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Designing a Risk Management Model for Power Plant Maintenance Using a Grounded Theory Approach

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A B S T R A C T

Maintenance and repair processes in thermal power plants continually face serious risk management challenges because of equipment complexity and the high-risk nature of operations. The present study aimed to develop a comprehensive risk management model in this field to enhance reliability and improve managerial decision-making. In terms of purpose, this study was applied, and methodologically, it employed a qualitative grounded theory approach based on the Strauss and Corbin framework. Data were collected through semi-structured interviews with 14 academic and industry experts in the thermal power plant sector and analyzed in MAXQDA using the three stages of open, axial, and selective coding. The findings resulted in the identification of 122 initial codes and 41 key components, which were ultimately explained within a paradigmatic model comprising six main categories: causal conditions, contextual conditions, the central phenomenon, intervening conditions, strategies, and consequences. By explaining the actions and interactions among technical, behavioral, structural, and environmental factors, the resulting model provides a comprehensive perspective on the logic of risk management within the indigenous context of Iran's power generation industry. The results not only enrich the risk management literature but also provide an operational framework that can assist power plant managers in designing effective risk management systems and optimizing resource allocation.

Keywords: *Risk management, maintenance and repair, power plant, grounded theory*

1. Introduction

Power plants are among the most complex industrial systems because their continuous operation depends on the coordinated performance of numerous mechanical, electrical, instrumentation, control, chemical, and structural components. Any failure in one of these subsystems may disrupt electricity generation, damage expensive equipment, endanger personnel, and produce environmental and economic consequences. Within this operational environment, maintenance and repair activities are not merely technical support functions but strategic processes that directly influence reliability, availability, production continuity, safety, and organizational performance. The increasing complexity of thermal and combined-cycle power plants, the aging of critical assets, the growing use of digital

technologies, and the integration of renewable and energy-storage systems have intensified the need for systematic maintenance planning and risk-informed decision-making. Traditional maintenance practices that rely primarily on fixed schedules or responses to breakdowns are increasingly insufficient for addressing the interacting technical, human, organizational, and environmental hazards present in modern power generation systems. Consequently, contemporary power plant management requires an integrated approach that connects maintenance management with risk analysis, reliability engineering, safety management, and strategic resource allocation (Horowitz & Arab-Mazar, 2024; Kiani & Khodaparast, 2024; Zio, 2023).

Maintenance management in power plants encompasses the planning, execution, monitoring, and improvement of activities intended to preserve or restore equipment functionality. Its effectiveness is commonly evaluated through indicators such as reliability, maintainability, availability, failure frequency, mean time between failures, mean time to repair, and operational efficiency. In power generation facilities, these indicators are particularly important because equipment failure can lead to unplanned shutdowns, reduced generation capacity, increased fuel consumption, higher maintenance expenditures, and threats to occupational and process safety. Reliability, availability, and maintainability analysis therefore provides an important analytical foundation for identifying critical equipment, predicting performance degradation, and determining appropriate maintenance intervals (Hemmati & Soleimani, 2023). However, maintenance decisions cannot be based solely on equipment failure probability. They must also consider the severity of potential consequences, the exposure of personnel, environmental impacts, operational priorities, financial limitations, spare-parts availability, regulatory requirements, and the interdependence of plant systems. This multidimensional nature of maintenance decision-making highlights the necessity of a risk management framework capable of combining diverse sources of evidence and balancing competing objectives.

Risk-based maintenance has emerged as an important response to these challenges. Unlike purely time-based maintenance, risk-based maintenance prioritizes equipment and activities according to the combined probability and consequences of failure. It seeks to allocate limited maintenance resources to the areas where failure would create the greatest operational, safety, environmental, or economic damage. In gas and thermal power plants, reliability-based and risk-based optimization models have shown that maintenance scheduling can be improved when equipment criticality, degradation behavior, failure probability, and consequence severity are analyzed jointly (Garcia & Torres, 2022; Kumar & Singh, 2024). This approach can reduce unnecessary interventions on low-risk assets while directing inspection, preventive maintenance, and condition-monitoring resources toward high-risk components. Nevertheless, the effectiveness of risk-based maintenance depends on the quality of operational data, the accuracy of failure models, the appropriateness of risk criteria, and the extent to which organizational and human factors are incorporated into the decision process. In many power plants, incomplete records, inconsistent reporting, uncertainty in expert judgments, and variations in operating conditions complicate the estimation of risk and reduce the precision of maintenance planning.

The technical sources of risk in power plant maintenance are diverse and frequently interconnected. Electrical hazards, fire and explosion, fuel and oil leakage, high-pressure steam systems, chemical exposure, turbine vibration, corrosion, erosion, fatigue, rotating machinery failure, and failures in instrumentation and control systems are among the most important threats. Thermal power plants are especially vulnerable to cascading failures because a local malfunction may propagate through connected subsystems and disrupt the stability of an entire generating unit. The risk profile of a power plant is also influenced by plant design, equipment age, fuel type, operating regime, maintenance history, environmental conditions, and the degree of automation. Advanced maintenance techniques, including reliability-centered maintenance and risk-based inspection, attempt to address these conditions by identifying failure modes, evaluating their consequences, and selecting maintenance actions consistent with equipment criticality (Nikseresht, 2023). Failure mode and effects analysis has also been applied in combined-cycle power plants to identify hazardous activities and rank operational and maintenance risks, demonstrating the value of structured risk-identification methods in plant environments (Babazadeh & Sadeghpour, 2023). Although such methods provide useful results, they often focus on specific equipment, processes, or risk categories and may not fully explain the broader system of factors through which risk management is shaped and implemented.

Human and organizational factors constitute another major dimension of maintenance risk. Maintenance operations are often conducted under time pressure, during shutdowns, in confined spaces, at height, near energized

systems, or in the presence of hazardous substances. Under such conditions, fatigue, insufficient training, weak supervision, inadequate communication, poor coordination, procedural violations, and incorrect risk perception can increase the likelihood of unsafe actions. Organizational structure, safety culture, leadership commitment, resource availability, and the quality of interdepartmental coordination influence how maintenance risks are recognized, communicated, and controlled. Moreover, organizational readiness for change can affect the adoption of advanced maintenance systems, digital monitoring technologies, and formal crisis-management practices. Research in power plant settings has indicated that attitudes toward organizational change, organizational excellence, interpersonal conflict, and crisis-management capacity are related dimensions of institutional preparedness (Izadi Yazdanabadi & Mohammadbagheri, 2024). Accordingly, an effective maintenance risk management model must extend beyond technical failure analysis and incorporate the organizational conditions that shape employee behavior, decision quality, and the implementation of preventive strategies.

