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An Investigation of Operator Situation Awareness Utilizing the Fuzzy Comprehensive Evaluation Method

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Abstract

The escalating complexity of power grids underscores the growing reliance on nuclear power for stability, highlighting the critical role of situational awareness in nuclear safety and operator well-being. Deficiencies in this awareness can result in incidents that threaten plant operations and workforce health, emphasizing the need for its enhancement to ensure operational efficiency and worker protection in a high-stakes industry. This research systematically identifies and categorizes factors contributing to situational awareness gaps using interdisciplinary principles. Analyzed within a stratified framework, these factors are targeted for improvement through procedural enhancements, team collaboration, knowledge exchange, and training, with the aim of bolstering safety and occupational health outcomes. The study introduces a three-tiered framework that identifies 22 Precursory Influencing Factors (PIFs) across four critical categories, addressing the safety and health challenges operators encounter in dynamic operational contexts. This framework is designed to proactively manage occupational health risks, thereby fostering a safer work environment and safeguarding the operational integrity and long-term health of nuclear plant personnel. By employing the Fuzzy Comprehensive Evaluation Method, the findings provide substantial insights for advancing nuclear power plant management, particularly concerning occupational health and safety. The study establishes a foundational framework for robust safety management, focusing on the well-being of operators. Anticipated outcomes include elevated safety standards and a culture prioritizing occupational health, leading to increased reliability, integrity, and a healthier work environment in nuclear operations.

Keywords: situation awareness, nuclear power plants, fuzzy comprehensive evaluation method, peak-shaving

1. Introduction

In any system, human actions are inextricably linked to the situational environment in which they occur. Human error, because of this context, is often a reflection of the environment in which individuals operate. Situation Awareness (SA) represents an individual's cognitive perception of their operational environment. Originally a concept within aviation psychology, SA describes a pilot's dynamic comprehension of the events unfolding within their specific situation. During World War I, SA was recognized as crucial for operational success, indicating a level of understanding of "what is happening" in each context. In 1988, Endsley formalized this concept at the International Human Factors Association's annual conference, defining SA as the understanding and anticipation of the environment's constituent elements within a specific time and space [1]. In the realm of human factors research, SA is characterized by an operator's accurate comprehension of the various components within a complex human-machine system, enabling informed decision-making[2].In the domain of nuclear energy, Pengcheng Li has proposed that SA encompasses the cognitive process and analytical outcome where an operator acquires state information related to the power plant through surveillance, processes this information using appropriate methods, and thereby ascertains the current state of the plant as well as makes educated predictions about its future status[3]. Endsley has highlighted the critical role of SA, noting that its absence is a contributing factor in 88% of commercial aviation accidents [1]. This underscores the significance of SA in preventing human-induced errors and subsequent safety incidents.

With the advent of digital nuclear power plants engaging in load-following operations, the variability in grid frequency due to load fluctuations necessitates frequent adjustments in reactor power output. These adjustments are characterized by fluctuating, high-amplitude, rapid, and complex waveforms. Operators must interact continuously with the control system to acquire real-time plant parameters, ensuring informed decision-making. Under such conditions, these operations become routine, potentially escalating the risk associated with nuclear power plant operations. From a safety technology perspective, the sustained high-intensity workload faced by operators in these scenarios increases the complexity of unit control and, consequently, the risk of SA-related errors.

While existing SA research has predominantly focused on aviation, nuclear power, and transportation sectors, there appears to be a gap in studies specifically addressing SA in the context of nuclear power plants participating in grid load balancing. This paper aims to bridge this gap by examining ways to enhance the SA of nuclear power plant operators during grid load-following operations, thereby mitigating the occurrence of unsafe practices from an SA perspective.

2. Comparison of Operator Task Characteristics

With the participation of a nuclear power plant in the grid peaking program, the operator's operations transition from unique power adjustments to routine tasks, requiring the execution of activities within predefined time windows. These involve a significant number of tasks classified as Class I and II, akin to transient event operations within nuclear facilities. The operational demands involve rapid fluctuations in the system environment, heightened pressures, increased operational intensity, and compounded consequences resulting from the operator's reduced temporal flexibility.

Compared to standard operational scenarios, digital nuclear power plants engaging in grid peaking impose additional stresses through frequent start-stop procedures, necessitating adaptations to dynamic situational states, individual performance, team shifts, and organizational adjustments.

Table 1 Comparison of the characteristics of operational tasks before and after peak-shaving

Comparison Points	Operational Tasks under Normal Conditions	Operational Tasks after Grid Peak-Shaving Operation
Operation Task	Operational tasks are relatively straightforward with a larger operational time window, allowing operators to plan and execute in advance.	The tasks consist of a variety of Class I and II operations. The tasks become more complex in operability, with a narrowed operational time window, often leaving insufficient time for pre-planning.
Operation Mode	Under normal conditions, operators can carry out operations as stipulated.	The tasks are emergent, and operators cannot make plans but must act according to the best contingency plans formulated by the site supervisor.
Operational Load	Composed of physical load, time load, psychological load, and a small part of information load.	In the initial phase of peak shaving, the physical, time, psychological, and information loads are greatly increased; in the middle and later stages of peak shaving, the operational load is similar to that under normal conditions.
Operational Pattern	The operator individually decides how to operate.	When faced with sudden peak-shaving tasks, the decision-making is no longer solely in the hands of the control room operator but is collectively discussed by all members of the control room operation team to reach a consensus. The final decision is made by the shift supervisor on duty.

Drawing from the literature [4], the subsequent table meticulously details the distinctive dissimilarities between the operations in a nuclear power plant during grid peaking activities and those under normal operating conditions, as illustrated in Table 1.

