Proceedings of the 33rd European Safety and Reliability Conference (ESREL 2023)
Edited by Mário P. Brito, Terje Aven, Piero Baraldi, Marko Čepin and Enrico Zio
 Published by Research Publishing, Singapore.
doi: 10.3850/978-981-18-8071-1_P436-cd

Response to Risks in Fuel, oil, and chemicals storage facilities aiming at Improving Reliability Using Success Tree Analysis – A Case Study

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Currently, most remote and isolated communities depend on the Reliability of fuel, oil, and chemical storage facilities. The size and complexity of storage facilities plants and the nature of the products handled means that analysis and control of the risks involved are required. Statistics show that the reduction in process accidents and the losses from major accidents in the oil and gas processing and storage industry have not decreased over the years. Current risk approaches in storage tanks emphasize improving the Reliability of the design rather than maintaining safe operation. In the last European Congress for Reliability and Safety held in 2022 in Dublin, the authors presented a method for improving Reliability by conducting risk assessment in the daily operation of chemical, fuel, and oil storage facilities plants based on a combination of PFMEA and BBN. The method allows sensitivity analysis and prioritization of preventive and corrective measures to minimize the probability of failure to maintain a safe operation. This study complements the one presented in Esrel 2022 and focuses specifically on the method for implementing the actions to address the high-scoring risks. As a result, the study shows how to vanquish the stakeholder's resistance to change to address the most significant risks in the process and improve the storage system's Reliability. The conclusion is that effective implementation of response actions can be effectively made based on the proposed implementation method. The contribution is significant since the proposed method allows process optimization and risk reduction in the storage of chemical products and permits decision-makers to assign funds for critical activities to implement actions that can impact the safety of the process and system reliability. The present study augments the knowledge of the process, maintenance, and safety engineers/managers and helps process improvement. It can impact the company's PFMEA and management of change processes and help understand performance and safety during fuel storage operations. Although conducted in a specific fuel storage facility, it can be generalized to other industries and fields of work whose safety is affected by change issues resulting in waste, rework, and unnecessary energy consumption. The study can change the practice and thoughts of professionals dealing with PFMEA in companies' operations.

Keywords: Risk assessment, BBN, PFMEA, Reliability, chemical storage facilities

1. Introduction

Consuming fuel, oil, chemical products, and infrastructures has brought substantial economic benefits. In contrast, storage brings exposure to hazards caused by hazardous materials, resulting in human losses, environmental damage, and substantial economic losses.

Chen et al. (2019) stated that significant hazards such as fire, explosion, and toxic release arising from loss of containments might occur due to intentional or unintentional causes.

Studies by Reniers and Cozzani et al. (2013) and Khan et al. (2015) show that the past years have witnessed an increase in the number, size, and diversity of chemical plants due to the increasing population and the increasing requirement for products (energy, chemicals, commodities, and food.

Serious accidents may result when risks are not identified and treated adequately. No previous work has addressed which operational risks interfere in executing product loading and storage effectively using PFMEA and BBN to prioritize these risks.

This study proposes a new method for risk assessment in the daily operation of chemical, fuel, and oil storage facility plants based on a combination of PFMEA and BBN. The method allows sensitivity analysis and prioritization of preventive and corrective measures to minimize the probability of failure to maintain a safe operation. This topic is significant because product loading and storage failure may lead to accidents. If risks are not identified and adequate responses are not provided, catastrophic accidents can happen. The work in question is unique when analyzing operational risks in product loading and storage with PFMEA and BBN methods since there is a gap in the literature regarding this subject. PFMEA is a tool used to assess and identify potential failures related to operational processes. Possible failure modes refer to weaknesses resulting in productivity, quality, and safety hindrances. The letter P, the acronym, stands for the process. A study was conducted in a fuel loading and storage facility to identify gaps and opportunities to improve risk management, safety, and quality. The study aims to respond to the following research questions:

Research Question 1: What risks are present in the studied fuel loading and storage facility?

Research Question 2: How to prioritize the risks using PFMEA and BBN?

Research Question 3: How to implement risk responses using Success Tree Analysis?

The study is structured as follows: Section 2 covers Literature Review, presenting previous studies on Risk Assessment in fuel, oil, and chemicals storage facilities and PFMEA and BBN and Reliability, section 3 addresses Methodology. Section 4 shows the results. Section 5 discusses the results, and section 6 the conclusion.