The transformation of power generation technologies has further expanded the scope of maintenance risk. Modern plants increasingly rely on automation, sensor networks, digital control systems, advanced diagnostic tools, and data-driven maintenance platforms. At the same time, the integration of solar, wind, hybrid, and large-scale energy-storage systems has created new combinations of electrical, cyber, chemical, thermal, and operational risks. Energy-storage facilities, for instance, require the optimization of charging and discharging processes while also managing equipment degradation, thermal behavior, system stability, and operational uncertainty (Motallebi-Nejad et al., 2023). These developments alter conventional failure patterns and require maintenance professionals to consider risks associated with batteries, power electronics, inverters, digital interfaces, cybersecurity, and new forms of human-system interaction. As plant technologies become more interconnected, risk management must account not only for component-level failure but also for system-level dependencies, data quality, software performance, and the potential propagation of disturbances across technical and organizational boundaries.

One of the principal challenges in power plant risk analysis is uncertainty. Operational data may be incomplete, imprecise, or influenced by changing environmental and loading conditions. Some failures are rare but potentially catastrophic, making statistical estimation difficult. In addition, expert assessments of probability, severity, detectability, and equipment criticality may be expressed linguistically rather than numerically. Conventional deterministic methods may not adequately represent these uncertainties, particularly when maintenance decisions depend on both quantitative data and professional judgment. Fuzzy logic has therefore gained substantial attention in maintenance optimization and risk assessment because it permits the representation of vague, incomplete, and subjective information. In energy industries, fuzzy logic models have been used to optimize maintenance priorities, combine multiple risk criteria, and support decisions when precise failure data are unavailable (Ahmed & Hassan, 2023). Fuzzy approaches can convert qualitative judgments such as “high probability,” “moderate severity,” or “low detectability” into structured analytical values, thereby enhancing the consistency and transparency of maintenance decisions.

The application of fuzzy models has also expanded to the broader management of complex energy systems. Such systems involve nonlinear relationships, interacting hazards, multiple stakeholders, and uncertain operational conditions. Fuzzy modeling provides a flexible mechanism for integrating technical indicators, expert knowledge, organizational criteria, and environmental considerations within a unified assessment framework (Chen & Li, 2023). In thermal power plant maintenance, fuzzy risk assessment can help rank equipment according to criticality, estimate the relative importance of failure modes, and identify maintenance actions that minimize the expected consequences of failure (Zhang & Liu, 2023). Fuzzy reliability-based maintenance planning similarly allows analysts to address uncertainty in failure behavior and determine intervention priorities for complex engineering systems (Yadav & Singh, 2023). These approaches are especially valuable when historical failure records are limited, when equipment operates under variable conditions, or when different experts assign different ratings to the same hazard.

Recent studies have developed more advanced frameworks that combine fuzzy logic with probabilistic analysis, reliability models, and multicriteria decision-making. Hybrid fuzzy-probabilistic approaches can simultaneously represent randomness and epistemic uncertainty, thereby producing more realistic estimates of risk in energy systems (Silva & Mendes, 2023). A fuzzy-probabilistic risk assessment model can account for

uncertainty in equipment condition, operational data, and expert judgment while retaining the probabilistic interpretation required for reliability analysis (Rodriguez & Perez, 2024). Similarly, fuzzy-based frameworks for power plant equipment can assess risk under uncertain and incomplete operational data and support the prioritization of maintenance interventions (Liu et al., 2024). These developments demonstrate that the integration of multiple analytical approaches can provide more robust results than reliance on a single technique. Nevertheless, such models often remain technically oriented and may not adequately capture the processes through which organizations interpret risk, negotiate priorities, adopt strategies, and evaluate consequences in real maintenance settings.

Multicriteria decision-making represents another important development in power plant risk assessment. Maintenance decisions typically involve multiple and sometimes conflicting criteria, including safety, cost, reliability, environmental impact, production requirements, inspection feasibility, and regulatory compliance. Fuzzy multicriteria methods enable decision-makers to weight these criteria and compare alternative maintenance actions under uncertainty (Song et al., 2024). Comprehensive risk analysis can also improve maintenance planning by combining failure likelihood, consequence severity, equipment condition, and organizational priorities in a structured decision framework (Park & Choi, 2024). Such models can enhance the rationality of resource allocation and help managers determine which assets require immediate intervention, intensified monitoring, redesign, or replacement. However, the practical adoption of multicriteria models depends on organizational capacity, data availability, stakeholder acceptance, and the alignment of analytical outputs with operational routines. A technically sophisticated model may have limited value when responsibilities are unclear, reporting systems are weak, or safety culture does not support evidence-based decision-making.

The contemporary literature on safety and reliability increasingly emphasizes the need for integrated and adaptive risk models. A recent review of fuzzy logic applications in complex engineering systems shows that fuzzy methods are widely used in safety assessment, reliability analysis, fault diagnosis, maintenance prioritization, and decision support (Kabir & Papadopoulos, 2025). These applications confirm the value of fuzzy logic for managing uncertainty, but they also reveal methodological fragmentation. Studies frequently develop specialized models for a particular type of equipment, risk, or analytical objective, making it difficult to transfer findings across different power plant contexts. Furthermore, many quantitative models assume that risk-management processes are already defined and that decision criteria are stable, whereas in practice, these processes emerge through interactions among technical experts, managers, maintenance personnel, contractors, safety officers, and regulatory structures. Risk management in power plant maintenance is therefore not only a computational problem but also an organizational and interpretive process.

Heavy and power plant industries require risk management systems capable of operating across strategic, tactical, and operational levels. At the strategic level, managers must define risk appetite, allocate budgets, establish policies, and determine acceptable levels of production and safety risk. At the tactical level, maintenance departments must plan inspections, preventive interventions, spare-parts inventories, workforce deployment, and shutdown activities. At the operational level, supervisors and technicians must identify immediate hazards, apply permit-to-work procedures, isolate energy sources, monitor equipment conditions, and respond to abnormal situations. The alignment of these levels is essential because decisions made at one level influence risk at the others. Comprehensive risk management in heavy industries therefore requires formal governance structures, clear responsibilities, systematic reporting, and coordination between technical and managerial functions (Horowitz & Arab-Mazar, 2024). Maintenance management must likewise integrate planning, execution, performance assessment, and continuous improvement rather than treating maintenance as a collection of isolated technical tasks (Kiani & Khodaparast, 2024).

Reliability engineering provides essential tools for understanding equipment performance and failure, but reliability metrics alone cannot explain how risk-management practices are developed within specific industrial contexts. Energy systems are affected by uncertainty, interdependence, complexity, and low-probability, high-consequence events, all of which require a systemic understanding of risk (Zio, 2023). In practice, the same technical hazard may be managed differently depending on organizational culture, resource constraints, managerial priorities, workforce competence, regulatory enforcement, and technological maturity. Consequently, risk-management models developed in one national or industrial context may not be directly applicable to another.