3. Classification and Screening of Basic Influencing Factors

Performance Influencing Factors (PIFs) refers to the elements that shape human behavior and operations. The presence of undesirable PIFs can, to a certain extent, elevate the risk of human-induced errors. The determinants of Situational Awareness (SA) are primarily elucidated through a synthesis of the influencing elements posited by various scholars in recent years.

However, given that previous research has predominantly concentrated on sectors such as aviation, aerospace, and maritime navigation—where factors are intricate and distinct from those affecting operators—initial screening has identified SA-related factors that correspond with the actual conditions of operators. This process has been conducted alongside a broad collection of potential influencing factors [5-16].In the context of digital nuclear power plants within power system peak-shaving operations, it is essential to focus on the unique characteristics and variances from conventional operational tasks. To achieve a profound comprehension of these distinguishing features and nuances, methodologies from human factors engineering, cognitive psychology, and behavioral sciences are integrated. Furthermore, accounting for all PIFs pertinent to sophisticated, large-scale systems, grounded in systems theory, culminates in the formation of a foundational framework for categorizing the basic PIFs that influence SA in digital nuclear power plants. This framework encompasses a spectrum of elements, including individual factors, team dynamics, situational state factors, organizational aspects, regulatory body influences, and governmental factors. Ultimately, considering the operational tasks of nuclear power plants post-integration into grid peak regulation, the factors contributing to SA deficiencies have been meticulously summarized and classified, as depicted in Figure 1.

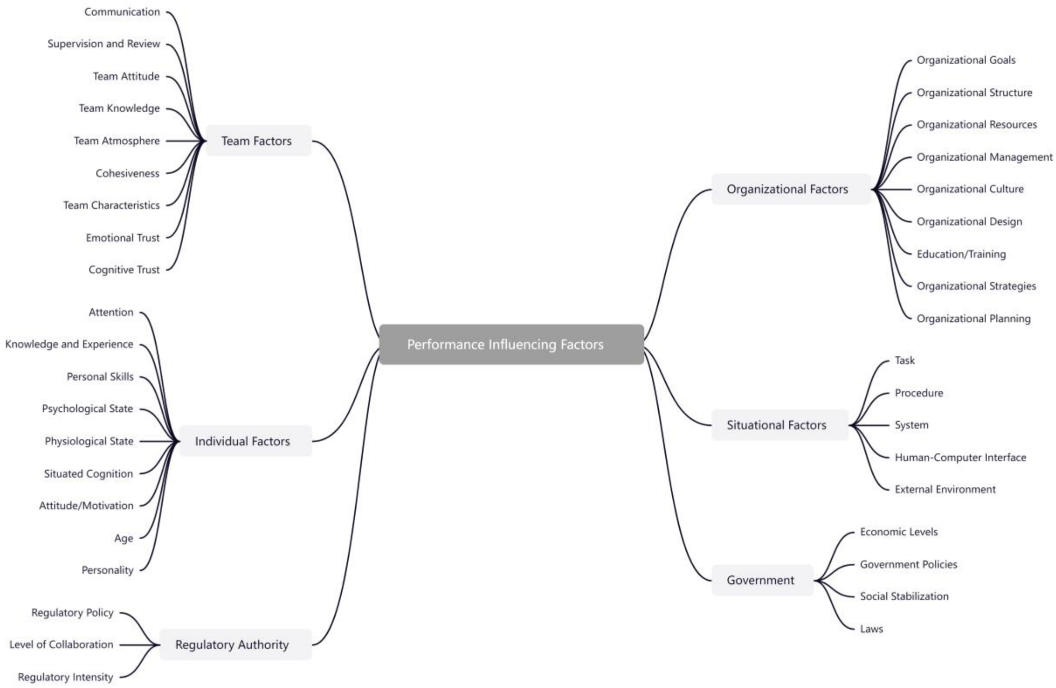

Fig. 1 Classification of operator SA failures in the context of nuclear plant peaking

To enhance the efficacy of the framework revisions, this study has drawn upon a subset of the literature [4-17]to amend the framework. Additionally, an analysis of the collected incident reports revealed an absence of representations of external organizational influences; hence, the impact of external organizational factors is not considered in this study. In alignment with the research by Li Pengcheng and the outcomes of our research team's investigations [3], the classification system described herein has been ultimately established.

Following the refinement of Performance Influencing Factors (PIFs) from an organizational vantage point, the categorization of factors influencing Situation Awareness (SA) errors within digital nuclear power plants is delineated in Figures 2 and Table 2. This study culminates in the establishment of a three-tiered set of PIFs, comprising 22 specific influencing factors and four overarching categories, which pertain to the potential safety factors confronting operators amidst an environment of continuous and rapid operational task changes. The set of PIFs is characterized by the following attributes:

(1) The classification's rationality is bolstered through an intricate consideration of the interrelationships and mutual influences among the PIFs.

(2) This classification is an extension of prior research, adapted to reflect the unique operational characteristics of nuclear power plant load following tasks. It has been refined through expert consultation and operator interviews, thereby enhancing its representativeness and applicability to real-world scenarios.

