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Abstract

The paper analyzes the ways in which artificial intelligence (IA) monitoring of fuel storage and warehousing activities can contribute to reducing the likelihood of hazardous events. By integrating smart surveillance technologies, predictive analytics, and automatic anomaly detection, risks can be identified in real time and prompt corrective measures can be implemented. The study highlights the benefits of using AI in increasing operational safety, reducing human error, and optimizing logistics processes in the energy sector, with a focus on preventing incidents with major potential.

Keywords

Prevention of work accidents; fuel depots; HIRA; artificial intelligence monitoring.

I. Introduction

Fuel storage and warehousing facilities are critical infrastructures within the energy supply chain. They ensure the safe handling, preservation, and distribution of highly flammable and potentially explosive materials. However, these environments are also characterized by elevated risks of fire, explosion, leakage, and occupational accidents resulting from both human and technical factors. The complexity of operations, coupled with the variability of human behavior and environmental conditions, significantly increases the probability of incident occurrence.

Traditional safety management systems, based on periodic inspections, manual reporting, and static risk assessments, are often insufficient to detect early deviations or weak signals that precede accidents. As industries transition towards digitalization and Industry 4.0 paradigms, there is a growing need for real-time monitoring, predictive analytics, and proactive intervention strategies to enhance operational safety.

Artificial Intelligence (AI) technologies, particularly machine learning (ML), computer vision, and anomaly detection algorithms, have emerged as transformative tools in this context. When integrated with sensor networks, video analytics, and industrial Internet of Things (IoT) architectures, AI systems can continuously analyze data streams, identify unsafe behaviors, detect abnormal process conditions, and generate early warnings before a critical event unfolds.

This paper investigates how AI-based monitoring systems can reduce the likelihood of hazardous events in fuel storage and warehousing environments. The study focuses on developing a proactive hazard analysis for monitoring workers' activities, equipment status, and environmental parameters, with the aim of detecting deviations that could lead to ignition sources, vapor emissions, or human errors.

The HIRA method (Hazard Identification and Risk Assessment) is one of the most widely used modern techniques for identifying and assessing risks in industrial environments. It represents one of the most effective practical approaches and is increasingly adopted by companies operating in high-risk sectors. When implemented correctly, it allows hazards to be identified as early as the operational planning stage, enabling the adoption of appropriate control measures.

II. Presentation of the HIRA Concept

Fuel depots are exposed to a wide range of hazards: from flammable substance leaks and toxic vapor emissions to operational errors, equipment failures, extreme weather conditions, or acts of negligence. By applying the HIRA method, critical scenarios can be analysed, risks associated with each activity (loading, unloading, maintenance, inspections) can be quantified, and rapid intervention or risk elimination measures can be planned from the design phase of the operation [1,2].

The application of the HIRA method can be elevated by integrating it with artificial intelligence systems and industrial sensors (IoT). Data collected in the field (temperatures, pressures, emissions) can be automatically correlated with operational plans and weather forecasts using AI. Thus, the HIRA matrix becomes a dynamic tool that is constantly updated, allowing preventive measures to be adapted in real time.

The risks associated with industrial activities in fuel depots are considerable, especially during loading and unloading operations. The accumulation of flammable vapours or toxic gases, as well as human errors such as incorrect hose coupling, can lead to explosions, fires, or severe intoxications. Modern technologies, especially mobile robotics and artificial intelligence (AI), offer real opportunities to transform the safety paradigm in these environments, shifting from reactive prevention to proactive prevention.

HIRA (Hazard Identification and Risk Assessment) is a systematic method used to identify hazards and assess the risks associated with activities carried out within an organization. It is an integral part of the Occupational Health and Safety Management System (OHSMS) and serves as the foundation for decision-making processes related to accident prevention and improved working conditions. The method is applicable across all industrial sectors and is compatible with international standards such as ISO 45001:2018 [3,4].

The HIRA method involves the following steps:

1. Hazard Identification. Analysing activities, processes, and equipment to detect any potential source of harm.
2. Determining Consequences. Establishing the possible effects of each identified hazard (e.g., accident, fire, poisoning, material damage, etc.).
3. Severity Assessment (S). Evaluating the seriousness of the consequences.
4. Likelihood Estimation (L). Assessing the frequency or chance of the hazard occurring.
5. Risk Calculation (R = S x L). Obtaining a risk score to prioritize interventions.
6. Establishing Control Measures. Measures may include elimination, substitution, isolation, technical or organizational controls, or personal protective equipment (PPE).
7. Monitoring and Review. Reassessing risks periodically or when processes/installations change.

The risk interpretation grid (R = S x L) is structured as follows:

- 1–4: Low risk – Acceptable. Current measures are maintained.
- 5–9: Moderate risk – Improvements needed; measures should be scheduled.
- 10–15: High risk – Immediate action required.
- 16–25: Unacceptable risk – Activity must be suspended until controls are implemented.