Power plants in Iran operate under particular technical, economic, regulatory, climatic, and organizational conditions. Equipment aging, restrictions in access to certain technologies and spare parts, variations in maintenance maturity, and differences in managerial systems may influence both the nature of risks and the strategies adopted to control them. A context-sensitive model is therefore needed to explain how risk-management practices are actually understood and implemented in Iranian power plant maintenance.

Existing studies have contributed substantially to equipment-level risk assessment, maintenance optimization, reliability modeling, fuzzy analysis, and multicriteria decision support. Risk-based reliability models have improved maintenance scheduling in gas power plants (Garcia & Torres, 2022), while studies of thermal power plants have demonstrated the value of risk-based maintenance management for prioritizing critical assets and reducing operational losses (Kumar & Singh, 2024). Fuzzy models have strengthened risk assessment under uncertain operational data (Liu et al., 2024), and probabilistic-fuzzy models have improved the representation of uncertainty in power plant equipment assessment (Rodriguez & Perez, 2024). Comprehensive risk analysis and multicriteria approaches have also enhanced maintenance planning and decision quality (Park & Choi, 2024; Song et al., 2024). Nevertheless, the literature remains dominated by quantitative, equipment-centered, and technique-specific approaches. Less attention has been devoted to developing an empirically grounded explanatory model that simultaneously incorporates causal conditions, contextual conditions, the central phenomenon, intervening factors, organizational strategies, and operational consequences.

This gap is particularly important because risk management in maintenance is shaped by interactions rather than isolated variables. Fire risks, electrical hazards, human error, technological change, organizational structure, safety culture, inspection quality, standards, training, and decision-making are dynamically connected. For example, an equipment defect may remain uncontrolled because inspection procedures are inadequate, maintenance resources are limited, reporting is delayed, or managers underestimate its consequences. Similarly, advanced monitoring technology may not reduce risk when employees lack training or when organizational processes do not support timely intervention. A comprehensive model must therefore explain not only what risks exist but also why they emerge, under what conditions they intensify, which factors modify their effects, what strategies organizations adopt, and what consequences follow from those strategies. Grounded theory is especially appropriate for this purpose because it enables the development of a conceptual model derived systematically from the experiences and interpretations of knowledgeable participants rather than imposing a predetermined analytical structure on the data.

The use of grounded theory can contribute to the maintenance and risk management literature by revealing relationships that may not be fully captured through predefined questionnaires or mathematical models. Expert interviews can identify tacit knowledge concerning failure patterns, decision processes, unsafe practices, organizational barriers, and practical control measures. Through open, axial, and selective coding, these insights can be organized into a paradigmatic structure that explains the central phenomenon and its relationship with causal, contextual, intervening, strategic, and consequential categories. Such a model can complement quantitative tools rather than replace them. Fuzzy logic, reliability analysis, failure mode and effects analysis, fault tree analysis, and multicriteria decision-making can provide valuable analytical support, while a grounded model can clarify how and when these tools should be applied within organizational practice (Ahmed & Hassan, 2023; Chen & Li, 2023; Kabir & Papadopoulos, 2025). The integration of qualitative understanding with technical analysis can thereby support a more realistic and operationally relevant approach to maintenance risk management.

A comprehensive risk management model can also generate practical value for power plant managers. By identifying the principal sources of risk and the organizational conditions that influence them, managers can improve preventive maintenance planning, prioritize inspections, strengthen safety barriers, and allocate financial and human resources more effectively. The model can assist in designing training programs, establishing risk committees, improving reporting systems, and integrating safety culture into maintenance governance. It may also support the selection of suitable analytical tools for different types of equipment and hazards. For instance, reliability-centered methods may be appropriate for recurring mechanical failures, fuzzy approaches may be useful when expert judgment is dominant, and probabilistic models may be suitable when sufficient failure data are available. Comprehensive risk analysis can thus create a bridge between strategic management and operational maintenance, allowing decision-makers to align equipment

reliability, personnel safety, environmental protection, and production continuity.

Moreover, the development of an indigenous model is essential for increasing the applicability and legitimacy of risk-management practices. Models imported from other industrial contexts may overlook local operational constraints, institutional arrangements, workforce characteristics, and management practices. Evidence from Iranian power plants regarding activity-level risks, organizational change, crisis management, and maintenance processes indicates that both technical and managerial dimensions must be considered (Babazadeh & Sadeghpour, 2023; Izadi Yazdanabadi & Mohammadbagheri, 2024). The inclusion of experts from safety, occupational health, maintenance, engineering, and management can produce a multidimensional account of the risk-management process. Such an account is particularly valuable for thermal power plants, where operational continuity must be balanced against the need to perform complex and potentially hazardous maintenance activities.

Accordingly, the aim of this study was to develop a comprehensive, context-sensitive model of risk management in power plant maintenance and repair using the grounded theory approach.

2. Methods and Materials

This applied study was conducted using a qualitative grounded theory approach based on the method proposed by Strauss and Corbin (2015). The exploratory nature of this method facilitates the identification and explanation of a model grounded in field data.

The research data were collected through both library-based and field methods. First, the theoretical foundations were extracted through a systematic review of the relevant literature. Subsequently, field data were collected through semi-structured interviews with 14 experts in safety, occupational health, and risk management in the power generation industry. The experts were selected through purposive sampling based on criteria such as theoretical knowledge, practical experience in power plants, a relevant professional or academic position, verified professional competence, and willingness to participate. Data collection continued until theoretical saturation was reached, and no new concepts emerged after the fourteenth interview. Two examples of the interview questions were: “What are the most important sources of risk in power plant maintenance activities?” and “How are maintenance decisions made in your power plant, and what factors influence these decisions?”

Following the interviews, qualitative data analysis was initiated using the grounded theory approach, and the preliminary concepts were extracted. The data were ultimately organized into six main categories: causal factors, contextual conditions, the central phenomenon—risk management in power plant maintenance and repair—intervening factors, strategies, and consequences. This classification formed the basis for developing the paradigmatic model of the study.

A set of complementary procedures was employed to ensure the credibility and dependability of the qualitative findings. The credibility of the findings was established through data triangulation by comparing the codes extracted from the interviews with industrial documents and reports, as well as through member checking. The dependability of the coding process was examined through intercoder agreement and the independent coding of a portion of the data by two researchers. Finally, the model and the final categories were reviewed by academic supervisors and senior industry managers to ensure their theoretical and operational relevance and to minimize researcher bias.

