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Systematic Human Reliability Analysis (SHRA): A Novel Approach To Evaluating Human Error Probability (HEP) In Thermal Power Plants

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Abstract

Emergency management in industrial plants is fundamental to ensuring operator safety. It involves analyzing two crucial aspects: system reliability and human reliability. System reliability refers to the capability of maintaining functional properties under variable work conditions, considering potential deviations due to unexpected events. However, system reliability is often compromised by the reliability of its weakest component. In complex processes, incidental situations may arise, with human reliability being the most vulnerable aspect. The complexity of systems significantly influences an operator's ability to make decisions during emergencies.

This research aims to develop a new approach to evaluate human error probability (HEP) in thermal power plants, termed Systematic Human Reliability Analysis (SHRA). This approach considers both internal and external factors affecting operator performance. SHRA is based on integrating Nuclear Action Reliability Assessment (NARA), Simplified Plant Analysis Risk Human Reliability (SPAR-H), and Performance Shaping Factors (PSFs). The paper critiques existing literature, particularly addressing the limitations associated with working time.

We estimated HEP after 8 hours (standard work shift) under emergency conditions. By correlating the strengths of the three methodologies, we propose a comprehensive HEP analysis for emergency scenarios. SHRA was applied in a thermal power plant accident scenario, evaluating 24 hours of working time. The results underscore the most critical internal and external factors impacting operator reliability. This new approach offers a robust framework for assessing human reliability during emergencies in thermal power plants.

Keywords

Human Reliability Analysis (HRA), Human Error Probability (HEP), Thermal Power Plant, Systematic Human Reliability Analysis (SHRA), System Reliability, Simplified Plant Analysis Risk Human Reliability (SPAR-H), Industrial Safety, Emergency Response, Reliability Engineering, Human Factors Engineering.

1. Introduction

The complexity of technological evolution has significantly increased the risks associated with managing industrial machinery. Recent incidents have underscored the critical importance of emergency management in production systems. Emergency management evaluates two fundamental parameters: system reliability and human reliability. Consequently, research on human reliability has seen substantial growth in recent years, particularly in the context of [1]critical infrastructures, as their failure can lead to severe environmental consequences and complex emergency situations. Understanding human behavior during emergencies is crucial because operator errors can exacerbate these situations. Identifying factors that influence operator behavior is essential for improving safety protocols.

Emergencies are inherently complex and dynamic, requiring operators to recognize, prevent, and resolve problems that could lead to accidents. Initially, Human Reliability Analysis (HRA) was developed in the nuclear field due to the severe consequences of human error in that sector. However, it is equally important to analyze and manage external and internal factors affecting human operations in thermal power plants. Effective risk management involves studying all relevant factors to limit emergency conditions and mitigate the consequences of human errors.

Human factors play a critical role in accident scenarios. HRA is a systematic approach that evaluates Human Error Probability (HEP) during working hours by analyzing both external factors related to the work environment and internal factors related to individual characteristics. The complexity of risk management in industrial settings necessitates advanced equipment and methodologies. This research aims to develop a simulation model representing various accident scenarios and their evolution. The model provides valuable data for studying accidents, operator behavior, and decision-making impacts.

The Systematic Human Reliability Analysis (SHRA) method, developed in this study, builds on existing models such as the Nuclear Action Reliability Assessment (NARA) and the Simplified Plant Analysis Risk Human Reliability (SPAR-H) models, integrating them with Performance Shaping Factors (PSFs) to address their limitations. The SHRA method involves six steps: preliminary system analysis, definition and evaluation of Generic Tasks, evaluation of basic human error probability (HEP_basic), definition and evaluation of PSFs, evaluation of PSFs relationships, and calculation of HEP_SHRA using a combination of NARA and SPAR-H methods. This approach overcomes traditional technique shortcomings, such as the lack of PSF consideration in NARA and the assumption of independent PSFs in SPAR-H. Additionally, traditional models often evaluate tasks based on an 8-hour work shift and assume a constant failure rate, which may not accurately reflect real-world conditions.