The HIRA method is one of the most comprehensive and versatile tools used in modern occupational health and safety management systems. Through its structured approach to identifying and assessing risks, HIRA plays a crucial role in protecting employees, optimizing technological processes, and ensuring organizational compliance with current legal requirements. When applied correctly and supported by continuous staff training, digital tools, and regular assessment reviews, HIRA becomes a dynamic, adaptable, and indispensable mechanism in any effective workplace accident prevention strategy.

For organizations in high-risk sectors, such as fuel storage and transportation, implementing the HIRA methodology is not just a recommendation, it is a necessity for reducing human, material, and reputational losses.

The HIRA risk assessment matrix combines two essential dimensions: the Severity (S) of possible consequences and the Likelihood (L) of an event occurring. Each cell in the matrix corresponds to a risk level, helping prioritize preventive actions. HIRA is recognized for its systematic nature and cross-sector applicability, making it a fundamental tool in modern prevention strategies. One of its main advantages lies in its ability to anticipate hazards before they result in unwanted events. Table 1 presents the main results of applying the HIRA method in fuel depots [5].

Table 1. Application of the HIRA Method in Fuel Depots

1	2	3	4	5	6	7	8	9	10
Activity	**Risk / Hazard**	**Consequence**	**S**	**L**	**Initial Risk**	**Preventive Measures**	**S**	**L**	**Residual Risk**
A-1: Fall from height	Climbing onto fuel truck tanks	Electrocution, serious injuries – death	5	2	MED	Installation of protective guardrails. Equipping workers with electrostatic personal protective equipment (PPE). Periodic inspection of equipment used for working at heights. Electrical power shutdown.	5	1	MED
A-2: Accumulation of flammable and toxic vapors	Explosion, acute poisoning and/or chemical burns	Death, explosion, chemical burns, serious injuries	5	3	HIGH	Signalling the danger of explosion, electrical hazard, and poisoning. Equipping with sensors for detecting flammable or toxic vapors. Inspection of valves, taps, and other sealing elements.	5	1	MED
A-3: Overfilling or exceeding maximum pressure limits	Explosion or acute poisoning	Death, explosion, chemical burns, serious injuries	5	3	HIGH	Equipping with sensors for detecting leaks and hazardous vapors. Regular verification of existing operating parameters against the values indicated by manometers and sensors.	5	1	MED
A-4: Human errors / non-compliance with work procedures	Incorrect hose connections and/or failure to ground	Explosion, fuel leaks causing chemical burns or poisoning	5	3	HIGH	Training workers on work procedures and specific occupational safety and emergency instructions. Clear marking of connection elements using different colors or signs. Equipping workers with appropriate electrostatic and waterproof personal protective equipment (PPE), according to the PPE allocation list.	5	1	MED
	Welding, maintenance, electrical inspections	Explosion, chemical burns, or acute poisoning	5	3	HIGH	Ensuring through control and supervision that maintenance teams carry out work with authorized personnel, following work procedures and wearing appropriate personal protective equipment (PPE).	5	1	MED
	Working in confined spaces with insufficient ventilation	Asphyxiation – death – acute poisoning, chemical burns	5	2	MED	Training workers on working in isolation conditions. Establishing a communication procedure with another person at least every 10 minutes.	4	1	LOW
A-5: Omissions	Failure to use PPE	Serious injuries	5	3	HIGH	Training workers on the importance and correct methods of using, storing, and inspecting personal protective equipment (PPE). Inspecting and sanctioning workers who do not wear PPE or do not use collective protection equipment (CPE)..	5	1	MED
A-6: Waste disposal	Soil contamination with hazardous substances	Pollution	3	3	MED	Use of selective waste collection bins. Training workers on types of waste, methods of collection, and how to differentiate between regular and contaminated waste.	2	1	LOW

In the context of analysing workplace accidents in the fuel storage and distribution sector, the application of the HIRA methodology (Hazard Identification and Risk Assessment) proves to be a fundamental tool for preventing and reducing occupational risks. Both from the theoretical perspectives presented in the HIRA assessment and from the examination of documented real incidents, several key conclusions emerge regarding the usefulness and effectiveness of this concept in practice:

- It enables a systematic approach to hazard identification.
- It provides a realistic framework for prioritizing interventions.
- Many of the reported accidents, especially those of human origin, such as failure to use personal protective equipment, incorrect handling of tank wagons, or lack of training, can be anticipated and prevented [6].

The HIRA method gains additional value when complemented by detection technologies, such as robots with emission sensors, thermal cameras, SCADA systems, and predictive analysis software. Correlating this data with the HIRA assessment allows not only for preventive diagnostics but also for a rapid and precise response in case of an incident. This significantly reduces the likelihood of major accidents occurring or escalating

III. Application of AI in Accident Prevention in Fuel Depots

As the complexity of operations in fuel depots increases, the use of advanced technologies becomes essential to ensure a safe, predictable working environment. Artificial Intelligence (AI) offers highly useful tools for both real-time monitoring of ongoing activities and for correlating field data with documentation and external conditions.

Two main directions for applying AI in this field are presented below:

One of the most promising applications of AI lies in the continuous monitoring of activities within the depot perimeter. By integrating smart video cameras, proximity, temperature, vibration, and gas sensors, AI can analyse behaviours in real time and detect deviations from standard procedures [7].

