



Determination of a Safe Buffer Zone for an Industrial Facility to Manage Air Pollutant Emissions

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Article Info	ABSTRACT
Article type: Research Article	Industrial facilities are continuously exposed to potential hazards that may lead to injuries, fatalities, and substantial financial losses. The development, advancement, and expansion of highly complex technologies in various industries have caused safety philosophy to shift from a post-incident approach to a pre-incident approach. The increasing application of this new approach and the reduction in the number of industrial accidents demonstrate the positive effects of this trend in accident reduction. The steel industry, as one of the key and strategic industries in the national economy, has always faced numerous challenges in the fields of safety, health, and environmental protection. The presence of hazardous materials and complex processes in this industry highlights the necessity of conducting detailed risk assessment and consequence modeling studies more than ever. In this study, credible scenarios were selected to determine fire zone distances, site boundaries, impacted areas around the industrial zone, individual risk assessment, and societal risk assessment. PHAST software was used for consequence modeling of process accidents, and SAFETI software was utilized for quantitative risk assessment. The results of consequence modeling showed that due to the presence of ammonia storage tanks in the studied company, most of the company's buildings are exposed to the harmful concentrations of this toxic substance. The harmful concentration of this toxic gas extends up to 190 meters outside the industrial site fence. Individual risk assessment revealed that the 10^{-4} per year risk contour covers parts of the area outside the industrial boundary, indicating unacceptable risk levels in some locations. Societal risk assessment also indicated that nearby residential areas are in the high-risk region. Therefore, it is necessary to strengthen safety protection layers, establish process safety management systems, and expand the company's boundary from the southeastern area by at least 190 meters to provide a suitable safe restricted area for air pollution management during emergency situations. The integration of consequence modeling with quantitative risk assessment enabled a comprehensive evaluation of both on-site and off-site hazards, providing a robust basis for evidence-based safety decision-making in complex industrial environments. The findings of this study provide a practical framework for land-use planning, emergency response preparedness, environmental protection, and sustainable safety management in steel production facilities.
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Introduction

The steel industry is recognized as one of the most important industrial sectors worldwide; however, it is associated with numerous process safety, environmental, and occupational health hazards. The storage and handling of hazardous materials such as ammonia, liquefied petroleum gas (LPG), hydrogen, natural gas, and hydrochloric acid can lead to severe incidents including toxic releases, fires, explosions, and environmental contamination. Modern safety management emphasizes proactive risk assessment and consequence modeling to prevent accidents before their occurrence. Accurate consequence assessment and quantitative risk analysis also provide a scientific basis for land-use planning, emergency preparedness, and the implementation of effective mitigation measures in high-hazard industrial facilities. The present study aimed to determine the safe restricted area and site boundary required for air pollution management and emergency planning in a steel manufacturing company. Specifically, the study focused on identifying credible accident scenarios, evaluating their consequences, determining Fire Zones (FZ), Restricted Areas (RA), and Impacted Areas (IA), and assessing individual and societal risks associated with process facilities.

Method

This research was conducted using a quantitative risk assessment (QRA) framework based on the requirements of IPS-C-SF-550, GS-EP-SAF-253, and DNV Technical Note 14 regarding process equipment failure frequencies. The study was performed in five stages: scenario selection, condition analysis, consequence modeling, frequency estimation, and risk evaluation. Credible scenarios involving ammonia vessels, LPG storage, hydrogen storage, natural gas pressure reduction stations, and acid storage tanks were identified through field investigations and process data analysis. Meteorological conditions were defined using regional wind rose data and three dominant weather categories (F/2, D/5, and D/15) representing different atmospheric stability classes and wind speeds. Consequence modeling was carried out using PHAST software to simulate toxic gas dispersion, jet fires, flash fires, pool fires, and vapor cloud explosions (VCE). The selected scenarios represented the most credible and potentially severe accidental releases based on the inventory of hazardous substances, operating conditions, and process configuration of the facility. Model input parameters, including operating pressure, temperature, inventory, and release characteristics, were obtained from plant technical documentation and validated through field observations. Subsequently, SAFETI software was employed to estimate individual and societal risk levels by integrating consequence severity with equipment failure frequencies. The analysis incorporated leak size categories, ignition probabilities, population distributions, occupancy assumptions, and explosion confinement characteristics to generate risk contours and evaluate safety distances around the industrial complex. The resulting risk contours and consequence distances were finally compared with internationally accepted risk acceptance criteria to identify vulnerable areas and support emergency response planning and land-use management decisions.