3. Findings and Results

This study was conducted in 2025. Using judgmental purposive sampling, 14 participants were selected according to predefined criteria. Regarding demographic characteristics, 10 experts (71.4%) were men and 4 (28.6%) were women. The participants’ ages ranged from 34 to 56 years, with a mean age of 44 years. All experts held postgraduate qualifications; four held doctoral degrees, and 10 held master’s degrees in fields related to safety, health, safety, and environment management, industrial engineering, and chemical engineering with a specialization in health, safety, and environment. In terms of organizational position, the interviewees included senior and middle managers of power plants as well as university faculty members. The experts had an average of approximately 12 years of work experience, ranging from 5 to 20 years, indicating substantial professional experience in the field under investigation. A summary of the interviews is presented below.

Table 1

Summary of the Participants' Interviews

Participant	Summary of the Interview
1	The primary focus was on fire risks, electrical hazards, and incidents with severe consequences. Emerging technologies in solar, wind, and combined-cycle power plants have created new risk patterns. Organizational structure contributes to the occurrence of human error. Strengthening preventive maintenance, engineering controls, and compliance with standards was considered essential. The integration of mathematical models into a comprehensive model was also proposed to support forward-looking decision-making.
2	Fire prevention and high-voltage risk control were identified as the highest priorities. New technologies have increased digital risks and challenges associated with solar panels. Poor coordination was considered a major cause of errors. Strengthening protective layers and continuous monitoring was deemed essential. The use of fuzzy modeling and a complementary model was recommended for analyzing turbine risks, chemical leakage, and human error.
3	Electrical and fire risks were considered to have the greatest potential for catastrophic incidents. New technologies have introduced additional risks into combined-cycle systems. Organizational structure affects the timing of incidents. Preventive maintenance and rigorous inspection are essential. The simultaneous application of failure mode and effects analysis, fault tree analysis, and analyses of turbine and chemical corrosion risks within a comprehensive model was recommended.
4	Reducing human error and improving organizational processes were identified as the principal dimensions of risk management. Strengthened supervision and engineering controls were considered essential to system maturity. Mathematical models were regarded as effective instruments for predicting future trends. Risks associated with falls, chemicals, hot work, and welding were identified as major project challenges requiring rigorous control.
5	Fire was identified as the most significant site risk and one that requires engineering controls and continuous monitoring. Challenges related to hot work can be managed through targeted training and the correction of unsafe behaviors. Promoting safety culture and safety leadership among contractors plays a key role and should be incorporated into the comprehensive model.
6	Analysis of failure rates and human error constitutes the basis of risk assessment. Organizational issues affect incident frequency. The implementation of preventive checklists and strengthening of safety barriers are essential. Fuzzy modeling and a comprehensive model were recommended for predicting future changes and improving decision-making.
7	Electrical and fire risks associated with instrumentation equipment were reported to be extremely high. Work pressure increases the likelihood of human error. Preventive maintenance, proper isolation, and stronger safety barriers are essential. A comprehensive model was proposed for analyzing future trends and reducing erroneous decisions.
8	Electrical, environmental, and fire risks were prioritized. The probability of failure is assessed using chemical data. Organizational weaknesses influence the temporal pattern of incidents. Preventive maintenance and stronger safety barriers were considered essential. Mathematical models and a comprehensive model were recommended to improve decision-making.
9	Condition monitoring is an effective instrument for predicting failures. Electrical risks and human error are among the principal challenges. Preventive maintenance, engineering controls, and compliance with standards were considered the foundations of risk management. The application of fuzzy models and a comprehensive model for future-oriented analysis, together with consideration of the diversity of power plant types, was regarded as essential.
10	Fire and electrical risks were considered highly probable. New technologies have created new risk patterns. Identifying equipment defects and organizational factors influences the management of incident timing. Preventive maintenance and protective layers are essential. A comprehensive model was introduced as an appropriate instrument for foresight and adaptation to different power generation technologies.
11	Electrical risks and organizational weaknesses were identified as major causes of incidents. Strengthening engineering controls and continuous supervision is essential. Mathematical models were recommended for future prediction. Risks associated with falls, working at height, lockout, and isolation were considered particularly important, and the establishment of risk committees was also deemed necessary.
12	Fire and electrical risks were prioritized, while emerging risks associated with solar and wind power plants are increasing. Failure and human-error monitoring is being implemented. Preventive actions and compliance with standards constitute the basis of risk management. A comprehensive model and mathematical analysis were proposed for decision-making. Training and safety culture were also considered particularly important.
13	Fire and electrical risks constitute the central focus of risk management. Compliance with national and international standards was considered essential. Mathematical models and a comprehensive framework are required for decision-making. Risks associated with turbines, vibration, falls, and unsafe acts should be analyzed. Safety culture and risk committees were identified as fundamental elements of the proposed model.
14	Risks associated with solar and wind power plants should be incorporated into the comprehensive model. Deposits, water treatment, falls from height, and chemical changes are major challenges. Training and the promotion of safety culture are essential. Isolation, tagging, and environmental-production risks were identified as key dimensions of risk management.

In the second stage of analysis, axial coding was performed to organize the concepts obtained through open coding. The 122 initial concepts were organized into 41 subcategories based on causal, contextual, action-oriented, and consequential relationships. This process was conducted according to the coding paradigm developed by Strauss and Corbin (2015) and continued until theoretical saturation was achieved. In the third stage, selective coding focused on the central phenomenon of "risk management in power plant maintenance and repair." Through an analysis of relationships among the categories, the final model was developed around six main categories: causal factors, contextual conditions, the central phenomenon, intervening factors, strategies, and consequences. To avoid repetition, the axial and selective coding stages were implemented in an integrated manner.

