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Phoenix HRA Methodology: Preliminary Investigation for Digital Control Rooms, Explicit Time Treatment, and Future Extensions

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Phoenix is a model-based HRA methodology developed to support the HRA of Nuclear Power Plants (NPP). Since its development, Phoenix has been applied to several case studies to test methodological and practical aspects. This paper discusses future extensions of Phoenix concerning: i) its use with dynamic PRA tools, and ii) its application to digital control rooms. It also discusses Phoenix Performance Influencing Factor (PIFs) and potential applications for inspection processes.

Keywords: Human Reliability Analysis, Phoenix, Digital Control Rooms, Nuclear Power Plants, Inspection

1. Introduction

Human Reliability Analysis (HRA) allows identifying, modeling, quantifying, and assessing human errors in diverse industrial and non-industrial contexts. Phoenix is a model-based HRA methodology developed to address the various issues in the field of HRA (N. J. Ekanem et al., 2016). It models human-system interaction and human error in four layers through Event Sequence Diagrams (ESDs), Fault Trees (FTs), and Bayesian Belief Networks (BBNs).

Phoenix was developed to support the HRA of Nuclear Power Plants (NPP). The methodology is generic and can be applied across different industries and environments, including oil & gas, aviation, power generation, and others.

Since its development, Phoenix has been applied to several case studies to test methodological and practical aspects concerning its application by HRA analysts. This paper discusses future extensions of Phoenix concerning: i) its use with dynamic PRA tools, and ii) its application to digital control rooms. It also discusses Phoenix Performance Influencing Factor (PIFs) and potential applications for inspection processes.

2. Phoenix HRA Methodology

Phoenix comprises four layers. The Human Failure Events (HFEs) identified in the PRA model are treated as *Critical Functions* (CFs) in Phoenix *Master ESD*. The Master ESD connects Critical Functions through an ESD. If the PRA models exist and HFEs are identified, they would each constitute a CF. Otherwise, the analysis starts with developing the PRA models and, ideally, concurrent and iterative development of the Master ESD.

The success or failure of each CF is modeled through a *Crew Response Tree* (CRT), a forward-branching tree that models the interaction between the crew and the plant identifying *Critical Tasks* (CTs). Next, the crew's failures to perform the CTs are modeled through Fault Trees (FTs), which consists of the human response model and lead to *Crew Failure Modes* (CFMs).

Phoenix FTs and CFMs follow the IDA cognitive model (Chang & Mosleh, 2007a; Smidts et al., 1997) - the crew may fail to perform the critical task if they 1) Fail to gather correct information, understand or pre-process the collected information (I); 2) Fail in situation assessment, problem-solving, and decision-making (D); or 3) fail during the execution of an action (A). The reader is referred to (N. J. Ekanem et al., 2016) for the complete set of FTs.

Finally, the influence of the context on the CFMs, i.e., the causal model, is modeled through Bayesian Networks (BBNs) consisting of CFMs and *Performance Influencing Factors* (PIFs). Phoenix PIFS are organized on a hierarchical structure containing three levels. Phoenix also models dependencies, through Bayesian updating (see (M. Ramos et al., 2021)

Phoenix integrated model comprises the Master ESD, CRTs, FTs with the relevant CFMs, and BBNs with the relevant PIFs. The integrated model allows for a qualitative HRA analysis, describing the scenarios that may lead to the HFE in cut-sets. Once the model is completed, the Human Error Probability (HEP) is quantified. Phoenix can be applied through a dedicated WebApp[a] or other software that connects ESDs, FTs, and BBNs such as Trilith (Groth et al., 2010) or the HCL Web App[b].

3. A close look into Phoenix PIFs and future use for inspection activities

Regulatory oversight and inspections are essential activities, aiming at assuring that all actions performed by an NPP licensee throughout the lifetime of a facility are carried out safely and meet the safety objectives and license conditions (International Atomic Energy Agency Vienna (Austria), 2018).

Following the Fukushima Dai-ichi NPS Accident (2011), the Japanese Nuclear Regulatory Authority (J-NRA) changed regulatory requirements from a Prescriptive Approach to Performance Approach inspections. The organization also established the Cause Analysis Guide (Nuclear Regulatory Authority, 2019) as one of the sources for nuclear safety inspectors to assess human and organizational factors.

Phoenix PIFs were analyzed according to the Cause Analysis Guide to bridge inspections and HRA, i.e., guiding integration of inspectors' findings into HRA studies when using Phoenix.

3.1 *Overview of Phoenix PIFs*

Phoenix PIF set was developed by aggregating the information from different sources and then refined into a single comprehensive set and structural hierarchy. This section summarizes the foundation of Phoenix PIFs. Please refer to (N. Ekanem, 2013) for an in-depth discussion and descriptions of each PIF.

Phoenix PIFs are initially based on the set of PIFs proposed by (Groth & Mosleh, 2012). Groth's PIF set was selected for the following reasons. First, it is a comprehensive set developed by aggregating information from PIF sets used in several HRA methods, including IDAC, SPAR-H, CREAM, HEART, THERP. It also incorporates the PIFs from US NRC's Good Practice for HRA (Kolaczkowski et al., 2005).

Second, it has a hierarchical structure that captures information about natural interdependencies among the PIFs. It can be expanded and collapsed as needed, promoting its use for quantitative and qualitative analysis.