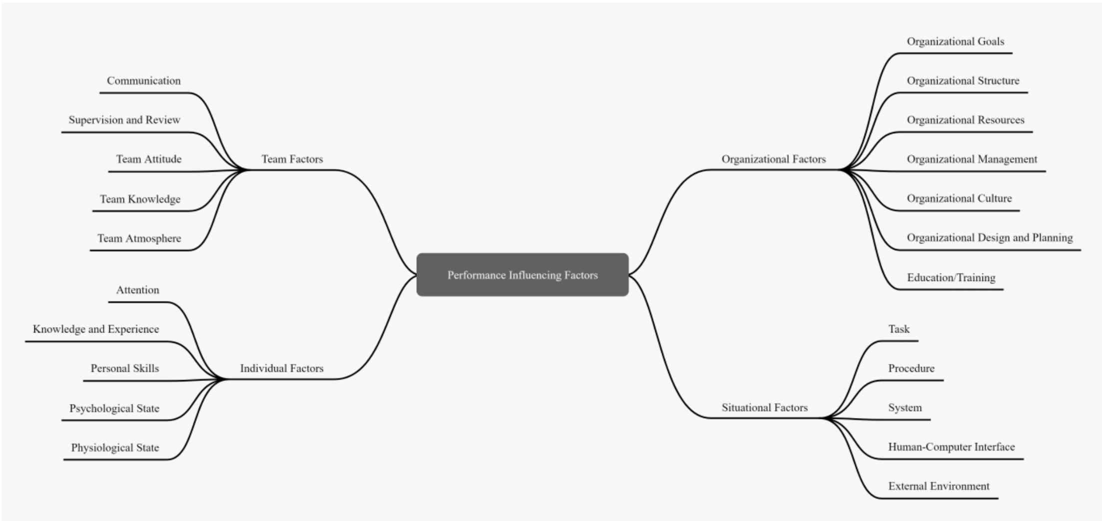

Fig. 2 Screened SA Failure Classification

Table 2 Description of SA

Performance Influencing Factors	Subcategories	The Specific Influences
Individual Factors (C1)	Attention (C11)	-Alertness to the surrounding environment. -Focus on the current task.
	Knowledge and Experience (C12)	-Frequency of performing analogous tasks. -Proficiency in knowledge pertinent to nuclear power operations.
	Personal Skills (C13)	-Social skills, etc. -Task execution capabilities: emergency response, practical skills.
	Psychological State (C14)	-Tension due to time load, task load, performance confidence, and perceived severity of decision-making outcomes. -Stress from frustration, conflict, and the urgency of uncertain pressures.
	Physiological State (C15)	-Bodily functions: sudden discomfort, fatigue, and physiological rhythm disruptions. -Perceptual limitations: speech clarity, visual and auditory impairments. -Physiological attributes: gender, age differences, physical defects, injuries.

Team Factors (C2)	Communication (C21)	-Effectiveness of communication. -Types of teams' exchanges. -Quality of team exchanges.
	Supervision and Review (C22)	-Oversight of task execution processes. -Supervision of team leaders' and members' behavior. -Coordination and cooperation among team members.
	Team Attitude (C23)	-Motivation for task completion, attitudes towards task execution. -Over-trust. -Biases in understanding roles and responsibilities. -Habitual mentalities. -Familiarity with perceived states.
	Team Knowledge (C24)	-Collective understanding of the nuclear power plant system. -Task-related knowledge of team members.
	Team Atmosphere (C25)	-Shared beliefs and values. -Awareness of one's role. -Team motivation: coordination and cohesion.
Situational Factors (C3)	Task (C31)	Task attributes: complexity, repetition, monotony, and risk level. -Task requirements: cognitive and action demands (speed, intensity, precision). -Expectations for communication, cooperation, calculation, and completion timelines.
	Procedure (C32)	-Completeness: thoroughness and adequacy, comprehensibility of procedure. -Correctness: standardization of terminology, decision-making criteria.
	System (C33)	-Hardware: reliability, usability, and user-friendliness. -System integrity: automation, complexity, redundancy, and reliability, feedback mechanisms. -Software: reliability, usability, and user-friendliness.
	Human-Computer Interface (C34)	-Information display: volume, comprehensibility, and recognizability of displayed information. -Human-computer interaction integrity: alarm recognizability, searchability, contradictory signal prompts. -Soft control: controller display, feedback, monitoring, and complexity of interface management tasks.
	External Environment (C35)	-Living environment: interpersonal tensions, life stress, social atmosphere, family incidents. -Working environment: accessibility, temperature, humidity, lighting, noise, cleanliness, and potential distractions.
Organizational Factors (C4)	Organizational Goals and Strategies (C41)	-Goals: safety, performance, and their integration, specificity, consistency, and prioritization. -Strategies: methods, management of primary and secondary issues, organizational hierarchy, responsibility, and authority, problem identification, and solution formulation.
	Organizational Structure (C42)	-Hierarchical features: structure type, number of the personnel. -Roles and responsibilities, delegation of authority. -Functional aspects: cross-functionality, redundancy, fragmentation, and incompleteness.