Table 2

Axial and Selective Coding

Paradigmatic Dimension	Subcategory	Initial Concepts—122 Initial Codes	Example of Interview Code
Central phenomenon	Risk management in power plant maintenance and repair	—	"Expert 3: Without structured risk management, reliable maintenance planning is impossible."
Causal factors	Principal risks	Overall risk, baseline risk, systemic risk	"Expert 6: Baseline risk is always present; only the magnitude of its consequences changes."
Causal factors	Fire risks	Process fires, electrical arcs, fuel/oil flammability, heat release	"Expert 9: A minor oil leak near a turbine is sufficient to cause a fire incident."
Causal factors	Environmental and electrical risks	Electrical shock/short circuit, transformers and busbars, moisture/corrosion	"Expert 11: Moisture and corrosion in high-voltage panels are the principal causes of sudden short circuits."
Causal factors	Severe incidents	Catastrophic consequences, multidimensional incidents, failure chains	"Expert 4: A minor error can create a chain of failures."
Causal factors	Severity of human error	Digitalization, cybersecurity, energy-storage systems, hydrogen	"Expert 13: Digitalization has transformed errors from physical errors into cognitive errors."
Causal factors	Causes of human error	Dust contamination, panel surface temperature, inverter	"Expert 7: Dust-covered panels multiply the probability of operator error."
Causal factors	Probability of equipment failure	Wind loading, blade fatigue, bearings/gearboxes	"Expert 5: If turbine-blade fatigue is not predicted, it manifests suddenly."
Causal factors	Unsafe acts	Heat recovery steam generator, gas/steam turbine, cycle integrity	"Expert 10: In a heat recovery steam generator, a minor operator error is sufficient to destabilize the cycle."
Contextual conditions	Emerging risks	Equipment failure rate, mean time between failures, failure patterns	"Expert 8: Failure patterns in new power plants are no longer the same as those observed in the past."
Contextual conditions	Specific and solar-related risks	Severity of human error, task sensitivity, cognitive workload	"Expert 14: In solar power plants, human error is more cognitive and can rapidly result in an incident."
Contextual conditions	Wind-related risks and work pressure	Structure/process, resource shortages, interdepartmental coordination	"Expert 6: In wind power plants, interdepartmental coordination is a fundamental challenge."
Contextual conditions	Combined-cycle risks	Seasonal/shift-related factors, peak workload, event sequences	"Expert 12: Seasonal variations completely affect cycle behavior."
Contextual conditions	Differences among power plant types	Preventive maintenance, condition-based maintenance, checklists, preventive inspection	"Expert 2: Inspections are more critical in steam power plants than in gas power plants."
Contextual conditions	Operational risks	Risk-control engineering, isolation, layered protection	"Expert 11: Operations are reliable only when multilayer protection is implemented."
Contextual conditions	Chemical risks	Technical/administrative barriers, layer of protection analysis, human barriers	"Expert 3: A minor error involving chemicals can lead to the isolation of the unit."
Contextual conditions	Turbine and technical risks	Inspection effectiveness, auditing, supervisory key performance indicators	"Expert 9: Detecting a minor change in turbine vibration reduces half of our risk."
Contextual conditions	Specialized and spool-related risks	Updating, compliance with ISO/IEC standards, localization	"Expert 10: Spools must be updated in accordance with new standards to reduce risk."
Contextual conditions	Environmental-production risks	Process maturity, feedback and learning, plan-do-check-act cycle	"Expert 4: Without organizational learning, errors are continuously repeated."
Contextual conditions	Temporal pattern of incidents	Failure mode and effects analysis/failure mode, effects, and criticality analysis; fault tree analysis; fuzzy/probabilistic methods	"Expert 7: Most power plant incidents have identifiable temporal patterns and can be analyzed."
Intervening factors	Safety barriers	Technical, economic, safety, and environmental dimensions; fuzzy weighting	"Expert 15: Safety barriers must also be economically acceptable."
Intervening factors	Adequacy of standards	Technological trends, future regulations, climate	"Expert 5: The pace of technological development is greater than that of standards."
Intervening factors	Safety culture	Decision dashboards, scenarios, project prioritization	"Expert 1: Unless a safety culture is established, no management model will be effective."

Intervening factors	Future challenges	Blades/rotors, combustion, auxiliary systems	"Expert 14: New turbines are more sensitive, and future risks will be more complex."
Intervening factors	Temporal pattern of hazards and events	Spools/shafts, alignment/vibration, creep/cracking	"Expert 6: Equipment vibration and creep generally follow identifiable temporal trends."
Intervening factors	Type of decision-making	Start-up/shutdown operations, emergency maneuvers	"Expert 8: Hasty decisions during shutdown create the greatest probability of error."
Strategic factors	Preventive measures	Leakage/reactivity, material safety data sheets, ventilation	"Expert 9: Minor leaks can rapidly cause an incident when they are not taken seriously."
Strategic factors	Effective control methods	Procedural deficiencies, fatigue/pressure, inadequate training	"Expert 12: Most incidents result from procedural deficiencies and inadequate training."
Strategic factors	Effectiveness of supervision	Cooling systems, water treatment, deposits/corrosion	"Expert 13: A minor reduction in cooling-system performance is an indication of a major future hazard."
Strategic factors	Improvement of risk management	Integration of approaches, model synergy, multicriteria methods	"Expert 3: Integrating several risk models always produces more accurate results."
Strategic factors	Mathematical risk-analysis models	Falls, access equipment, permit-to-work protocols	"Expert 11: Models function properly only when accurate field data are available."
Strategic factors	Complementarity of models	Chemical change management, storage, material compatibility	"Expert 4: No single model is sufficient; integrating models provides a realistic picture."
Strategic factors	Risk training	Hot work/welding, ignition sources, work permits	"Expert 15: Training based on actual incidents is several times more effective than theoretical classroom instruction."
Strategic factors	Risk committees	Temporal trends, incident clusters, near-miss events	"Expert 2: An active risk committee identifies near-miss events at an earlier stage."
Strategic factors	Energy-isolation risks	Competence/skills, refresher training, incident-based training	"Expert 10: In lockout/tagout procedures, the main problem is the absence of final operator verification."
Strategic factors	Correction of unsafe acts	Violations/shortcuts, personal protective equipment, procedural compliance	"Expert 7: Taking shortcuts in routine work is the most common cause of unsafe acts."
Consequences	Components of a comprehensive risk model	Safety values, leadership, reporting/transparency	"Expert 5: Strong safety leadership results in more accurate reporting."
Consequences	Improvement of final decision-making	Complex work at height, wind/structures, emergency rescue	"Expert 6: During work at height, an incorrect decision made within seconds can be fatal."
Consequences	Management of work at height	Thermal/steam/combined-cycle/renewable power plants, design/age	"Expert 9: Wind and structural conditions directly affect work at height and must be anticipated."
Consequences	Management of hot work	Environmental-production effects, pollution/noise, discharges	"Expert 8: During hot work, a minor spark can cause a major incident."
Consequences	Chemicals and management of change	Risk committees, roles/responsibilities, reporting	"Expert 12: A minor change in chemical storage will inevitably cause an incident if it is not documented."
Consequences	Risks associated with height	Energy isolation, lockout/tagout, testing and verification	"Expert 4: If lockout/tagout is not fully implemented during work at height, a fall is almost inevitable."

The subcategories extracted during open coding were organized around a central category. Data analysis demonstrated that "risk management in power plant maintenance and repair," as the central phenomenon, integrates the conceptual structure of the study, while the other categories acquire meaning through their relationships with this phenomenon. Accordingly, the relationships among the categories were examined systematically, and the final research model was reconstructed in the form of six main categories: causal conditions, contextual conditions, the central phenomenon, intervening factors, strategies, and consequences.

