Regular maintenance of equipment, such as material handling equipmentand electrical systems, can help prevent malfunctions that could lead to a fire. This includes inspecting equipment forwear and tear, replacing damaged components, and testing electrical systems to ensure they are functioning properly.Cleaning of floors, equipment, and surfaces can help prevent the accumulation of combustible materials, including dust, debris, and flammable liquids. This can be done through regular sweeping, mopping, and dusting, as well as theuse of dust collection systems and air cleaning technologies.

Monitoring and Testing

Monitoring and testing can have a significant impact on warehouse fire prevention by helping to identify potential hazards and ensuring that fire prevention systems and equipment are functioning properly. Regular monitoring of thewarehouse can help identify potential fire hazards before they become a problem. This can include monitoring equipment for wear and tear, identifying potential ignition sources, and checking storage areas for improperly storedflammable materials. Moreover, this can help ensure that the warehouse is in compliance with fire safety regulationsand standards. This can include monitoring compliance with building codes, safety regulations, and industry-specific standards, as well as implementing best practices for fire prevention.

Proposed Future work

The bow tie analysis provides a simplified and robust approach to managing hazards. Limited studies in the literature were found on industrial facilities application hence collaborative work on utilizing this powerful technique in firecases from an industry perspective is highly needed to provide a systematic approach and promote safety culture.

Conclusion

In conclusion, the bow tie analysis approach is a powerful tool that gives a holistic approach to present a hazard assessment integrated with anticipated threats and potential consequences with their barriers and safety controls. In this study, the bow-tie analysis was used to assess the fire at warehouse scenario followed by a generalized framework that provides a systematic approach to fire hazards in warehouses. Finally, a generalized mitigation measure to controlfire at the warehouse was further discussed. This technique has proved its effectiveness in many applications. Althoughcase scenarios of fire are limited in literature, a more optimistic view on using this approach to control fire in industrial facilities is proposed.

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Biography

Areej Bin Amro is a Quality Health Safety and Environment engineer. Currently pursuing a master's degree in engineering in health science and environment at the industrial engineering department at Khalaf University. She has published a conference paper at the IEOM conference that was awarded as the best track paper. Areej has completed a research project with the Brain science institute and Riken CBS Toyota collaboration center. Her research of interest includes safety systems, human factors, environmental studies and optimizations. She is a member of the emirates nature WWF youth council and MIT boot camps, alumni.

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