For example, systems can automatically identify if a worker is not wearing personal protective equipment, if a vehicle is parked in a restricted area, or if a loading operation is taking place outside the allocated hours. These technologies can send instant alerts to the control room or occupational safety officers, significantly reducing response time and the likelihood of hazard escalation.

Additionally, through machine learning algorithms, AI can learn normal activity patterns and flag atypical behaviours, predicting potential incidents or human errors before they occur. The second major direction for AI use is the integrated analysis of data from multiple sources: industrial sensors, thermal cameras, inspection drones, maintenance records, operation logs, and weather data.

Using AI algorithms, all this disparate data can be interconnected into a centralized system that analyses risks in real time and proposes customized preventive measures. For instance, if AI detects a rising temperature in a depot area, finds in the database that the last maintenance of the pump in that area was delayed, and weather conditions indicate a heatwave, it can generate an automatic warning for a controlled shutdown of operations [8,9].

This contextual correlation offers a clear advantage over traditional methods, which rely solely on scheduled inspections or post-incident interventions. Moreover, AI can propose dynamic predictive maintenance plans and automatically manage revision decisions based on equipment history, usage intensity, and external factors such as humidity, wind, or atmospheric pressure - critical in a fuel depot where fuel vaporization can reach dangerous levels.

IV. Proposed AI Measures for Reducing the Likelihood of an Incident

To understand the practical applicability of AI in occupational safety, it is important to highlight some of the most relevant ways in which technology contributes to accident prevention. These measures are currently being implemented in the oil and fuel storage sectors:

AI-powered intelligent video surveillance systems. Behavioural analysis cameras automatically detect violations of safety rules, such as lack of PPE, access to restricted areas, dangerous crowding, or improper use of equipment. AI learns normal activity patterns and signals abnormal behaviours in real time.

Crawler-type robots for ground inspections. In high-risk areas such as tanks or technical galleries, crawler robots equipped with multiple sensors (temperature, gas, vibration) can be used to collect data from inaccessible or dangerous zones. Controlled by AI algorithms, these robots send alerts if they detect leaks, cracks, abnormal temperatures, or explosive atmospheres.

Correlation of field data with predictive maintenance. AI simultaneously analyses data collected from industrial sensors (pressure, flow, temperature) and correlates it with maintenance history. If it detects abnormal equipment operation and overdue maintenance, the system can trigger automatic alerts or temporary shutdowns until the issue is resolved, thus preventing accidents caused by wear or ignored malfunctions.

Integration of weather data into risk analysis. AI systems can retrieve real-time weather data (wind, temperature, humidity, atmospheric pressure) and correlate it with operational risks. For example, during strong winds or heatwaves, AI can restrict high-risk operations such as fuel transfer or opening inspection hatches to prevent flammable vapor clouds or accidental explosions.

AI expert systems for decision-making in critical situations. In emergencies (leaks, fires, pressure variations), AI systems can quickly evaluate multiple possible scenarios and propose automated decisions such as stopping pumps, activating emergency ventilation, closing valves, or rapidly notifying emergency services. This eliminates delays and reduces human error under stress.

The risks associated with industrial activities in fuel depots are significant, especially during loading and unloading operations. The accumulation of flammable vapours or toxic gases, along with human errors like incorrect hose connections, can lead to explosions, fires, or severe poisoning. Modern technologies, especially mobile robotics and AI, offer real opportunities to shift the safety paradigm from reactive prevention to proactive prevention [10,11].

These proposed measures address an urgent need in fuel handling safety. By integrating environmental sensors, AI, and mobile robotics, hazards can be anticipated, context analysed, and real-time alerts issued. These solutions do not fully replace human supervision but provide critical redundancy under operational stress. Investment in AI systems is justified by the reduction in incidents, material losses, and risks to workers' lives.

V. Conclusions

The application of Artificial Intelligence in preventing workplace accidents in fuel depots marks a fundamental shift in the operational safety paradigm. AI is not merely an extension of existing monitoring capabilities it completely transforms how risks are perceived and managed.

With its ability to analyse large volumes of data in real time from industrial sensors, smart cameras, maintenance records, and weather forecasts, AI offers a holistic, dynamic, and anticipatory view of potential hazards.

Moreover, AI acts as an expert system that complements human intervention, significantly reducing the chances of evaluation errors or delayed reactions in critical moments. In a field like fuel storage, where a single incident can cause massive human, financial, and environmental losses, speed and accuracy of response are vital. AI thus contributes not only to early anomaly detection but also to effective prevention through intelligent, automated corrective actions [12,13].

At the same time, through continuous learning and adaptation to the specifics of each facility, AI systems can become trusted partners for safety and maintenance teams, offering predictions based on historical behaviour and current context. Integrating these technologies with traditional risk assessment methods like HIRA, provides a hybrid approach of maximum efficiency and responsibility.

In conclusion, the use of AI is not just a viable option but an urgent necessity in modernizing prevention systems in high-risk facilities. Implementing these solutions in fuel depots represents a decisive step toward an organizational culture focused on active prevention, predictive management, and sustainable safety across all operational components.

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