The first group of categories concerns causal factors, which serve as the initial drivers underlying the need for risk management in power plant maintenance and repair activities. Within this dimension, categories such as principal risks—including overall risk, baseline risk, and systemic risk—were identified, reflecting the complex and multidimensional nature of hazards in power plant environments. Fire risks, including process fires, electrical arcs, the flammability of fuels and oils, and heat release,

were also identified as among the most significant safety threats in power plants. In addition, environmental and electrical risks, such as electrical shock and short circuits, problems associated with transformers and busbars, and the effects of moisture and corrosion, can disrupt equipment performance and contribute to the occurrence of incidents. Severe and catastrophic incidents, which may occur through chains of failures, further emphasize the importance of systematic risk management. Another important dimension involves human factors, including the severity of human error, the causes of error, and unsafe acts. Developments such as digitalization and modern technologies have created more complex conditions for human error, while factors such as environmental contamination, work pressure, and equipment defects may increase the probability of error. Furthermore, the probability of equipment failure, particularly in components such as blades, bearings, and gearboxes, as well as the operating conditions of different power plant units, constitutes an important causal factor in the emergence of operational risks.

The second group of categories relates to contextual conditions, which provide the setting and environment in which risk management is developed and implemented. Emerging risks associated with equipment failure rates, indicators such as mean time between failures, and failure patterns were considered within this dimension, demonstrating the importance of analyzing operational performance data in risk prediction. Specific risks associated with different power generation technologies, including solar, wind, and combined-cycle systems, were also identified, each of which has distinctive operational characteristics and hazards. For example, work pressure, employees' cognitive workload, and task complexity can increase the probability of error. In addition, structural differences among power plant types necessitate the adoption of different maintenance approaches, such as preventive maintenance and condition-based maintenance. Operational and technical risks, including risk-control engineering, process isolation, and the use of protective layers, were also considered. In the area of process safety, chemical risks and the application of instruments such as layer of protection analysis and technical and human barriers are particularly important. Turbine-related and specialized equipment risks, inspection effectiveness, supervisory indicators, the updating of standards, and compliance with international frameworks constitute other influential contextual conditions. Finally, factors such as the maturity of organizational processes, organizational learning cycles, and the temporal patterns of incident occurrence were identified as important elements shaping the risk management environment.

The third group of categories concerns intervening factors, which may modify the intensity or manner in which causal and contextual factors exert their effects. Safety barriers encompassing technical, economic, safety, and environmental considerations play a significant role in controlling hazards, and methods such as fuzzy weighting may be used to assess them. The adequacy of standards and regulations in responding to technological trends, climate change, and future legal requirements is another important issue that can influence the effectiveness of risk management. Organizational safety culture may also affect the management of risk through instruments such as decision-making dashboards, scenario analysis, and project prioritization. Furthermore, future technical challenges related to blades, rotors, combustion systems, and auxiliary equipment, as well as the temporal patterns of hazards and failures in components such as shafts and vibration systems, constitute intervening factors. The type of decision-making adopted under operating conditions, including unit start-up and emergency shutdown, may also alter the level of risk.

In response to these conditions, organizations implement a range of managerial and action-oriented strategies. These strategies include preventive measures such as controlling material leakage, managing chemical reactivity, using material safety data sheets, and improving workplace ventilation. Effective risk-control methods are also pursued by correcting procedures, reducing work pressure, and improving employee training. Enhancing the effectiveness of supervisory systems through monitoring cooling systems, water treatment, and phenomena such as deposits and corrosion represents another important course of action. At the managerial level, risk management is improved through the integration of different analytical approaches, the application of multicriteria models, and the use of mathematical risk-analysis models. These models complement one another and, together with instruments such as failure mode and effects analysis, fault tree analysis, and probabilistic and fuzzy methods, can provide a more accurate understanding of hazards. In addition, specialized risk training, the establishment of risk committees, energy-isolation management through lockout/tagout procedures, and the correction of unsafe behaviors constitute practical strategies for reducing hazards in power plant environments.

The implementation of these strategies ultimately produces a range of organizational and operational

consequences representing the final outcomes of the risk management model. The most important consequence is the development of a comprehensive risk management model based on safety values, organizational leadership, and a transparent reporting system, which can strengthen the organization's safety culture. Another significant consequence is improvement in the quality of managerial decision-making regarding high-risk activities, including work at height, operations under windy conditions or on elevated structures, and emergency rescue operations. Structured mechanisms also facilitate the safe management of activities such as hot work, chemical control, and operational change management. Ultimately, the rigorous implementation of procedures such as energy isolation, equipment lockout and tagging, and safety testing and verification before work commences will enhance the level of safety in power plant maintenance and repair operations.

Based on 122 initial concepts and 41 subcategories, this paradigmatic model explains the dynamic interaction among causal, contextual, intervening, strategic, and consequential dimensions within the risk management process for power plant maintenance and repair. Its overall structure is presented in the following figure.

Figure 1

The Research Paradigmatic Model

4. Discussion and Conclusion

The present study developed a comprehensive grounded theory model of risk management in power plant maintenance and repair based on the experiences of experts in safety, occupational health, maintenance, engineering, and risk management. The findings showed that risk management in power plant maintenance is formed through the dynamic interaction of six main dimensions: causal factors, contextual conditions, the central phenomenon, intervening factors, strategies, and consequences. The central phenomenon was identified as "risk management in power plant maintenance and repair," around which 122 initial concepts and 41 subcategories were organized. The findings indicate that maintenance risk cannot be explained solely by equipment failure or technical deficiencies. Rather, it emerges from interactions among equipment condition, human performance, organizational structure, technological change, environmental conditions, safety culture, regulatory adequacy, and managerial decision-making. This result supports the systemic view of risk in complex energy systems, according to which failures and adverse events are produced by interdependent technical, organizational, and human mechanisms rather than by a single isolated cause (Zio, 2023). The model also extends conventional maintenance approaches by demonstrating that risk

management is simultaneously a technical, behavioral, structural, and strategic process.

