Conceptualizing Performance Shaping Factors in Main Control Rooms of Nuclear Power Plants: A Preliminary Study

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Abstract. Human errors are widely-accepted to be a major contributor to incidents and accidents in complex, safety-critical systems. Human reliability is influenced by individual, organizational, and environmental factors, which are called as performance shaping factors (PSFs). Identifying and managing PSFs are important for quantifying human error probability in human reliability analysis (HRA) and preventing human errors in main control rooms (MCRs) of nuclear power plants (NPPs). This study proposes a conceptualization framework for PSFs to identify and organize PSFs in MCRs of NPPs. It describes PSFs at three levels, components, factors (i.e., dimensions), and indicators. The expected result is the full-set PSF model for MCRs of NPPs. The future study is to weight and rank the PSFs from this full-set PSF model and to identify the elite-set PSF model with key PSFs to inform the HRA quantitative analysis.

Keywords: Human reliability analysis · Performance shaping factors · Main control rooms · Nuclear power plants · Conceptualization

1 Introduction

Safety-critical systems (e.g., nuclear power plants and air traffic control) have extremely high requirements on safety and reliability. Technological, individual, organization, and social elements can influence the reliability of safety-critical systems. With the rapid developments of technologies, the contribution of human errors and organizational weakness to system failures is becoming significant. It is widely-accepted that human errors and organizational weakness are a major contributor to incidents and accidents in safety-critical systems. For nuclear power plants (NPPs), 80 % of significant events can be related to human and organization errors [1]. More than 50 % of operating events in NPPs in China were implicated with operator errors from 1991 to 2011 [2]. Highly reliable human performance is required to maintain the integrity of complex, safety-critical systems as NPPs.

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Human reliability is influenced by individual, organizational, and environmental factors, which are called as performance shaping factors (PSFs) [3]. A PSF can also be called as a performance influencing factor (PIF), error producing context (EPC), or common performance condition (CPC). Human error probability (HEP) can be quantified by the PSFs in the human reliability analysis (HRA). Three types of PSF-based quantitative methods were suggested. The HEP of a human failure event (HFE) can be obtained by modifying its nominal HEP with the multipliers of PSFs (see [4]), the HEP of a HFE can be a function of its PSFs (see [5]), or the HEP of a HFE in various combinations of PSF levels can be directly estimated by expert judgments or other techniques (see [17]). Therefore, in order to assess human reliability, first and most importantly, the PSFs in safety-critical systems should be identified.

Several sources can be used to identify PSFs in a complex system, including HRA methods, human performance database, accident investigation, and operator survey. Dozens of PSF classification systems were suggested. Three major problems of PSFs were found in the literature. First, the PSFs overlap with each other and their definitions are not clear within several HRA methods [6], and PSFs are defined at various levels between HRA methods. Second, the range of PSFs covered is not appropriate for several HRA methods [6]. That is, the content validity of several PSF systems is not satisfied [7]. For example, the PSFs related to organization and digital human-system interfaces are not well covered by the first-generation HRA methods. Third, several PSF models may cover too many PSFs, which may influence the quantitative predicting ability of HRA methods. The International HRA Empirical Study [6] suggested that addressing a wide range of PSFs may contribute to the HRA qualitative analysis, and however, it may influence the HRA quantitative analysis negatively. A PSF model with a few key factors can produce reasonable HEPs [6].

The current study will focus on the first two major PSF problems. It will conceptualize PSFs in digital MCRs following a systematic process and clarify the components, factors (i.e., dimensions), and indicators in PSF systems. The results of this study will be used to identify and weight the key PSFs for the HRA quantitative analysis, which is beyond the scope of the current study. The next is organized as follows. Section 2 will describe the conceptualization process, propose a model of PSF components, and introduce the sources of PSF factors and indicators that we referred to. Section 3 will present the suggested PSF model with the list of PSF factors and indicators. Section 4 will make a short discussion and conclude this study.

2 Conceptualization Process

This study proposes a conceptualization framework for PSFs in MCRs. It borrows the process to define task complexity in Liu and Li [8], which follows the general conceptualization process in social science [9]. Its basic idea is to describe PSFs at three levels, components, factors, and indicators. PSFs build the context of MCRs. Thus, the PSF components are the components in the MCR system. The components in a MCR, for example, include individual, crew, organization, etc. For each MCR component, it has one or more PSF factors (i.e., dimensions) that affect human performance. For example, the PSF factors for the individual component can be fatigue, experience/training, stress, etc. In social science, the term "dimension" is preferred. The term "factor" is used in place of "dimension" in the context of HRA. The PSF factors are abstract, and operationalized and represented by their indicators. Take the fatigue PSF for example, its indicators can be working continuously for considerable number of hours, frequent changes of shift, night work, etc.