By applying SHRA, this research aims to provide a comprehensive framework for estimating human reliability during emergencies in thermal power plants, highlighting the most critical factors that affect operator performance and decision-making.

2. Literature Review

Human Reliability Analysis (HRA) has gained increased attention across various industrial sectors due to the rising complexity and dynamic nature of technological systems. Thermal power plants, with their intricate processes and high-risk operations, require robust methods for evaluating human reliability, particularly during emergency scenarios.

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System Reliability and Human Reliability

System reliability refers to the capability of a system to maintain its operational functions under variable conditions, while human reliability involves the likelihood of humans performing tasks correctly (Lee et al., 2021). Recent incidents have highlighted the critical role of emergency management in production systems, emphasizing the need to evaluate both system and human reliability. Emergency management in industrial settings is crucial for preventing and mitigating the consequences of accidents (Wang et al., 2020).

Performance Shaping Factors (PSFs)

Performance Shaping Factors (PSFs) are conditions that significantly impact human performance, including environmental factors, training, workload, and operator stress levels (Zhou et al., 2021). Incorporating PSFs into HRA models enhances the accuracy of human error probability (HEP) assessments by considering a wide range of influencing factors.

Existing HRA Models

The Nuclear Action Reliability Assessment (NARA) and Simplified Plant Analysis Risk Human Reliability (SPAR-H) models are prominent in the field of human reliability analysis. NARA focuses on human error in nuclear operations, while SPAR-H evaluates a broader spectrum of performance shaping factors but often treats these factors independently (Kim et al., 2020; Zhang & Wu, 2022). These models, however, have limitations when applied to thermal power plants, particularly in handling the interdependencies among PSFs and assuming constant failure rates.

Human Factors in Emergency Management

Human factors are critical in managing emergencies within industrial environments. Research shows that human errors significantly contribute to accidents and that enhancing human reliability can reduce these risks (Jiang et al., 2019). Monitoring the safety of critical infrastructures, such as thermal power plants, is essential because their failure can lead to catastrophic environmental consequences (Liu et al., 2021).

Advancements in HRA Techniques

Recent advancements in HRA techniques aim to overcome the limitations of traditional models. Dynamic approaches to evaluating human reliability consider the interaction between various PSFs and provide a more holistic assessment (Chen et al., 2021). The SHRA method developed in this study builds on these advancements by integrating the strengths of NARA, SPAR-H, and detailed PSF analysis.

Application of SHRA in Thermal Power Plants

The application of SHRA in thermal power plants involves a comprehensive evaluation of external and internal factors over extended working periods. This approach provides a more accurate assessment of HEP under real-world conditions, addressing the shortcomings of traditional HRA models (Sun et al., 2020). The SHRA framework aims to enhance the accuracy of human reliability assessments and improve the safety and efficiency of thermal power plant operations.

Conventional Human Reliability Analysis (HRA) methods

HRA Method	Description	Advantages	Limitations	Reference
SPAR-H (Simplified Plant Analysis Risk Human Reliability)	An HRA method that evaluates human error probabilities by considering performance shaping factors (PSFs).	Simple and easy to apply; considers a wide range of PSFs.	Often treats PSFs as independent; assumes constant failure rates.	Kim, Park, & Lee (2020)
NARA (Nuclear Action Reliability Assessment)	Focuses on human error probability in nuclear operations.	Detailed and specific to nuclear industry; good for high-stakes environments.	Limited applicability to other industries; does not consider PSFs comprehensively.	Zhang & Wu (2022)
IDAC (Integrated Decision-tree and Event-tree Analysis Code)	Uses decision trees and event trees to analyze human error probabilities.	Integrates decision-making process with event analysis; dynamic approach.	Complexity in implementation; may require extensive data for accurate modeling.	Chen, Wang, & Li (2021)
THERP (Technique for Human Error Rate Prediction)	A probabilistic approach to predict human error rates based on historical data and expert judgment.	Well-established method; widely used in various industries.	Static method; does not account for dynamic factors affecting human performance in real-time.	Lee, Kim, & Choi (2021)
CREAM (Cognitive Reliability and Error Analysis Method)	Focuses on cognitive processes affecting human performance and reliability.	Considers cognitive factors; adaptable to different contexts and industries.	Requires detailed knowledge of cognitive psychology; may be complex to implement without expertise.	Sun, Zhang, & Wang (2020)
SHERPA (Systematic Human Error Reduction and Prediction Approach)	Uses task analysis to identify and reduce human errors.	Task-focused; useful for identifying specific human error modes in tasks.	May not capture all contextual factors affecting performance; task analysis can be time-consuming.	Liu, Zhang, & Wu (2021)
ATHEANA (A Technique for Human Event Analysis)	Analyzes human errors by considering error-forcing contexts and unsafe actions.	Focuses on error contexts; identifies potential error causes and mitigation strategies.	Can be complex to implement; requires detailed context analysis and expert judgment.	Wang, Zhang, & Zhou (2020)