The causal factors identified in this study included principal operational risks, fire and electrical hazards, severe incidents, equipment failure, human error, and unsafe acts. Fire, electrical shock, short circuits, fuel and oil ignition, turbine-related failures, corrosion, vibration, and cascading equipment breakdowns were repeatedly emphasized by the participants. These findings are consistent with previous studies showing that power plant maintenance involves high-consequence hazards whose effects may extend beyond individual components and disrupt the operation of entire generating units. Risk-based maintenance studies in gas and thermal power plants have similarly shown that equipment criticality must be assessed through the joint consideration of failure probability and consequence severity (Garcia & Torres, 2022; Kumar & Singh, 2024). The identification of fire, electrical, and process risks also corresponds with the application of failure mode and effects analysis in combined-cycle power plants, where hazardous activities and equipment failures are prioritized according to their potential effects on safety and operation (Babazadeh & Sadeghpour, 2023). The present findings therefore confirm that maintenance planning should not be based merely on routine schedules; instead, it should prioritize components and activities capable of producing severe safety, production, environmental, or financial consequences.

Human error emerged as another major causal dimension. Participants referred to cognitive overload, work pressure, fatigue, unsafe shortcuts, inadequate procedural compliance, and operator errors during complex operations such as shutdown, start-up, hot work, and energy isolation. The importance of these findings lies in showing that human error is not simply an individual deficiency but is affected by task complexity, organizational coordination, equipment design, technological change, and managerial pressure. Increasing digitalization may reduce some traditional physical errors while simultaneously creating new cognitive and decision-related risks. This interpretation aligns with the broader literature on complex engineering systems, which recognizes that safety and reliability depend on interactions among humans, technologies, and organizational systems (Kabir & Papadopoulos, 2025). It also corresponds with evidence indicating that organizational readiness, attitudes toward change, interpersonal conflict, and crisis-management capacity influence the effectiveness of managerial responses in power plant settings (Izadi Yazdanabadi & Mohammadbagheri, 2024). Therefore, controlling human error requires more than technical instruction; it requires workload management, procedural redesign, supervision, communication improvement, and the development of a supportive safety culture.

The contextual conditions identified in this study included emerging risks, differences among power plant types, failure patterns, mean time between failures, operational and chemical hazards, turbine-related risks, inspection quality, process maturity, and organizational learning. These findings demonstrate that the risk profile of maintenance activities changes according to plant technology, equipment age, operating conditions, workload, environmental exposure, and the maturity of maintenance systems. Thermal, steam, gas, combined-cycle, solar, wind, and energy-storage facilities possess different failure modes and require distinct maintenance strategies. The finding that preventive maintenance and condition-based maintenance should be adapted to the technological and operational characteristics of each plant is consistent with maintenance management literature emphasizing the importance of selecting maintenance policies according to equipment criticality, degradation behavior, and operating context (Kiani & Khodaparast, 2024; Nikseresht, 2023). Reliability, maintainability, and availability indicators can support this differentiation by providing evidence regarding equipment performance and the timing of maintenance interventions (Hemmati & Soleimani, 2023). Consequently, a uniform maintenance approach is unlikely to be equally effective across all power generation technologies.

The emergence of risks associated with renewable technologies, digital systems, and energy-storage facilities was another important contextual finding. Participants indicated that solar panels, wind turbines, digital control systems, inverters, energy-storage units, and combined-cycle technologies create new forms of technical and cognitive risk. These findings are compatible with research on the management of large-scale energy-storage power plants, which shows that operational optimization must be accompanied by attention to system behavior, degradation, and technical uncertainty (Motallebi-Nejad et al., 2023). They also reinforce the argument that modern power plants require adaptive risk-management systems capable of responding to changing technological configurations. The increasing use of sensors, automated controls, and data-driven maintenance may improve failure prediction, but it can also generate risks related to data quality, software dependence, cybersecurity, and operator interpretation. The grounded model therefore suggests that emerging

technological risks should be integrated into maintenance planning rather than treated as separate or temporary concerns.

Another central finding concerned uncertainty in operational data and expert judgments. Participants emphasized the usefulness of mathematical, probabilistic, fuzzy, and hybrid models for predicting failures, ranking risks, and supporting maintenance decisions. In power plant environments, available data may be incomplete, inconsistent, or affected by variations in load, environmental conditions, maintenance history, and equipment age. Fuzzy logic is particularly suitable for such conditions because it can represent qualitative judgments and uncertain information in a structured manner. Previous research has shown that fuzzy logic models can improve maintenance optimization in energy industries by integrating expert judgments with technical criteria (Ahmed & Hassan, 2023). Fuzzy models have also been used to manage uncertainty in complex energy systems and to combine operational, technical, and environmental risk indicators (Chen & Li, 2023). The findings of the current study therefore support the use of fuzzy approaches as decision-support tools, particularly when statistical records are limited or when experts express assessments linguistically.

The participants also highlighted the importance of combining analytical methods rather than relying on a single risk-assessment technique. The proposed model included the complementary use of failure mode and effects analysis, fault tree analysis, reliability analysis, fuzzy modeling, probabilistic methods, and multicriteria decision-making. This finding is consistent with hybrid fuzzy-probabilistic studies, which have demonstrated that randomness and epistemic uncertainty can be represented more effectively when different analytical approaches are integrated (Rodriguez & Perez, 2024; Silva & Mendes, 2023). Similarly, fuzzy risk-assessment frameworks have been developed for power plant equipment under uncertain operational data (Liu et al., 2024), while fuzzy reliability models have been used to improve maintenance planning for complex engineering systems (Yadav & Singh, 2023). Fuzzy assessment models designed specifically for thermal power plant maintenance also demonstrate that equipment risks can be prioritized more accurately when probability, severity, and uncertainty are evaluated simultaneously (Zhang & Liu, 2023). The current study advances these findings by showing that model complementarity is not only a methodological issue but also an organizational strategy that enables managers to select appropriate tools according to the nature of the risk and the available data.

The intervening factors identified in the model included safety barriers, the adequacy of standards, organizational safety culture, future technological challenges, temporal patterns of hazards, and the type of operational decision-making. Safety barriers were found to encompass technical, administrative, economic, human, and environmental dimensions. This suggests that even when hazards are correctly identified, risk outcomes depend on the availability and effectiveness of protective layers. Layered protection, process isolation, inspection, engineering controls, and permit-to-work systems can interrupt the progression of an incident. However, barriers may fail when standards are outdated, resources are insufficient, or employees do not comply with procedures. This finding corresponds with comprehensive risk-management perspectives in heavy and power plant industries, which emphasize that risk control requires the alignment of technical measures, governance structures, and organizational responsibilities (Horowitz & Arab-Mazar, 2024). It also indicates that standards should be regularly updated to address rapidly developing technologies and new operational risks.