2. Literature Review

2.1 Risk Assessment in fuel, oil, and chemicals storage facilities

Rigas and Sklavounos (2005) highlighted common hazards from hydrogen storage and distribution systems and revealed potential accidents that hydrogen may produce under certain conditions. In this study, the Hazard analysis performed was based on the Event Tree Analysis Method and examined the outcomes of an accidental hydrogen release.

Jackson's (2006) study presented a model that predicted product concentrations downwind from the sources below tolerable concentrations by WHO and US-OSHA. The highest 24 hours of benzene concentration was used to assess the maximum carcinogenic risk amongst the population exposed downwind. The author presents a method for risk analysis in chemical and allied industries based on (HAZOP) and quantitative analysis of the most relevant risks by developing fault trees analysis (FTA). FTA results allow prioritizing the preventive and corrective measures to minimize the probability of failure.

Landucci et al. (2017) used a probabilistic risk analysis approach supported by a model based on Bayesian Networks to address the quantitative assessment of the attack likelihood and to incorporate the functional analysis of physical protection systems (PPS) applied to the security of Process and storage installations.

Villa et al. (2016) analyzed risk assessment progress during the last decades to offer an overview of its recent developments and possible future direction for chemical and process industries. The study concluded that the general approach of Quantitative Risk Assessment (QRA) has been unchanged since its origin in the early 1980s. It remarked that QRA has continuously evolved in different forms. Its application areas have enlarged meaningfully beyond process safety, where it has traditionally been developed and used for chemical industries. Moradi & Groth (2022) explored how to systematically draw together the advances in PHM and PRA to provide a more forward-looking, model- and data-driven approach for assessing and predicting the risks.

Malviya and Rushaid (2018) modeled the calculation or estimation of numerical values (or graphical representation) that describe the credible physical outcomes of loss of containment scenarios involving f1ammable explosives and toxic materials concerning their impact on people's assets or safety functions. The study points out the need to risk assessment and consequence modeling of process plants and hazardous storage facilities. It has become critical due to the trend towards more extensive and more complex units that process toxic, flammable, and otherwise hazardous chemicals under extreme temperature and pressure conditions. Vilchez et al. (1995) made a historical analysis of accidents in chemical plants and hazardous materials transportation. Fuentes-Bargues et al. (2017) conducted a fuel storage terminal risk analysis using HAZOP and FTA.

2.2 PFMEA, BBN, and Reliability

Mkrtchyan et al. (2022) studied the risk profile of refineries from an insurers' perspective. A top-down approach is employed to derive key performance indicators (KPIs) for two events historically known as leading causes of significant accidents in refineries, i.e., fire and vapor cloud explosion. Bayesian Belief Networks (BBNs) are used to develop a probabilistic model for measuring risk indication of refineries for fire and explosion events via a planned approach to elicit and synthesize available knowledge from domain experts. Hassan (2022) proposed a new approach, called the modified PFMEA, by integrating the noted benefits of hybrid PFMEA with Fuzzy Rule Base (FRB) and PFMEA with Grey Relations Theory (GRT) in order to overcome the identified drawbacks. The study utilized both the fuzzy and the grey theory to include experts' diverse opinions and to assign a relative weight to each assessment factor in the risk assessment. Rey et al. (2017) stated that Fuzzy rule-based systems (FRBs) are a common alternative for applying fuzzy logic in different areas and real-world problems. Fuzzy rule-based systems (FRBs) are models based on fuzzy sets that express knowledge in a set of fuzzy rules to address complex real-world problems. The concepts are popular because FRBSs allow coping with uncertainty, imprecision, and nonlinearity.

Patil et al. (2019) stated that Grey Relation analysis is applied between known and unknown information, which is Grey. Condition with clearly defined information is named as white and no information as black, in between as Grey. The grey theory is applied in various filed, including manufacturing, process, and service operations. Saeid et al. (2022) used Bayesian Network on an ammonia storage unit in a fertilizers production plant. Root Cause Analysis (RCA) was used to identify all the failure modes which could result in an undesirable incident. Wang et al. (2021) study concluded that failure mode and effects analysis (PFMEA) is a powerful analysis method in risk evaluation. It states that the assessment results may not be sufficiently accurate due to the uncertainty in the risk analysis process. The study used the cloud model (CM) to reduce the uncertainty, especially randomness and fuzziness, in the evaluation process to improve the PFMEA. Aswin et al. (2022) proposed a method for better decision-making and developing the maintenance strategies for complex systems by comparing the results of Fuzzy-FMECA and grey theory results. In this analysis, failure modes were identified, and the fuzzy logic was used to prioritize them using linguistic terms and an if-then rule-based system in Matlab fuzzy toolbox. Bendib et al. (2021) presented a risk assessment methodology implemented based on integrating two methods, D-HIGRAPH and HAZOP. The approach was applied to the LPG storage Area in the SKIKDA refinery (the most critical refinery in Algeria). Several recommendations were raised from the study to improve plant safety.