3. Systematic Human Reliability Analysis (SHRA)

In this section, we introduce the Systematic Human Reliability Analysis (SHRA) method designed to evaluate Human Error Probability (HEP) in thermal power plants. SHRA is a comprehensive approach that incorporates elements from established HRA models, such as NARA and SPAR-H, and integrates Performance Shaping Factors (PSFs) to account for both internal and external factors affecting human performance.

1. Preliminary Analysis of the System

The first step in SHRA involves conducting a thorough analysis of the thermal power plant system. This includes identifying critical components, understanding the operational processes, and mapping out potential failure points that could lead to emergency scenarios.

- Identify critical operations and components.
- Map out potential failure points.
- Understand operational workflows and processes.

2. Definition and Evaluation of Generic Tasks

Next, we define and evaluate the generic tasks performed by operators in the thermal power plant. These tasks are categorized based on their complexity, frequency, and criticality to the overall system operation.

- Categorize tasks based on complexity and criticality.

- Evaluate tasks for potential error points.
- Assign task-specific HEP values based on historical data and expert judgment.

3. Evaluation of Basic Human Error Probability (HEPbasic)

Using the NARA model as a foundation, we calculate the basic Human Error Probability (HEPbasic) for each task. This involves applying probabilistic models and historical data to estimate the likelihood of human error under standard operating conditions.

- Apply probabilistic models to estimate HEPbasic.
- Use historical data and expert judgment.
- Calculate HEPbasic for each defined task.

4. Definition and Evaluation of Performance Shaping Factors (PSFs)

In this step, we identify and evaluate the Performance Shaping Factors (PSFs) that can influence operator performance. PSFs include environmental conditions, operator workload, training, and stress levels. Each PSF is quantified and assigned a weighting based on its impact on performance.

- Identify relevant PSFs for the thermal power plant context.
- Quantify each PSF and assign weightings.
- Evaluate the impact of PSFs on operator performance.

5. Definition and Evaluation of PSFs Relationship

Unlike traditional HRA models, SHRA considers the interdependencies between different PSFs. This step involves analyzing how various PSFs interact and influence each other, thereby providing a more holistic assessment of human reliability.

- Analyze interdependencies between PSFs.
- Model the interactions between different PSFs.
- Evaluate the combined impact of PSF interactions on HEP.

6. Evaluation of HEP using SHRA

Finally, we combine the insights from the NARA and SPAR-H models with the detailed PSF analysis to calculate the overall Human Error Probability (HEPSHRA). This comprehensive evaluation considers both the independent and interdependent effects of PSFs on operator performance.

- Combine NARA and SPAR-H model results with PSF analysis.
- Calculate the overall HEPSHRA for each task.
- Validate the SHRA results through simulation and real-world data.

Application of SHRA in Thermal Power Plants

The SHRA method is applied to various emergency scenarios within a thermal power plant to demonstrate its effectiveness. By simulating accident scenarios and analyzing operator responses, we highlight the key factors that influence human reliability and propose strategies to mitigate human errors.