Thus, the conceptualization process for PSFs has three steps:

- Step 1 is to identify and define components in the PSF system. Section 2.1 will propose a eight-component model for PSFs.
- Step 2 is to identify the PSF factors and indicators for each MCR component. Two researchers with the background of human factors and HRA identified approximately 500 indicators from the literature review. Section 2.2 will introduce the referred sources of PSF factors and indicators.
- Step 3 is to re-group and classify PSF indicators into PSF factors. These two researchers independently classified PSF indicators and reached the consensus finally. Section 3 will present the identified PSF factors and illustrate their indicators.

2.1 PSF Component

The MCR in NPPs is a complex sociotechnical system. Several models can be found to describe the components of sociotechnical systems and to classify contextual factors in several complex domains. In aviation, Edwards [10] and then Hawkins [11] developed the well-known SHELL model, in order to organize and classify contextual factors that influence pilot performance. The components in the SHELL model include Software, Hardware (i.e. physical elements), Environment, and Liveware (i.e. human elements). Several deviations of SHELL model [12, 13] were suggested to add the management and organization component. Bea [14] suggested a model of seven components for offshore structure systems, which are operators, organizations, procedure, equipment, structure, environments, and interfaces. Carayon et al. [15] suggested a model of five components in work systems for patient safety. They are person, organization, tasks, technology and tools, and environment. In the nuclear power industry, Kim and Jung [16] classified PSFs into four groups, human, system (including man-machine interface), task (including procedures), and environment (team and organization, physical working environment). Several common components are considered in the aforementioned models. They are human/liveware, organization/
management, environment, hardware/system structure/equipment, man-machine interface/human-system interface.

With regard to the digital MCRs in NPPs, we would like to decompose the PSF systems into eight components as follows:

- 1 Operator: Individuals that operating NPPs, including MCR operators and field operators. It covers individual characteristics, including the competency of problem solving (e.g., knowledge, skills, abilities) and other characteristics.

- 2 Crew: Operating crews in MCRs. It covers crew characteristics.
- 3 Organization: Support from higher-level organizations, including resource support, training support, safety culture, management support and policies.
- 4 Human-System Interface (HSI): Ways and means of interaction between the crew and the system. It mainly refers to the displays and controls in HSI.
- 5 System: Physical system *per se*.
- 6 Working Environment: Internal and external environments in MCRs.
- 7 Procedure: Computerized- and paper-procedures, guidelines, checklists, standards, etc.
- 8 Task: High-level cognitive activities in specific task environments.

Human elements in MCRs are classified into two components: operator and crew. The former refers to individual capacity, knowledge, trait, etc. The later refers to teamwork characteristics such as leadership, communication and coordination. Procedure and task are considered separately. Procedure will more refer to the usability and quality of procedure systems. Besides proceduralized tasks (i.e., following procedures step by step), crews have to perform other higher-level cognitive activities (e.g., continuous monitoring, situation assessment, diagnosis and analysis, response planning) [6], which are covered by the task component.

2.2 Sources of PSF Factors and Indicators

The PSF factors and indicators in the MCRs are extracted from four major sources: HRA methods, human performance database, human event reports, and other sources. Due to the limited space, we cannot name all of the sources that we referred to.

HRA methods provide dozens of PSF models. Each HRA method has its own PSF model. Here give several examples. The Technique for Human Error Rate Prediction (THERP) method [3] classifies PSFs into two types: external PSFs, including work environment (e.g., equipment design, written procedures or oral instructions), internal PSFs, including individual characteristics of operators (e.g., skills, motivations, and experience), and psychological and physiological stress. The Standardized Plant Analysis Risk-Human Reliability Analysis (SPAR-H) method [4] considers eight PSFs, available time, stress/stressors, complexity, experience/training, procedures, ergonomics/HMI, fitness for duty, and work process. Two new HRA methods, the Integrated Human Event Analysis System (IDHEAS) [17] and Phoenix [18] provide a complete set of PSFs.