2.3 Success Tree Analysis

Fault tree analysis is a well-known method to quantify dependability parameters such as Reliability and safety. The top event in a fault tree is a system failure event, and the primary inputs of the tree are events that cause a system failure. Success tree analysis uses the exact representation of the system as fault trees. However, the top event is system success, and the primary inputs of the tree are those leading to system success.

Ring and Courts (2001) examined the suitability of the goal tree-success tree (GTST) technique to consider the design and production process systematically and thus to provide feedback on producibility requirements into the initial design phase. Weber, F. (2019) outlined how a study assistant can implement functionalities derived from research about goal-setting and self-regulation. Johnson (2013) and Wild (2005) combined success trees and fault trees to properly define goals and possible problems in the aviation and telecommunication fields.

3. Method

3.1. Selecting the Population and Sample

The study adopted the approach of building theory from Case Study Research (Eisenhardt, 1898) and Hancock et al. (2021). It combined data from archives, interviews, and observations in fuel storage facilities with different storage and operation capabilities. The sample for the study was the process of receiving and storing fuel in typical storage facilities in Brazil. The author provides maintenance services to such facilities and is knowledgeable about the process.
The number of site stakeholders participating in the study is listed in Table 1. These stakeholders were selected based on their expertise in a specific domain. The sample size is appropriate and significant since all the studied areas are covered.

Table 1 - Stakeholders participating in the study

Area	Function	Number participants	Time of experience (years)
Engineering	Maintenance Engineer	1	10
Quality	Quality Engineer	1	35
Operation	Product Receiving Inspector	1	5
Operation	Product Supplier representative	1	5
Operation	Safety Engineer	1	5

3.2. Using Instruments and Tools

A detailed process map of receiving and storing products was prepared to understand the process variables. A macro flow diagram was prepared to show the unloading, storage, and loading for product distribution (fuel, oil, or chemicals). The boundary for the analysis was defined, and a microflow diagram was prepared for specific process purposes.

3.3. Data Collection

The most critical step in the high-level process flow diagram was identified, and it was broken down into detailed level process diagram steps.
Then, each failure mode's potential effect impact) on both internal e external customers were identified.
The potential cause of each failure mode was analyzed based on how often (probability) the failure could occur and it could be detected (detection). The rating for impact, probability, and detectability was assigned, and the RPN was calculated. Data to implement the Success Tree Analysis was obtained from the stakeholders.

3.4. Data Analysis & Actions

The operation process was mapped out with the help of process stakeholders, and an in-depth literature review on storage facilities was conducted to identify risk factors. PFMEA was conducted in storage tanks operation, focusing on the most critical process step in the high-level process flow diagram. BBN combines the potential failure modes leading to an accident (fire and explosion), allowing a sensitivity analysis to identify the most critical mode. The risk responses were defined, and a success tree was created to organize the implementation.

4. Results

4.1 Operation Process Map

The studied plant is divided into three systems (Figure 1), corresponding to unloading, storage, and loading for distribution.

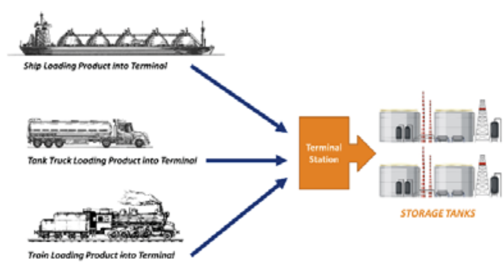


Figure 1 – Activities of Plant

The macro flow diagram prepared to show the unloading, storage, and loading for the distribution of the product (fuel, oil, or chemicals) is shown in Figure 2.