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	Organizational Resources (C43)	-Time Resources: This category includes the assessment of both effective time, which is the duration allocated for task completion, and available time, which refers to the total time at the disposal of the workforce for operational activities. -Information Resources: The availability of superior instructions is crucial for guiding operations. Additionally, the analysis method should encompass all relevant information, including process details and directives concerning objects, methodologies, and tools utilized within the organization. -Human Resources: The management of human resources involves performance evaluations that measure the efficiency and effectiveness of employees, as well as the strategic employee selection processes that ensure the right personnel are in the right positions. -Other Resources: Spatial and economic resources are also pivotal, with spatial resources referring to the physical areas required for operations and economic resources indicating the financial means to support them. -Material Resources: Lastly, material resources are fundamental and include all the tangible assets such as equipment, tools, spare parts, and raw materials necessary for the functioning of the organization.
	Organizational Management (C44)	-Leadership. -Task allocation, staffing, scheduling. -Supervision, auditing, and evaluation. -Cooperation and coordination. -Personnel management.
	Organizational Culture (C45)	-Safety culture, encompassing attitudes, measures, and feedback mechanisms. -Organizational climate, including employee cohesion and collective identity.
	Organizational Design and Planning (C46)	-Organizational Design encompasses the strategic formulation of goals, the architectural planning of systems, and the methodical structuring of processes and workflow design to align with operational objectives. -Planning Comprehensiveness emphasizes the integration of plans that are not only complete and executable but also demonstrate efficacy in various operational aspects, ensuring they are robust and adaptable to change. -Organizational Planning involves the development of comprehensive strategies that address key areas such as security, resource allocation, emergency preparedness, and the cultivation of harmonious organizational relationships, thereby ensuring a cohesive and resilient organizational structure.
	Education/Training (C47)	-Training Attributes: This category includes the assessment of instructor competence, the design and implementation of training programs and tools, and the strategic allocation of resources essential for fostering an effective learning environment. -Training Process: The process is governed by a meticulously crafted training plan that is subject to rigorous supervision to ensure its execution aligns with the set objectives. The effectiveness and quality of training are continuously evaluated to measure the impact on performance and to identify areas for improvement.

4. Methods

To ascertain the significance of each Performance Influencing Factor (PIF) within the work environment with precision, this study employs a hybrid approach (Fuzzy Comprehensive Evaluation Method), integrating the Analytic Hierarchy Process (AHP)[18] with the Fuzzy Comprehensive Evaluation. Through a series of composite operations, an evaluation index matrix for primary and secondary factors is constructed. By merging the weights of general behavioral impact indicators with those of secondary behavioral impact indicators, the weights of individual PIFs are derived, elucidating their relative importance in the work environment. This process is further substantiated through questionnaire surveys for validation and precision enhancement. The evaluation procedure encompasses the subsequent stages:

(1) Establishment of PIF Set $U=\left(u_1,u_2,...,u_m\right)$ for Evaluation: The formation of a comprehensive set of PIFs that require assessment.

(2) Construction of Rubric Set $V=\left(V_1,V_2,...,V_{\mathrm{n}}\right)$ for PIFs: Each PIF is associated with a set of evaluative criteria, typically ranging from 3 to 5 levels, to facilitate the assessment.

(3) Formation of Fuzzy Judgment Matrix (R):

For each PIF, the degree of membership to the evaluative criteria is determined, i.e., the degree of association with the defined levels of the rubric. Given the evaluative criteria set: $r_i=\left(r_{i1},r_{i2},...,r_{im}\right)$, a fuzzy judgment matrix $R=\left(r_{ij}\right)_{mxn}=\begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix}$ is constructed from m PIFs to establish a fuzzy relationship from U (the universal set) to V (the set of evaluations);

(4) Weight Determination Using AHP: Utilizing the Analytic Hierarchy Process (AHP), this study assigns a weight to each Performance Influencing Factor (PIF), thereby deriving the weight vector $A=\left(a_1,a_2,...a_m\right)$. Given the varying degrees of significance among the Performance Influencing Factors (PIFs), the corresponding reference values allocated to each are consequently distinct. To accurately capture the distinctive significance of each Performance Influencing Factor (PIF), this study meticulously assigns a weight $a_i\left(i=1,2,...,m\right)$ to each PIF, subsequently normalizing these weights to fulfill the essential condition that the sum of the weights equals unity, expressed mathematically as $\sum_{i=1}^{m} a_i = 1$;

(5) Fuzzy Computation

The application of an appropriate fuzzy operator to the object of study facilitates the synthesis of the weight vector with the fuzzy judgment matrix R, yielding the evaluation result vector B. This process elucidates the degree of membership of the graded fuzzy subsets of each Performance Shaping Factor (PSF) when considered holistically, thereby enabling a comprehensive determination of the evaluation subject's grade.

Let $b_j\left(j=1,2,...,n\right)$ represent the aggregate affiliation of each PSF, then the subsequent analysis can be conducted based on this collective measure of membership, then $B=A\circ R=\left(a_1,a_2,...,a_m\right)\circ\begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix}=\left(b_1,b_2,...,b_n\right)$.

5. Analysis of Results

A comprehensive survey was conducted, distributing a total of 15 questionnaires among seasoned human factors experts, each expert over 15 years of specialized experience within the nuclear power sector. The panel comprised 5 experts well-versed in the human factors domain and an additional 10 experts with hands-on operational experience at nuclear power plants. The collective assessment of the PSFs by the experts is detailed in Table 4.

Table 3 The Judgment on PSF

PIFS	Significant	General	Not Significant
Individual Factors (C1)	7/15	7/15	1/15
Team Factors (C2)	8/15	2/5	1/15
Situational Factors (C3)	7/15	1/5	1/3
Organizational Factors (C4)	7/15	4/15	3/15
Attention (C11)	1/3	4/15	2/5
Knowledge and Experience (C12)	3/5	1/3	1/15
Personal Skills (C13)	13/15	1/15	1/15
Psychological State (C14)	4/5	2/15	1/15
Physiological State (C15)	3/5	1/5	1/5
Communication (C21)	8/15	4/15	1/5
Supervision and Review (C22)	1/3	2/5	4/15
Team Attitude (C23)	6/15	6/15	1/5
Team Knowledge (C24)	4/5	1/15	2/15
Team Atmosphere (C25)	2/5	7/15	2/15
Task (C31)	7/15	4/15	4/15
Procedure (C32)	7/15	1/5	1/3
System (C33)	7/15	2/5	2/15
Human-Computer Interface (C34)	2/3	2/15	1/5
External Environment (C35)	1/5	3/5	1/5
Organizational Goals and Strategies (C41)	2/15	2/3	1/5
Organizational Structure (C42)	4/15	1/3	2/5
Organizational Resources (C43)	3/5	4/15	2/15
Organizational Management (C44)	2/5	1/3	4/15
Organizational Culture (C45)	2/3	4/15	1/15
Organizational Design and Planning (C46)	2/5	1/3	4/15
Education/Training (C47)	11/15	1/5	1/15

The data underwent processing utilizing the Analytic Hierarchy Process (AHP) in conjunction with the fuzzy composite judgment method.