Human performance database studies have PSF models to organize the contextual information. For example, the Scenario Authoring, Characterization, and Debriefing Application (SACADA) database [19] classifies PSFs into two groups: overarching factors (e.g., workload and time criticality) that affect all macrocognitive functions and factors that affect specific macrocognitive functions.

Human event reports provide the information of near-misses, incidents, and accidents related to humans. One well-known human event database in NPPs is the Human Event Repository and Analysis (HERA) system [20]. It identifies 11 types of PSFs including indicators.

Other sources include complexity surveys in MCRs, cognitive experiments, and human factors guidelines, etc. One latest study [21] by the authors, which identified and compared complexity factors in conventional and digital MCRs, is referred to. Cognitive experiments can provide the magnitude of the PSF effect on operators [22]. These sources are great complementary to the aforementioned sources.

3 Results

The expected result in the conceptualization process is to build a hierarchy model with three levels in the PSF system (see Fig. 1). The following text will detail the identified PSF factors including their indicators for each component.

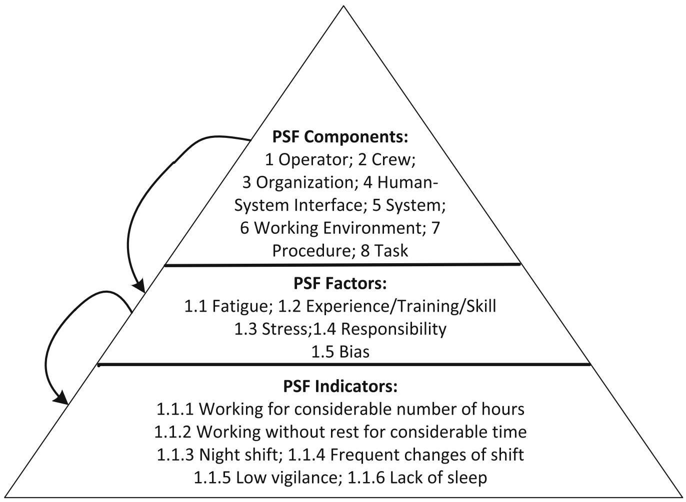

Fig. 1. Components, factors, and Indicators of the PSF system

3.1 Operator Component

Five PSF factors including their indicators belonging to the operator component are suggested as follows:

- 1.1 Fatigue
  - 1.1.1 Working continuously for considerable number of hours
  - 1.1.2 Working without rest for considerable time
  - 1.1.3 Night shifts
  - 1.1.4 Frequent changes of shift
  - 1.1.5 Low vigilance
  - 1.1.6 Lack of sleep
- 1.2 Experience/training/skill
  - 1.2.1 Amount of time passed since training

  - 1.2.2 Periodic training not provided
  - 1.2.3 Years of experience
  - 1.2.4 Knowledge level on system/equipment
  - 1.2.5 Similarity between the training and the actual situation
  - 1.2.6 Problems in the training process
  - 1.2.7 Insufficient training
  - 1.2.8 Lack of experience
- 1.3 Stress
  - 1.3.1 Perceived urgency
  - 1.3.2 Apprehension or nervousness associated with the importance of an event
  - 1.3.3 Muscular tension
  - 1.3.4 Fear of failure
  - 1.3.5 Perceived severity
  - 1.3.6 Perceived threat to themselves and others
  - 1.3.7 Performing task under high-jeopardy risk
- 1.4 Responsibility
  - 1.4.1 Responsibility for society
  - 1.4.2 Responsibility for the person
  - 1.4.3 Responsibility for the plant
- 1.5 Bias
  - 1.5.1 Overconfidence
  - 1.5.2 Risk taking
  - 1.5.3 Cognitive bias

3.2 Crew Component

Six PSF factors including their indicators belonging to the crew component are suggested as follows:

- 2.1 Communication requirement
  - 2.1.1 A large amount of communication required
  - 2.1.2 Outside discussions with other staff or even offsite entities needed
- 2.2 Communication availability
  - 2.2.1 Unavailable communication systems
  - 2.2.2 Unreliable communication systems
  - 2.2.3 Standard communication structure/protocol not followed
  - 2.2.4 No communication/key information not communicated
  - 2.2.5 Communication not timely
- 2.3 Communication quality
  - 2.3.1 Received information is not consistent with the transmitted information
  - 2.3.2 Information misunderstood or misinterpreted
  - 2.3.3 Disturbing factors (e.g., noise and interruptions)
  - 2.3.4 Verbal communication with similar sounding words (e.g., “increase” and “decrease”)