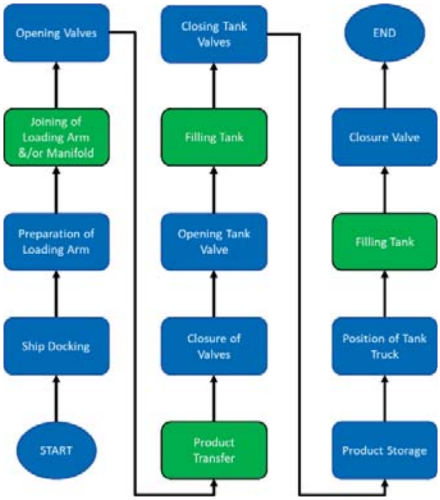


Figure 2 – Macro Flow Diagram

The stakeholders detailed the step marked in green, and the activities are shown in Figure 3.

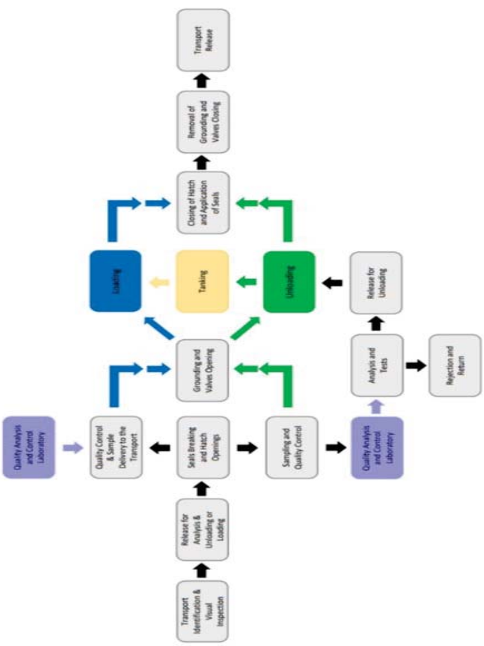
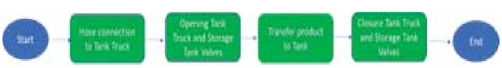


Figure 3 – Activities of loading and unloading

Usually, through an identification system, a security policy releases the transport vehicle and its driver. Driver and vehicle documentation are compared with the tracking and identification system information. The responsible operator for release and access inspects the general condition of the transport vehicle and checks the existence and use of mandatory personal protective equipment. If there is any divergence in the previous steps, the system generates a Non-Conformity (NC), informs the respective driver, and indicates the procedure to be adopted. With access authorization and inspection approval, the vehicle and its driver are directed to the internal waiting space, awaiting information from the system and responsible personnel, designating which platform and appropriate bay to go to. The driver awaits procedure instructions with the tank truck stopped and turned off. As soon as the unloading bay is vacant, the driver positions the vehicle in the analysis and unloading bay. The correct positioning is verified by a tracking system (RFID). If this vehicle is wrongly positioned, the system will correct itself, generating a visual alert on the electronic panel (PE) and a Non-Conformity (NC). The driver waits for the procedure instruction with the truck stopped and turned off. With the vehicle parked in the bay and identified, labels are printed to be attached to the product samples. The platform operator inspects, then breaks and collects the top and bottom seals on the vehicle and opens the hatches. This same operator collects product samples (s), labels the samples, and sends them to the product quality analysis and control room. When loading, as soon as the loading bay is vacant, the driver positions the vehicle in the intended bay, where he receives samples of the product being loaded. The other processes occur precisely the same way as when unloading. Before starting both loading and unloading, the vehicle driver or platform operator connects the ground, connects the unloading hoses, opens the manual valves at the bottom of the vehicle, and enables the start of unloading with the local button. The "SKID" control checks grounding and selects and opens the valve according to the product. When the very low deaerator tank level (SKID) is reached on unloading, the system shuts down the pump. For loading, the system turns off the pump to reach the high level of the deaerator tank level (SKID). The driver or platform operator closes off the vehicle tank inlets and outlets, disconnects and tidies up hoses and grounding, and seals vehicle hatches. The vehicle driver heads to the exit gate, being tracked (RFID). The supervisory system sends a command to issue the unloading receipt to the driver, who will return the TAG received at the entrance. The gate will then be opened, indicating, through a visual signal, the release of the vehicle from the terminal. For vehicles being loaded, a receipt for the loaded product is issued.