Results

The results demonstrated that ammonia storage facilities constituted the most significant hazard source within the studied steel company. Consequence modeling revealed that toxic ammonia releases generated the largest impact distances compared with fire and explosion scenarios. For Fire Zone determination, dominant consequences were identified as jet fires for ammonia and hydrogen systems, flash fires for LPG storage, and vapor cloud explosions for the natural gas pressure reduction station. The maximum fire zone distances reached 60 m for ammonia storage facilities and 63 m for LPG flash-fire scenarios. Restricted area assessment showed that ammonia release scenarios produced the most critical outcomes. The maximum toxic dispersion distance based on the LC1% criterion reached 218 m under unfavorable meteorological

conditions. The results also demonstrated a strong influence of atmospheric stability and wind speed on toxic dispersion distances, with stable atmospheric conditions producing the largest impact zones. These findings highlight the importance of incorporating site-specific meteorological data into quantitative risk assessments for industrial facilities. Evaluation of site boundaries indicated that harmful ammonia concentrations could extend approximately 190 m beyond the existing industrial fence line, particularly in the southeastern direction. Individual risk analysis demonstrated that the 10^{-4} per year risk contour extended beyond the process area and covered portions of the surrounding environment, indicating unacceptable risk levels in some locations. Furthermore, the ALARP (As Low As Reasonably Practicable) zone extended several hundred meters beyond the facility boundary. Societal risk assessment revealed that nearby residential areas could be exposed to elevated risk levels, placing the facility within the high-risk region of the societal risk acceptance criteria. Comparison of the analyzed scenarios indicated that toxic releases contributed more substantially to off-site risk than fire or explosion events, emphasizing the need to prioritize preventive and mitigation measures for ammonia storage systems. These findings indicate that ammonia storage units represent the dominant contributors to both individual and societal risks.

Conclusions

The findings confirm that consequence modeling and quantitative risk assessment provide effective tools for defining safe industrial boundaries and improving air pollution management during emergency situations. Among all identified hazards, ammonia release scenarios were found to be the governing factor in determining site boundaries and safety distances. Because toxic ammonia concentrations may extend up to 190 m outside the existing fence line, expansion of the southeastern site boundary is recommended. In addition, strengthening independent protection layers, implementing risk-based inspection programs, improving maintenance and integrity management systems, and enhancing process safety management (PSM) practices are necessary to reduce the likelihood and consequences of hazardous releases. Future development projects should consider the identified Fire Zones, Restricted Areas, and Impacted Areas to prevent the construction of vulnerable facilities within unacceptable risk regions. The integration of consequence modeling with quantitative risk assessment enabled a comprehensive evaluation of both on-site and off-site hazards, providing a robust basis for evidence-based safety decision-making in complex industrial environments. The results of this study provide a practical framework for land-use planning, emergency response preparedness, environmental protection, and sustainable safety management in steel production facilities. Furthermore, the findings emphasize that risk-informed design and operational decision-making can substantially enhance the resilience of industrial facilities against low-probability but high-consequence accidents. The generated risk contours may serve as valuable decision-support tools for regulatory authorities, plant managers, and emergency response organizations when establishing exclusion zones and prioritizing risk reduction measures. Although the present study focused on a steel manufacturing complex, the proposed methodology is transferable to other high-hazard industrial sectors where toxic and flammable materials are processed or stored. Future research should integrate dynamic operational data, real-time monitoring technologies, and probabilistic meteorological models to further improve the reliability of consequence prediction and emergency planning strategies.

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