- 2.4 Leadership
  - 2.4.1 Progress not adequately monitored
  - 2.4.2 Supervisor too involved in tasks, inadequate oversight
  - 2.4.3 Lack of adequate, real-time command and control of activities
  - 2.4.4 Supervisor overconfident and tough
  - 2.4.5 No supervision, excessive trust, failed to question
  - 2.4.6 Team members' duties and tasks not specified
- 2.5 Team cohesion
  - 2.5.1 Lack of commitment and willingness to thoroughly complete the task
  - 2.5.2 Mistrust between team members
  - 2.5.3 Strained interpersonal relationships
- 2.6 Team collaboration
  - 2.6.1 Other members' performance and activities not monitored and checked
  - 2.6.2 Only focusing on their own tasks
  - 2.6.3 Unaware of her/his duties, goals, responsibilities, and role
  - 2.6.4 Lack of training to work together
  - 2.6.5 Limited experience in working together

3.3 Organization Component

Two PSF factors including their indicators belonging to the organization component are suggested as follows:

- 3.1 Safety culture
  - 3.1.1 Routine violation
  - 3.1.2 Safety-production trade-off. Making decisions with sacrificing safety. Focusing on production rather than safety
  - 3.1.3 Lack of openness in communication; limited communication channels; poor information flow
  - 3.1.4 Lack of willingness to fix problems
  - 3.1.5 Non-compliance with regulatory requirements
  - 3.1.6 Failure to correct known deficiencies and ignoring warning signs
  - 3.1.7 Deficiency in self-assessment and effectiveness review
  - 3.1.8 Overconfidence and complacency
  - 3.1.9 Oversight groups failed to question
- 3.2 Resource management
  - 3.2.1 Inappropriate organizational placement of personnel resources
  - 3.2.2 Inappropriate organizational assignment of tasks

3.4 Human-System Interface Component

Four PSF factors including their indicators belonging to the HSI component are suggested as follows:

- 4.1 Information availability
  - 4.1.1 Missing key indicators and cues information
  - 4.1.2 Key indicators and cues information masked
  - 4.1.3 Missing key alarms
  - 4.1.4 Little redundancy in key information
  - 4.1.5 No feedback
  - 4.1.6 Slow feedback
- 4.2 Information ambiguity
  - 4.2.1 Small indications/problems of visibility
  - 4.2.2 Slight change of information
  - 4.2.3 Cues/alarms not salient
  - 4.2.4 Symptom of one fault is masked by another fault
  - 4.2.5 Ambiguity of alarms
- 4.3 Information unreliability
  - 4.3.1 Misleading information that points to an incorrect diagnosis
  - 4.3.2 Conflicting information that points to more than multiple diagnosis or conflicts with other information sources
  - 4.3.3 False alarms
  - 4.3.4 Other events (e.g., fire) lead some indications to be missing, spurious, or failed
  - 4.3.5 Failed indicators
- 4.4 Information overload
  - 4.4.1 Many alarms
  - 4.4.2 Lots of information in displays or panels
  - 4.4.3 Much information changing simultaneously
  - 4.4.4 Many extraneous/unrelated alarms

3.5 System Component

Four PSF factors including their indicators belonging to the system component are suggested as follows:

- 5.1 System unreliability
  - 5.1.1 Multiple faults
  - 5.1.2 Low fault tolerance level
  - 5.1.3 Multiple equipments unavailable
- 5.2 System complexity
  - 5.2.1 Number of sub-systems and components
  - 5.2.2 Number of coupled components
  - 5.2.3 System interdependencies not well defined
  - 5.2.4 Low transparency of system structures or behaviors
  - 5.2.5 Non-transparent behaviors of the automatic system
  - 5.2.6 Difficult to find out what changes in the process are caused by fault(s) directly, and what changes are caused by the automatic system

- 5.3 System dynamics
  - 5.3.1 Highly unstable plant situation, sensitive to operator operations
  - 5.3.2 Number of dynamic changing variables
  - 5.3.3 Quick change of critical parameters

3.6 Working Environment Component

Two PSF factors including their indicators belonging to the working environment component are suggested as follows:

- Habitability
  - 6.1.1 Noise, which makes communication challenging
  - 6.1.2 Too heat or too cold
  - 6.1.3 Poor lighting/illumination
  - 6.1.4 With radiation
  - 6.1.5 With smoke
  - 6.1.6 With toxic gas
- Workplace quality
  - 6.2.1 Poor workplace layout and configuration
  - 6.2.2 Narrow work space
  - 6.2.3 Inappropriate postings/signs

3.7 Procedure Component

Two PSF factors including their indicators belonging to the procedure component are suggested as follows:

- 7.1 Procedure complexity
  - 7.1.1 Number of steps
  - 7.1.2 Transitioning between multiple procedures
  - 7.1.3 Complicated logic between steps
- 7.2 Procedure quality
  - 7.2.1 Ambiguity, unclear, non-detailed steps
  - 7.2.2 Incorrect procedure content
  - 7.2.3 Missing one or more steps. Procedure content not complete
  - 7.2.4 Lack of necessary instructions
  - 7.2.5 Mismatch between procedure and scenario
  - 7.2.6 Conflicts between procedure and industry practice
  - 7.2.7 Required to perform calculations to get the required information
  - 7.2.8 Double negatives in procedure text
  - 7.2.9 Confusing words (e.g., “increase” or “decrease”) in procedure text

3.8 Task Component

Six PSF factors including their indicators belonging to the task component are suggested as follows:

- 8.1 Goal complexity
  - 8.1.1 Number of simultaneous goals
  - 8.1.2 Competing or conflicting goals
- 8.2 Information acquisition complexity
  - 8.2.1 Demands to memorize information
  - 8.2.2 Needs of mental calculations or translation
  - 8.2.3 Demands to track and monitor information continuously
  - 8.2.4 Needs to integrate and combine information from different parts of the process and information systems
  - 8.2.5 Problems in separating important from less important information
- 8.3 Information analysis complexity
  - 8.3.1 Ambiguity of the situation
  - 8.3.2 Difficult to identify the most important symptom of the fault
  - 8.3.3 Difficult to predict future plant states
  - 8.3.4 Difficult to find the chronological order of problems observed
  - 8.3.5 Difficult to prioritize the most important fault to focus on
- 8.4 Decision making complexity
  - 8.4.1 Several different alternative diagnosis to choose
  - 8.4.2 Several procedures to choose
- 8.5 Action implementation complexity
  - 8.5.1 A large number of manual actions required
  - 8.5.2 Special sequencing or coordination required
  - 8.5.3 Precision and careful operations required
  - 8.5.4 Control actions that require constant monitoring and manipulation
  - 8.5.5 Many procedures to perform simultaneously
- 8.6 Time pressure
  - 8.6.1 Limited time to focus on tasks
  - 8.6.2 Available time is lower than the required time
  - 8.6.3 Simultaneous tasks required or planned with demands of high attention
  - 8.6.4 Need to respond fast due to time pressure
  - 8.6.5 Urgently need to act on the process to stabilize it

4 Discussion and Conclusions

This study is to conceptualize the PSF model in digital MCRs of NPPs. It shows the preliminary result of this study. The obtained PSF hierarchy model can be expanded to deeper levels if necessary. It can add more PSF components, factors, and indicators. We must caution that the proposed PSF model is not the final one. We are still working on a sound, structured PSF model.

Three excellent PSF hierarchy models [16, 18, 23] have been provided. Kim and Jung [16] classified PSFs into four main groups: human, system, task, and environment. For each group, several subgroups were suggested. Groth and Mosleh [23] organized PSF into five major categories, organization-based, team-based, person-based, situation/stressors-based, and machine-based. Ekanem et al. [18] proposed the three-level of PSFs in which the top level includes HSI, procedures, resources, team effectiveness, knowledge/abilities, bias, stress, task load, and time constraint. One difference between the current study and the three studies may be that it clarifies the difference between components, factors, and indicators in a PSF system.

The final aim of this study is not just to provide a full-set PSF model. The full-set PSF model is required to inform the HRA qualitative analysis and to describe the contextual information from the operating events in NPPs. However, the full-set PSF model is not appropriate for the HRA quantitative analysis which requires a parsimonious PSF model. The future work is to rank and weight PSFs in NPP MCRs, in order to obtain the elite-set PSF model.

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