The classification of C1 individual factors, C2 team factors, C3 situational factors, and C4 organizational factors as delineated in Table 3 is prioritized based on the magnitude of their weights, with the sequence C2>C4>C1>C3. Notably, C2 team factors exert the most substantial influence, while C3 situational factors have the least. This ranking suggests that team factors (C2) are the predominant contributors to the likelihood of human error. A detailed analysis of the weight distribution among these categories of PIFs is presented below:

Within the C1 category, which encompasses individual factors, the hierarchy of weights has been established as follows: C12 Knowledge and Experience takes precedence over C11 Attention, which in turn supersedes C13 Personal Skills, followed by C14 Psychological State, with C15 Physiological State holding the least weight. The critical role of knowledge and experience (C12) and attention (C11) is highlighted, as these factors exert a substantial influence on the operator's SA level. They are considered the primary determinants of the operator's capacity to manage the control unit and maintain a high level of safety awareness. The significance of these factors in the context of load-following tasks is underscored by the rapid fluctuation of unit state parameters compared to standard operating conditions. Operators must possess a robust knowledge and experience base to swiftly adapt to changes in system parameters and execute the correct operations within the designated time

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frame, thereby ensuring the unit's stable operation. Attention (C11) is equally pivotal, enabling operators to promptly detect pivotal shifts in system parameters and take appropriate actions to maintain system stability. To this end, enhancing the educational and training regimen to elevate the operator's knowledge and experience is suggested. Additionally, improving the working environment and minimizing distractions are proposed strategies to bolster the operator's attention. While the weights of personal skills (C13), psychological state (C14), and physiological state (C15) are comparatively lower, their collective impact cannot be overlooked. A comprehensive consideration of these factors, alongside the implementation of tailored strategies, is essential to optimize overall performance and safety within the operational context.

Table 4 PIFs set weighting results

PIFs	Weighting
Individual Factors (C1)	0.24257
Team Factors (C2)	0.26733
Situational Factors (C3)	0.23762
Organizational Factors (C4)	0.25248
Attention (C11)	0.23827
Knowledge and Experience (C12)	0.29964
Personal Skills (C13)	0.10108
Psychological State (C14)	0.03249
Physiological State (C15)	0.00361
Communication (C21)	0.20352
Supervision and Review (C22)	0.22083
Team Attitude (C23)	0.37500
Team Knowledge (C24)	0.36667
Team Atmosphere (C25)	0.21250
Task (C31)	0.14179
Procedure (C32)	0.20896
System (C33)	0.13433
Human-Computer Interface (C34)	0.38806
External Environment (C35)	0.12687
Organizational Goals and Strategies (C41)	0.03207
Organizational Structure (C42)	0.03499
Organizational Resources (C43)	0.03790
Organizational Management (C44)	0.15160
Organizational Culture (C45)	0.26531
Organizational Design and Planning (C46)	0.22157
Education/Training (C47)	0.25656

The ranking of the factors within the C2 category, which pertains to team factors, is organized as follows:C23 team attitude takes precedence over C24 team knowledge, which in turn is more significant than C22 supervision and review, followed by C25 team atmosphere, with C21 communication bringing up the rear. Team attitude and team knowledge are identified as the primary PIFs. The team proactively addresses peak-load tasks by leveraging real-time system information to select appropriate operational procedures. The Chief of Duty, acting as the coordinator, exercises adept management in distributing subtasks among the team. This robust distribution strategy ensures that each team member is optimally utilized, facilitates coordinated effort, and ultimately leads to the smooth fulfillment of the peak load management tasks. The meticulous approach reflects a high level of preparedness and adaptability within the team, which is essential for maintaining operational efficiency and coordination, especially during critical periods of fluctuating demand. Furthermore, the profundity of the team's understanding of the power plant system and the requisite operational tasks significantly facilitates the successful completion of operation protocols within the defined temporal parameters. This deep-seated familiarity with both the complexities of the power generation process and the specific task at hand is instrumental in ensuring the sustained stability of the power system. The proactive mastery of these vital competencies by the team plays a pivotal role in enhancing operational efficiency, facilitating swift decision-making, and ultimately promoting a robust and reliable power supply, even when facing abrupt changes in demand levels. Moreover, the imperative to augment the oversight and assessment of team operations persists. It is crucial to cultivate a supportive and unified work climate that nurtures trust and the spirit of cooperation among team constituents. Such fostering of mutual reliance not only fortifies the psychological safety of the team but also enriches the collective efficacy, thereby mitigating operational risks and elevating the attainment of shared objectives. Furthermore, the enhancement of communicative efficiency plays a pivotal role in facilitating seamless information dissemination and collaborative knowledge exchange among team members. This fluid interaction not only elevates overall work performance but also diminishes the incidence of information discrepancies, thereby safeguarding the integrity of the operational process.