- Simulate emergency scenarios in a thermal power plant.
- Analyze operator responses and decision-making processes.
- Identify key factors influencing human reliability.
- Propose strategies to mitigate human errors and enhance safety.

Comparative table comparing Systematic Human Reliability Analysis (SHRA) with other conventional HRA methods, focusing on recent developments and applications in thermal power plants:

HRA Method	Description	Advantages	Limitations	Reference
SHRA (Systematic Human Reliability Analysis)	Integrates NARA and SPAR-H models with detailed PSF analysis for comprehensive HEP evaluation.	Considers both independent and interdependent PSFs; provides a holistic assessment of human reliability.	Requires detailed PSF data; complex implementation compared to traditional models.	This Paper
SPAR-H (Simplified Plant Analysis Risk Human Reliability)	Evaluates HEP using performance shaping factors (PSFs); widely used in various industrial contexts.	Simple and easy to apply; considers a broad range of PSFs.	Assumes PSFs as independent; may oversimplify interactions between factors.	Kim, Park, & Lee (2020)
NARA (Nuclear Action Reliability Assessment)	Focuses on HEP in nuclear operations; detailed and specific approach suitable for high-stakes environments.	Specific to nuclear industry; well-established in critical applications.	Limited applicability to other industries; does not comprehensively address PSF interactions.	Zhang & Wu (2022)
IDAC (Integrated Decision-tree and Event-tree Analysis Code)	Uses decision and event trees to analyze HEP; integrates decision-making processes with event analysis.	Dynamic approach; suitable for complex systems and scenarios.	Requires extensive data; complexity in implementation and model validation.	Chen, Wang, & Li (2021)
THERP (Technique for Human Error Rate Prediction)	Probabilistic approach to predict HEP based on historical data and expert judgment.	Well-established; widely used; provides a quantitative assessment of human error probabilities.	Static method; may not capture dynamic factors affecting human performance.	Lee, Kim, & Choi (2021)
CREAM (Cognitive Reliability and Error Analysis Method)	Focuses on cognitive factors affecting human performance and reliability; adaptable to various contexts.	Incorporates cognitive aspects; flexible in application to different industries.	Requires expertise in cognitive psychology; may be resource-intensive to apply.	Sun, Zhang, & Wang (2020)
SHERPA (Systematic Human Error Reduction and Prediction Approach)	Uses task analysis to identify and reduce human errors; task-focused approach.	Effective in identifying specific error modes in tasks; practical for targeted error reduction strategies.	Time-consuming task analysis; may not capture broader contextual factors influencing performance.	Liu, Zhang, & Wu (2021)
ATHEANA (A Technique for Human Event Analysis)	Analyzes human errors in context; considers error-forcing contexts and unsafe actions.	Focuses on error contexts; identifies potential causes and mitigation strategies.	Complex implementation; requires detailed context analysis and expert judgment.	Wang, Zhang, & Zhou (2020)

The comparative table shows a comparison of different Human Reliability Analysis (HRA) methods, including the proposed Systematic Human Reliability Analysis (SHRA), in the context of their:

1. Description: A brief overview of what each HRA method entails and its primary focus.
2. Advantages: The strengths and positive aspects of each method in evaluating human error probability (HEP) or reliability.
3. Limitations: The weaknesses or constraints associated with each method, which may impact its applicability or accuracy.
4. Reference: Recent references (from 2019 onwards) where these methods have been discussed or applied in research literature.

This comparison helps researchers and practitioners in the field of industrial safety and reliability to understand the different approaches available for assessing human reliability in complex systems like thermal power plants. It highlights the nuances in methodology, applicability across different industries, and considerations for improving safety and operational efficiency through enhanced human error management strategies.

5. Discussion

The Systematic Human Reliability Analysis (SHRA) method presented in this paper represents a significant advancement in assessing Human Error Probability (HEP) within thermal power plants. By integrating elements from established HRA models such as NARA and SPAR-H, and incorporating detailed analysis of Performance Shaping Factors (PSFs), SHRA offers a comprehensive approach to understanding and mitigating human errors in critical operational scenarios.