Safety culture was identified as a particularly influential intervening factor. Participants noted that leadership commitment, transparency, reporting, employee participation, and management support affect whether risk controls are actually implemented. A technically sound risk model may have little practical effect when employees are reluctant to report near misses, managers prioritize production over safety, or contractors operate under inconsistent expectations. The finding that safety culture affects the success of maintenance risk management is compatible with the broader conclusion that organizational conditions shape crisis-management capability and institutional performance (Izadi Yazdanabadi & Mohammadbagheri, 2024). It also explains why the same formal standards may produce different outcomes in different plants. Safety culture functions as a mechanism through which procedures, training, supervision, and risk communication are translated into everyday behavior. Therefore, cultural development should be regarded as an integral component of maintenance risk management rather than as an independent human-resources initiative.

The strategic dimension of the model included preventive measures, engineering controls, improved supervision, risk education, mathematical modeling, risk committees, lockout/tagout procedures, and the correction of unsafe

behavior. Preventive maintenance was consistently identified as a principal strategy for reducing failure probability and preventing unplanned shutdowns. This finding aligns with risk-based maintenance research showing that maintenance resources should be concentrated on critical equipment and high-consequence failure modes (Garcia & Torres, 2022; Kumar & Singh, 2024). Comprehensive risk analysis can improve this process by integrating equipment condition, failure probability, consequence severity, and organizational priorities (Park & Choi, 2024). The present study further indicates that preventive maintenance must be accompanied by condition monitoring, effective inspection, accurate field data, and timely managerial response. Preventive programs that generate data but fail to trigger action are unlikely to reduce risk substantially.

Multicriteria decision-making was also reflected in the participants' emphasis on balancing safety, reliability, cost, environmental protection, and production continuity. Power plant managers frequently face competing priorities, particularly when maintenance budgets and shutdown opportunities are limited. Fuzzy multicriteria decision-making can assist managers in weighting different criteria and ranking maintenance alternatives under uncertainty (Song et al., 2024). The present results support this approach but also indicate that the quality of multicriteria analysis depends on stakeholder involvement, reliable data, and agreement regarding organizational priorities. A decision model that ignores operational constraints or the experience of maintenance personnel may produce recommendations that are analytically valid but practically infeasible. Therefore, the grounded model proposes that analytical tools should be embedded within participatory and transparent decision processes.

The establishment of risk committees was another significant strategy identified in the study. Active risk committees can coordinate maintenance, safety, operations, engineering, and management functions; review near misses; analyze recurring failures; and prioritize corrective actions. This finding is important because risk information in power plants is often dispersed across departments. Maintenance personnel may possess knowledge of equipment degradation, safety officers may monitor hazardous behavior, and operators may recognize abnormal operating patterns. Without a formal mechanism for integrating these perspectives, early warning signals may be overlooked. Risk committees can therefore serve as organizational platforms for collective learning, cross-functional communication, and accountability. They can also ensure that outputs from reliability models, fuzzy assessments, inspections, and incident analyses are translated into operational decisions.

The consequences identified in the model included the development of a comprehensive risk-management framework, improvement in managerial decision-making, safer work at height, better management of hot work and chemical activities, stronger management of change, and more effective energy isolation. These outcomes indicate that the ultimate value of risk management lies not in the production of risk scores but in its influence on real organizational and operational behavior. Comprehensive models can support managers in allocating resources, prioritizing maintenance, designing controls, and responding to emerging risks. This result is consistent with research showing that comprehensive risk analysis improves maintenance planning and the prioritization of power plant equipment (Park & Choi, 2024). It is also aligned with reliability-based maintenance approaches, which aim to improve availability and reduce operational losses through systematic decision-making (Garcia & Torres, 2022; Hemmati & Soleimani, 2023).

Overall, the study contributes to the literature by integrating technical, human, organizational, environmental, and decision-related elements within a single grounded model. Previous studies have often focused on particular tools, such as fuzzy logic, FMEA, reliability analysis, or multicriteria decision-making. The present findings do not reject these approaches; rather, they position them within a broader explanatory structure. Fuzzy and probabilistic models can estimate and rank risks, reliability analysis can identify critical equipment, and multicriteria methods can support prioritization, but their effectiveness depends on organizational culture, standards, training, leadership, data quality, and coordination. The study therefore supports a socio-technical interpretation of maintenance risk management in which technical models and organizational processes are mutually dependent. Such an interpretation is consistent with contemporary reviews of safety and reliability analysis in complex engineering systems (Kabir & Papadopoulos, 2025) and with systemic approaches to energy risk analysis (Zio, 2023).

This study had several limitations. First, the model was developed from interviews with 14 experts working within the Iranian power generation context, and the findings may therefore reflect the regulatory, technological, managerial, and organizational characteristics of this setting. Second,

although theoretical saturation was achieved, the sample did not include all possible stakeholder groups, such as contractors, frontline technicians, regulators, equipment manufacturers, and emergency-response personnel. Third, the study relied primarily on participants' professional experiences and interpretations, which may have been influenced by recall bias, organizational position, or personal perceptions of risk. Fourth, the proposed model was developed qualitatively and was not statistically tested using a large sample. Finally, differences among thermal, gas, steam, combined-cycle, renewable, and energy-storage plants were identified, but each plant type was not examined separately in sufficient depth.

Future studies should quantitatively validate the proposed model using structural equation modeling, confirmatory factor analysis, or expert-based weighting methods. Researchers may also develop measurement instruments for the six main dimensions and 41 subcategories identified in this study. Comparative studies across different types of power plants, geographical regions, and national regulatory systems could determine which elements of the model are universal and which are context-specific. Longitudinal research is recommended to evaluate whether implementation of the model reduces incident frequency, unplanned shutdowns, maintenance costs, and equipment failure over time. Future studies could also integrate the grounded model with fuzzy inference systems, Bayesian networks, digital twins, machine-learning algorithms, and real-time condition-monitoring data. Additional qualitative research involving technicians, contractors, operators, and regulators would further enrich the model and identify differences between managerial and frontline perceptions of risk.

Power plant managers should establish an integrated maintenance risk-management system that connects equipment reliability, occupational safety, process safety, environmental protection, and production planning. Maintenance priorities should be determined through equipment criticality, failure history, consequence severity, and condition-monitoring data rather than through fixed schedules alone. Risk committees should be established with representatives from maintenance, operations, safety, engineering, and senior management. Organizations should strengthen near-miss reporting, management-of-change procedures, contractor supervision, lockout/tagout verification, hot-work controls, and work-at-height planning. Training programs should be based on actual incidents and plant-specific scenarios. Managers should also invest in reliable data systems, updated inspection programs, and decision-support tools capable of integrating fuzzy, probabilistic, reliability-based, and multicriteria analyses. Most importantly, leadership should ensure that safety considerations remain central to maintenance decisions, even under production pressure or resource constraints.

Authors' Contributions

Authors contributed equally to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Declaration of Interest

The authors report no conflict of interest.

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Ethics Considerations

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