In the C3 situational factors, the ranking of precedence for weights is as follows: C34 Human-Computer Interface is accorded the highest priority, followed by C32 Procedure, with C31 Task, C33 System, and C35 External Environment trailing in sequence. This hierarchical arrangement elucidates the relative importance of each factor in influencing a manipulator's level of Situation Awareness (SA). The salience of the Human-Computer Interface and adherence to Procedure emerge as pivotal elements, implying that these aspects hold a more decisive role compared to others in determining the proficiency of manipulators in maintaining elevated levels of SA. This suggests that optimizing the interaction between operators and technological systems, as well as ensuring procedural compliance, could be critical focal points for enhancing SA and operational effectiveness in complex human-machine scenarios. Currently, within China, a definitive protocol for peak-load management remains absent; the existing framework is merely a set of guidelines. These guidelines may be marred by issues such as ambiguous descriptions and incomplete operational steps. There is an imperative need to formulate comprehensive operational procedures and processes to safeguard the safe and efficient execution of peak-load tasks. Currently, an intuitive and user-friendly human-computer interface tailored for peak-load management has not been developed. This may be attributed to the fact that nuclear power plants in China have not yet extensively engaged in grid peak-shaving operations, resulting in a lack of targeted HMI design to meet the specific demands of such tasks. Consequently, a rigorous assessment of the human-computer interaction design, coupled with the systematic collection of user feedback, is essential to enhance the interface's usability. It is imperative to focus on the rational distribution and strategic prioritization of tasks to ensure seamless workflow and optimal performance. Additionally, conducting thorough task analysis and optimization facilitates a balanced allocation of responsibilities and prevents task overload, thereby fostering increased operational efficiency.

In the realm of C4 organizational factors, the relative importance of various elements has been systematically evaluated and sorted accordingly: Organizational culture (C45) is considered the foundation, with a weight that precedes Education/training (C47), Organizational design and planning (C46), Organizational management (C44), Organizational resources (C43), Organizational structure (C42), and Organizational goals and strategies (C41) in descending order of significance. These latter elements, though significant, are perceived as more influential than the overarching framework of Organizational goals and strategies. Conferring particular weight to elements such as Organizational culture and Education/training highlights the critical role these factors play in shaping the organizational environment and workforce competence. This ranking underscores that it is the cultural ethos and the efficacy of continuous learning and development that significantly influence an organization's ability to adapt to challenges, innovate, and achieve its strategic objectives. The prioritization of Organizational culture and Education/training is a testament to the modern organization’s emphasis on nurturing a positive learning atmosphere and establishing robust processes for the growth and development of its members. In summary, the structured hierarchy of importance thus derived serves as a strategic map for organizations to allocate resources, focus their developmental efforts, and foster an environment conducive to their long-term success and sustainability. The cultivation of an exemplary nuclear safety culture stands at the vanguard of employee advancement, laying the groundwork for fostering impeccable work ethics and contributing considerably to the sustained operational reliability of nuclear power infrastructures. Concurrently, it is imperative to focus on the implementation of an efficient organizational structure and the delineation of unambiguous role responsibilities to nurture a constructive and salubrious organizational ethos. Moreover, a steadfast commitment to the paramount importance of comprehensive employee educational and training programs must be ensconced, complemented by the recognition of the criticality of robust organizational governance and leadership cultivation strategies.

To rigorously substantiate the analytical findings and ascertain the predominant factors influencing Situational Awareness (SA) within digital nuclear power plants, an extensive collection of event reports was conducted. Utilizing the operational experience feedback platforms of the World Association of Nuclear Operators (WANO) and the National Nuclear Safety Administration (NNSA), a total of 179 human factor event reports associated with operator behavioral errors were meticulously screened. These reports pertain to transient operational conditions, such as step-load increases and decreases, occurring in nuclear power plants globally. In instances where a single event report encompassed one to multiple SA deficiencies, similar SA errors were consolidated into a unified category to preclude repetitive enumeration. The aggregated statistical outcomes about the principal Performance Influencing Factors (PIFs) are delineated in Figure 3.

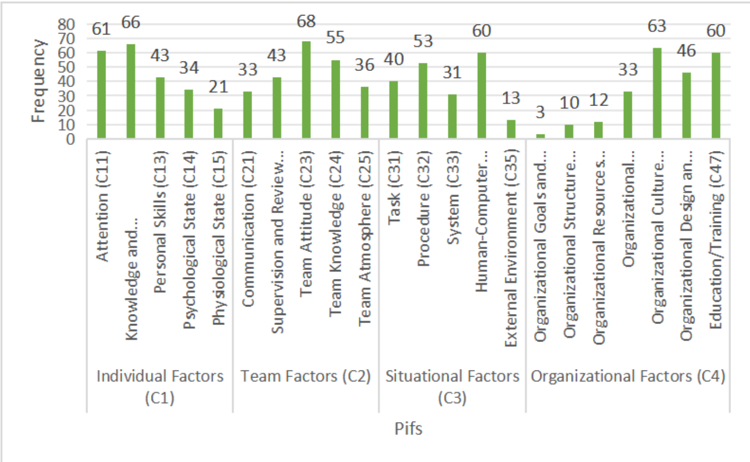

Fig. 3 Key PIFs statistics

It is evident that the computational outcomes closely align with insights gleaned from in-depth interviews conducted with seasoned experts. Within the analysis of the 179 reported incidents attributed to human factors, it became apparent that various factors – ranging from procedural adherence and team demeanor to operational knowledge, experiential learning, organizational ethos, and educational initiatives – exerted differential influences on situational awareness. Notably, these impacts were collectively substantial, thus indicating a marked influence on the level of situational awareness among nuclear power plant personnel. Consequently, this comprehensive evaluation underscores the multifaceted role of these elements in shaping scenarios within power plant operations, highlighting their importance for safety and efficiency.