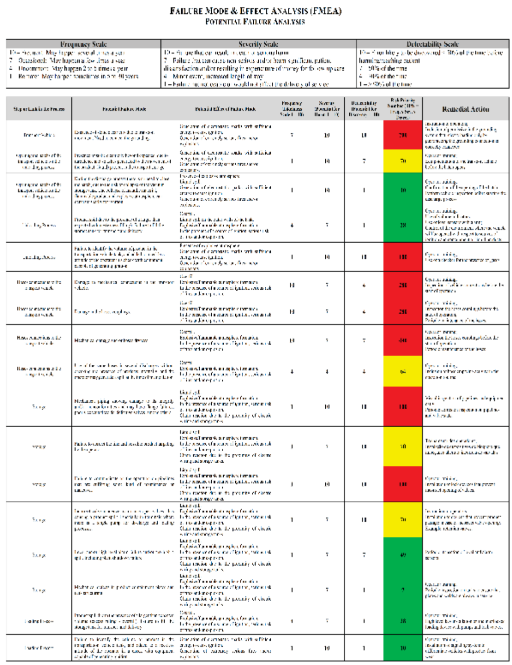
During unloading, all vehicles have the product quality monitored online by instruments, with all information stored in a database. The vehicle with the out-of-specification product will be refused and returned to the Shippers. The adequate amount unloaded from the vehicle will be considered and calculated through the volumetric meter installed in the SKID. In case of system failure, the amount will be determined by the tonnage arrow of the vehicle's tank, to be compared with the volume contained in the Invoice accompanying the same. This balance made between the volume calculated through the volumetric meter and the one indicated in the Invoice cannot present a difference more significant than 0.5% (half percent). If a more significant difference exists, an Anomaly Report is issued to the Shippers for the necessary measures. Suppose the terminal/base system has road weighing scales. In that case, both unloading and loading can be confirmed and verified through proper weighing at the terminal's entrance and on the respective platform, both for unloading and loading. The boundary for the analysis was defined, and a microflow diagram was prepared for the most critical step in the macro flow, which is the tank filling. The microflow is shown in Figure 4.



4.2 PFMEA for Storage Tanks Operation

The failure modes identified in the detailed level process diagram steps were defined based on Fuentes-Bargues et al. (2017) study. The potential effect (impact) of each failure mode on internal e external customers is identified and recorded in the PFMEA worksheet shown in Table 2. The potential cause of each failure mode was analyzed based on how often (probability) the failure could occur and how it could be detected (detection). The information was also recorded in the worksheet. The impact, probability, and detectability ratings were assigned, and the RPN was calculated and recorded in the same worksheet.

Table 2 – PFMEA worksheet



The risks with high RPN (above 320) are marked in red, the medium RPN (80-240) in yellow, and the lower RPN (8-40) are marked in green. The following steps from the microflow diagram were analyzed in-depth for failure mode based on Fuentes-Bargues et al. (2017) study: Opening Tank Truck and Storage Tank Valves, Hose connection to Tank Truck, and transferring the product to the tank. The potential effects of the failure modes (detailed in the PFMEA worksheet) were identified were: more level than expected (overfill) due to a faulty level sensor (high score risk – red), Incorrect valve setting, and failure to recognize problems. Accumulation of static electricity due to liquid projected by jet (high score risk – red). Liquid enters the tank being filled. The movement of liquid in the tank causes turbulence and splashing. Product over Flow. The spill of liquid on the external tank walls. Creation of an inflammable atmosphere as fuel hits the floor. If a source of ignition exists, there is a severe risk of explosion and pool fire with a chain reaction to affect nearby tanks. The production of electrostatic charge with sufficient energy to cause ignition is the generation of severe fires and explosions. The remedial actions should be Training employees. Level sensors periodical inspection. Maintenance of state of all valves. Use of automatic level alarms. Use of volume indicators. Spill containment with a capacity greater than the tanks. Use the filling tube consistently below the liquid surface. Flow should be reduced. Ensure fluids slide along the walls of tanks. Ensure the speed of fluid should not exceed 7 m/s. Ensure air humidity should is around 60%.

4.3 BBN and Sensitivity Analysis

BBN can combine the potential failure modes leading to an accident (fire and explosion), allowing a sensitivity analysis to identify the most critical failure mode. Figure 5 shows the BBN and the combination of failure modes. The risk factors obtained with PFMEA can be combined using BBN, which allows a sensitivity analysis and process safety improvement by focusing on the most critical operational aspects.