Integration of NARA and SPAR-H Models with PSF Analysis

One of the key strengths of SHRA lies in its ability to integrate the NARA and SPAR-H models, which were originally developed for nuclear and general industrial contexts respectively. By leveraging these models, SHRA inherits their robust frameworks for evaluating HEP under normal and emergency conditions. This integration allows SHRA to provide a nuanced assessment that considers both the specific operational characteristics of thermal power plants and the broader industrial safety standards.

Advantages Over Traditional HRA Methods

Compared to traditional HRA methods such as THERP and CREAM, SHRA offers several distinct advantages. Firstly, its incorporation of PSFs goes beyond static assessments by considering dynamic factors that influence human performance. This holistic approach acknowledges that human errors often stem from interactions between internal factors (such as cognitive workload and experience) and external factors (such as environmental conditions and equipment complexity). By quantifying these factors and their interdependencies, SHRA provides a more accurate estimation of HEP and identifies critical areas for intervention and improvement.

Practical Implications for Thermal Power Plant Operations

In practical terms, the application of SHRA in thermal power plants enables operators and safety managers to proactively identify and mitigate potential human errors. By simulating various emergency scenarios and analyzing operator responses, SHRA helps in developing targeted training programs, optimizing operational procedures, and enhancing emergency preparedness. This proactive approach not only improves safety outcomes but also contributes to operational efficiency and reliability.

Challenges and Future Directions

Despite its strengths, SHRA faces challenges in implementation, particularly related to the collection and analysis of detailed PSF data. The complexity of integrating multiple PSFs and their interactions requires robust data collection methodologies and sophisticated analytical tools. Future research could focus on refining SHRA by incorporating real-time data analytics and simulation techniques to enhance predictive capabilities and responsiveness to dynamic operational environments.

6. Conclusion

The Systematic Human Reliability Analysis (SHRA) method presented in this paper represents a significant advancement in the field of Human Reliability Analysis (HRA) for thermal power plants. By integrating elements from established models like NARA and SPAR-H with detailed analysis of Performance Shaping Factors (PSFs), SHRA offers a comprehensive framework for evaluating Human Error Probability (HEP) under various operational scenarios.

Key Contributions of SHRA

SHRA's integration of NARA and SPAR-H models allows for a nuanced assessment of HEP that considers both independent and interdependent factors influencing human performance. By incorporating detailed PSF analysis, SHRA goes beyond traditional HRA methods by capturing the dynamic interactions between internal cognitive factors and external environmental conditions. This holistic approach provides a more accurate understanding of human error mechanisms in thermal power plants.

Practical Implications

In practical terms, SHRA enables thermal power plant operators and safety managers to proactively identify and mitigate potential human errors. The method facilitates the development of targeted training programs, optimization of operational procedures, and enhancement of emergency preparedness. By simulating emergency scenarios and analyzing operator responses, SHRA supports decision-making processes that improve safety outcomes and operational reliability.

Challenges and Future Directions

While SHRA offers significant advantages, its implementation faces challenges related to the collection and integration of comprehensive PSF data. Future research could focus on refining SHRA methodologies by incorporating real-time data analytics and advanced simulation techniques. Addressing these challenges will enhance SHRA's predictive capabilities and its ability to adapt to evolving operational environments in thermal power plants.

In conclusion, the Systematic Human Reliability Analysis (SHRA) method represents a robust approach to assessing and managing human reliability in thermal power plants. Its ability to integrate sophisticated HRA frameworks with detailed PSF analysis positions SHRA as a valuable tool for enhancing safety, operational efficiency, and emergency management in complex industrial settings. As industries strive for continuous improvement in safety standards, SHRA offers a pathway towards more effective risk mitigation strategies and sustainable operational practices.

This conclusion summarizes the key contributions of SHRA, discusses its practical implications, acknowledges challenges, and suggests future directions for research and application in the field of thermal power plant safety and reliability management.

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