6. Prevention Strategy for Situational Awareness Failures

To avert lapses in Situational Awareness (SA), this study builds upon the findings of the analysis and offers a comprehensive set of considerations and recommendations. These encompass procedure, team attitudes, team knowledge, knowledge and experience, organizational culture, and education and training. The development of these recommendations is informed by authoritative guidelines such as "Recruitment, Training, and Authorization of Personnel in Nuclear Power Plants'' and "Guidelines for Developing Comprehensive Training and Retraining Initiatives for Nuclear Power Plant Operators''.

6.1 Preventing Situational Awareness Errors through Procedure Development

Currently, there is an absence of specific operational procedures tailored for peak-load tasks within the domestic context. In the event of such tasks, operators must rely on the start-stop procedures of the reactor for guidance. It is imperative to develop procedures that are specifically aligned with the unique demands of peak-load operations. A critical aspect of this development is the clarity and comprehensibility of the procedures. The ability of operators to readily comprehend and accurately execute the procedures is paramount for enhancing system stability. Furthermore, in the rapidly advancing landscape of technology, it is essential that procedures must evolve to incorporate novel interaction methods, interface designs, and data visualization techniques. These innovative technologies have the potential to offer interfaces that are more intuitive, comprehensible, and user-friendly. Such advancements can significantly augment the operator's capacity to effectively interpret and apply the guidance provided within the procedures.

6.2 Mitigating Situational Awareness Failures through Team Attitude

In the realm of nuclear power plant operations, the occurrence of unpredicted peaking tasks necessitates prompt and effective responses from the operational team. Given that an operator's daily operation checklist might lack specific guidance for such emergent situations, it becomes imperative for the shift supervisor to initiate a collaborative team meeting aimed at decision-making. The efficacy of the team's collective action in this context is fundamental to addressing the challenges posed by sudden spikes in operational demand. Furthermore, during the handling of such unforeseen requirements, operators must foster an open-minded approach that embraces novel technical solutions and methodologies, alongside a readiness to integrate them within the established framework of operations. Equally important is the maintenance of a respectful and compliant attitude towards traditional nuclear safety philosophies and operational protocols. This attitude ensures that while operators are encouraged to adopt new techniques, they also remain firmly anchored to the bedrock principles that underpin nuclear safety. The harmonization of these dual imperatives – the application of innovative solutions and the adherence to fundamental safety practices – is crucial for safeguarding both operational integrity and personnel well-being in the nuclear energy sector. Therefore, crew members must prioritize a balance between a willingness to learn from new technologies and a deep-seated respect for established safety protocols. In summary, the prevention of situational awareness errors can be significantly bolstered by a team dynamic that encourages active discussion, open-mindedness to new methods, and a steadfast commitment to foundational safety practices. This holistic approach not only enhances the capacity to respond adaptively to sudden operational peaks but also ensures a robust and sustainable safety culture within the nuclear power plant environment.

6.3 Preventing Situational Awareness Failures through Team Knowledge

The proficiency of nuclear power plant (NPP) crews is pivotal in ensuring a seamless and safe operation, particularly in the face of dynamic and potentially challenging scenarios. As such, each team member must be deeply knowledgeable not only in the technical intricacies of NPP operations but also in the identification of potential issues and their strategic management plans. Moreover, a comprehensive grasp of the core principles of nuclear safety is essential to maintain the integrity of risk management and operational excellence.

In addition to nuclear safety principles, crews must possess a comprehensive understanding and operational competence with the latest digital tools and systems that are becoming increasingly integral to NPP management. This includes a working knowledge of how such technologies may be effectively utilized for routine operations, as well as the criteria for transitioning to backup or manual control systems when required. The rapid evolution of technology necessitates a flexible approach to learning, which should be facilitated by formal education and specialized training. However, the value of peer-to-peer knowledge transfer cannot be overstated; it serves as a complementary mechanism for enhancing team proficiency.

By fostering an environment that values education, continuous skill development, and constructive knowledge-sharing among teams, nuclear power plants can reinforce their front-line defenses against situational awareness failures. This holistic strategy ensures that crews are not only knowledgeable but also adept in utilizing their expertise to navigate complex operations and mitigate potential hazards effectively. It also underscores the importance of a collaborative approach to maintaining a high standard of safety and operational efficiency within the nuclear power industry.

6.4 Preventing Situational Awareness Failures through Knowledge and Experience

Knowledge and experience are foundational components that can be cultivated through educational programs or training initiatives, as well as through dynamic interactions and knowledge-sharing among workgroups. While preventive measures related to education and training are detailed in subsequent sections, it is essential to emphasize the proactive accumulation and dissemination of operational insights within shift teams. These insights, encompassing both efficacious strategies and encountered challenges, should be integrated into the revision of operational protocols and the enrichment of training materials.

Such a collaborative approach not only facilitates individual learning but also enhances the collective experience of the shift team, drawing from practical lessons learned. Continuous learning and practical application, in turn, refine operational quality and mitigate the likelihood of errors. Communication emerges as an indispensable element, especially during peak operations when an increased task load necessitates the acquisition of elusive information through effective communication channels. This facilitates the optimization of operational timing and alleviates time-related pressures.

However, it is crucial to strike a balance, ensuring that communication remains moderate to prevent excessive interactions from diverting attention and diminishing situational awareness. Addressing ineffective communication, such as miscommunication or insufficient exchange, as identified in incident reports, requires the adoption of "Safe Communication" practices. This concept, an alternative interpretation of optimal communication strategies, underscores the conveyance of information or team manipulators' thought processes with precision and clarity, ensuring accurate comprehension by the recipient.