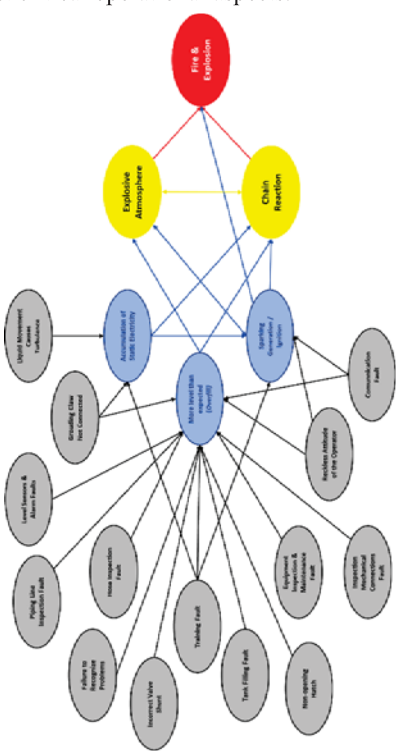


Figure 5 – BBN combining Failure modes

The proposed method revealed some interesting results that may help to overcome some of the above-described problems. It offers a set of evaluation parameters and makes the decision-makers more aware of the impact and probability of the high-scoring risks. PFMEA provides the risk scores for the risks. As explained in the introduction and literature review, PFMEA has gained momentum in the industry in recent years. Several papers have been published addressing the use of PFMEA in different domains, such as maintenance strategy, selection of industrial machinery safety devices, and risk assessment. The target of the study was to propose a method to prioritize the risks in the loading and storage of products and provide responses to these risks that could affect operational safety and sustainability. Safety is a fundamental resource for the industry, especially in storing chemical products. The results found using the method developed in this study support the results found in the literature review. They contribute by showing that the most critical risks in the loading and storage of products should be ordered based on their probability of detectability and severity and consider the nature of these risks. Thus, risks with high scores have a higher chance of generating a failure and should be prioritized. The model can help load and storage facilities better understand how to prioritize the allocation of resources to treat operational risks in loading and storing products (fuel, oil, and chemicals).

4.3 Success Tree Analysis

The Safe Operation of chemical storage facilities can be attained by implementing the actions defined in the success tree for the responses defined in PFMEA.

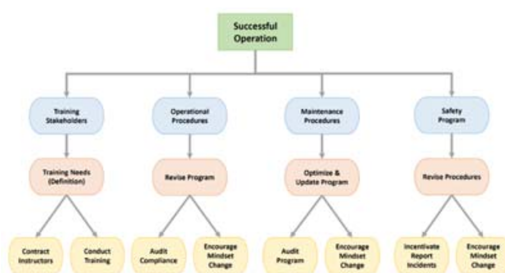


Figure 6 – Success Goal Tree

5. Conclusion

This study contributes to other researchers' previous findings since most did not cover a quantitative approach using PFMEA and BBN in risk assessment of loading and storage of products. This paper aimed to fill this gap by proposing a method to apply PFMEA and BBN to prioritize risks in the storage of products (fuel, oil, and chemicals) which can be attained by implementing success tree analysis. The implications are relevant since the operational process can be conducted more safely when adopting the proposed method. The study was conducted based on the experience and knowledge of the main stakeholders on the subject. Changing how risk is prioritized encompasses changes in human behavior, work patterns, and values in response to risks anticipating strategic, resource, or technology changes. The proposed method is essential for several reasons. First, risk assessment using PFMEA is gaining importance in the industry. Second, this study combines the PFMEA and BBN approaches and considers the risk of product loading and storage as decision-making criteria. Third, the paper shows that the risk factors identified in this study must be controlled to avoid critical parts failure.

The probability and impact of risks associated with product loading and storage are predicted quantitatively, and preventive actions are defined to minimize the downtime of the product loading and storage process. In response to the first research question, *"What risks are present in the studied fuel loading and storage facility?"* The risks identified in the literature review and in the study were listed in the PFMEA worksheet. The worksheet shows the risks and their respective prioritization. In response to the Second Research Question, *"How to prioritize the risks using PFMEA and (BBN)?"*. The risks were prioritized by their score value, and the scores were obtained by multiplying the probability, impact, and detectability. In response to the Third Research Question, "How to implement risk responses using Success Tree Analysis??" The PFMEA worksheet provided detailed response actions for each failure mode, and a success tree was used to organize the answers and defines a visual representation of the required responses, thus describing the operation mode with minimal risks and the implementation of change in organizational culture and stakeholder mentality.

In conclusion, this paper conceptualizes and demonstrates a new method illustrated with an example of application on product loading and storage. The proposed new risk assessment method is key to identifying the most significant risks impacting product loading and storage and opening up new research avenues for the future that can be applied similarly in different industries.

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