Safe communication necessitates a feedback loop, where the information sender verifies the receiver's understanding, confirming alignment with the intended message. This process, comprising "safe expression" and "three-way communication," involves a cyclical "send-feedback-confirmation" sequence among the sender, receiver, and sender. The integrity of this cycle is paramount, as most communication errors stem from its disruption. Three-way communication ensures mutual understanding among all parties, reducing the incidence of verbal communication errors, while safe expression lubricates the three-way communication process.

6.5 Preventing Situational Awareness Failures through Organizational Culture

The cultivation of a robust organizational culture is a pivotal component in the prevention of human-induced errors within nuclear power plants. An exemplary organizational culture not only heightens employees' safety consciousness but also fortifies their sense of responsibility, ensuring a perpetual state of vigilance in all work-related activities.

Strategies for Fostering a Positive Organizational Culture:

(1) Emphasizing Safety: It is imperative to inculcate an organizational culture that prioritizes safety over productivity. This involves fostering an environment where open communication is encouraged, mistakes are acknowledged honestly, and lessons are learned from these experiences.

(2) Continuous Education and Training: Ongoing educational programs and training sessions are essential to equip operators with the requisite knowledge and skills. The development of regular training modules specific to peak-load tasks is vital to bolster operators' understanding of safety protocols and to enhance their professional competencies.

(3) Feedback and Improvement: Encouraging operators to provide feedback on safety concerns and to engage in open discussions regarding potential improvements is crucial. This participatory approach cultivates a sense of ownership and shared responsibility for safety.

(4) Clear Authority and Responsibility Structures: Establishing clear lines of authority, responsibility systems, and task delegation is fundamental. It is equally important to have comprehensive response plans in place to address potential accidents effectively.

(5) Recognition and Incentives: Recognizing and rewarding individuals who exemplify outstanding safety behavior is key to reinforcing a strong safety culture.

(6) Adaptability and Flexibility: As technology advances and new challenges emerge, the organizational culture must remain adaptable and flexible, allowing for necessary adjustments to be made promptly.

(7) Management Processes and Security Protocols: Implementing systematic organizational management processes and security protocols for load-adjustment tasks is essential. Regular reviews and updates to security policies and procedures ensure their ongoing effectiveness.

(8) Commitment from All Levels: The establishment of a pervasive safety culture requires the commitment and active involvement of all organizational levels, from leadership to frontline employees.

(9) By instituting a strong safety culture, an organization can significantly mitigate the risk of Situational Awareness (SA) errors, thereby enhancing the overall safety of nuclear power operations. This cultural shift demands a unified approach, with every member of the organization playing a vital role in upholding safety standards.

6.6 Education and Training as Precautions Against Situational Awareness Errors

The educational and training regimen for nuclear power plant operators is an essential element in the prevention of human error. Such programs are designed to equip employees with the requisite knowledge and skills to execute their responsibilities effectively, as well as a comprehensive understanding of safety protocols and procedures. Given the intricate and recurrent demands of peak-load operations, operators must possess a high caliber of expertise, knowledge, technical proficiency, and training to manage these tasks and ensure the ongoing stability of the nuclear power infrastructure.

All operators must undergo a foundational curriculum that integrates theoretical knowledge with hands-on operational skills, enabling them to become well-versed in their job functions and the operational dynamics of nuclear power plants, along with the pertinent safety regulations. To further enhance their adaptability under peak-load conditions, operators must undergo periodic retraining on unfamiliar regulatory knowledge and operational methodologies, ensuring their expertise remains current.

Exposure to simulated reactor control systems is also a critical component of training, enabling operators to gain proficiency in their operational duties. Simulation exercises provide a controlled environment where operators can practice emergency response scenarios, thereby honing their crisis management capabilities.

Incorporating safety culture training into the educational curriculum for all employees is vital to underscore the significance of safety and to foster a consistent focus on safety consciousness. The inclusion of human error case studies within the educational framework serves to illuminate the factors that can precipitate Situational Awareness (SA) lapses, equipping operators with the knowledge to preempt and mitigate such errors.

Establishing avenues for operators to offer feedback on educational and training modules is essential for their continuous refinement. Mechanisms may include regular surveys to gauge the efficacy of training programs and to pinpoint areas for enhancement. It is also crucial to take into account other influential factors such as occupational stress, fatigue, and distractions when devising these strategies. Regular assessments and feedback loops are necessary to ensure the ongoing relevance and effectiveness of these educational and training initiatives.

7. Conclusion

This study leverages Situational Awareness (SA) theory to investigate the factors that impinge upon the situational awareness errors of operators during the grid peak-shaving process. Employing the Analytic Hierarchy Process (AHP) and Fuzzy Comprehensive Evaluation (FCE), the study systematically screens the causative factors underlying the operators' SA errors. Subsequently, by integrating the AHP and FCE methods, this paper formulates a viable strategy for the prevention and control of SA errors among operators.

The proposed strategies offer a comprehensive approach to mitigating SA errors, encompassing detailed preventive measures in the realms of operational protocols, team attitudes, collective knowledge, experiential knowledge, organizational culture, and educational training. These strategies are designed to significantly diminish the incidence of SA errors among operators and, by extension, reduce the risk of safety accidents within nuclear power plants.

The findings of this research contribute valuable insights into the management of nuclear power plants, providing a reference for the establishment of more robust safety management frameworks. The adoption of these strategies can enhance operational safety and contribute to the overall integrity and reliability of nuclear power operations.

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