Third, it is orthogonally defined: PIFs have no overlap in their definition even though they may be related. Finally, it is also neutrally defined, enabling each PIF to impact human performance depending positively or negatively on the situation in context.

Groth's PIF set includes IDAC as a source. However, Phoenix re-structures the set to incorporate additional features of the IDAC model, as it provides a logical flow of information necessary for developing a directed model.

After incorporating features of the PIFs from IDAC, it was also ensured that Phoenix PIF set met the requirements indicated in the US NRC's Good Practice for HRA and can be modified to interface with existing HRA methods like SPAR-H.

Phoenix PIF sturcture and definitions consider the imoact of the PIFs in human performance. When an abnormal event occurs in the plant, the crew starts trying to solve the problem (safely stabilizing the plant) by responding cognitively, emotionally, and physically. These three types of responses are

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[a] Developed by the B. John Garrick Institute for the Risk Sciences, UCLA.

[b] Developed by the B. John Garrick Institute for the Risk Sciences, UCLA. < https://apps.risksciences.ucla.edu/>

interdependent and form the crew's response spectrum, modeled by IDA (the human response model). Thus, to determine the impact of the PIFs on the crew's performance, it is necessary to organize the PIFs in terms of the crew's natural response spectrum. Therefore, the PIFs have been organized into eight (8) main groups to look at the frontline factors that directly affect/impact human performance. The groups (Level 1 PIFs) are Knowledge/Abilities and Bias which maps to cognitive response, Stress maps to emotional response, while Procedures, Resources, Team Effectiveness, Human System Interface (HSI), Task Load, all map to physical world.

The PIFs are classified into levels within the groups, forming a hierarchical structure that can be fully expanded for qualitative analysis and collapsed for use in quantitative analysis. They are organized to show the beginning of a causal model. The PIF groups are orthogonally defined in a sense, meaning that we have attempted to reduce the overlap in their definitions (but not totally) even though the groups may be related to each other. Level 1 PIFs directly impact human performance through the CFMs. Level 2 PIFs either directly affect or form parts of the level 1 PIFs; the same applies to the level 3 PIFs.

3.2. *Phoenix PIFs and The Direct Causes Guide*

The human factors in the Cause Analysis Guide are classified as Primary, Secondary and Tertiary items of Causes of Error. The tertiary items were crossed with Phoenix PIFs definitions to identify to which PIF the factor related. The goal is that inspectors' findings can be used for HRA through Phoenix. Phoenix PIF definitions were also thoroughly reviewed for clarity and easier identification through additional examples.

Table 1 presents a sample of the analysis performed. Five primary causes of error were analyzed, comprising 63 tertiary factors. All these factors found correspondence to Phoenix PIFs.

Some work processes and management factors, broadly related to the PIF Procedures, could benefit from a more direct correspondence in Phoenix PIF – potentially through a Level 2 or Level 3 PIF. These include:

- 5.2.1 Inappropriate management provisions
- 5.2.3 Inappropriate work plan
- 5.2.4 Inappropriate Plan Change (Last minute changes, etc.)

Further investigation will examine the correspondence between the factors above and additional ones related to organizational factors, considering important features that need to be preserved in Phoenix PIF set, such as orthogonality and modelling through observable and measurable factors. Further analysis will also include additional guidance and standards used in inspection activities.

4. Modeling time in Phoenix for use with Dynamic PRA tools

Dynamic Probabilistic Risk Assessment (PRA) is a form of PRA that explicitly models plant elements and their behaviors over time (Siu, 1994). One area that requires more research for dynamic PRA is applying Performance Shaping Factors (PSFs) to the models (Vedros et al., 2021), which can leverage integration with dynamic HRA such as the Accident Dynamic Simulator and Information, Decision, and Action in a Crew context (ADS-IDAC) (Chang & Mosleh, 2007b). While ADS-IDAC provides an advanced dynamic HRA framework, its application requires a simulation environment and can be complex and resource-consuming. This section describes the more explicit inclusion of time-related aspects to Phoenix towards a preliminary version of a "semi-dynamic" Phoenix. The semi-dynamic Phoenix aims at easier integration with dynamic PRA tools without the complexities of a full dynamic HRA method.

It should be noted that contextual time-related aspects are already modelled in the Phoenix framework. The CRT represents the steps in a sequential manner, as a snapshot of the dynamics of the plant. When selecting the CFMs and the PIFs, the analyst must consider the context modelled by the CRT. For instance, following the failure of equipment, the crew stress is likely to increase. When assessing the state of the PIF stress for a CRT CT, the analyst must consider that this CT follows an equipment failure and, thus, stress at this time step is likely higher than for the previous CT. This approach applies to all PIF selection: the analyst must consider the context brought by the CRT.

4.1 *Modelling the impact of time*

The impact of time will be modelled through two elements concerning different aspects: the "physical time" (direct impact on the CT failure) and the “perceived time” (indirect impact through the PIFs). Those include the elements:

- Time available: the available time for the crew to perform the task and, e.g., prevent core damage;
- Time required: the time the crew takes to perform the task (considering information processing, decision-making, action taking);

Time Available and Time Required can be modelled through different distributions (e.g. normal, gamma, Weibull). The difference between the time available and the time required is modeled through the *Time Constraint*. The probability of Time Constraint will refer thus to the probability that the crew has less time than available to perform a task. Consider Time Available (T_{Av}) and Time Required (T_{Req}) being modelled through two normal distribution; where μ_{TAv} and μ_{TReq} are the means of the time available and time required distributions, respectively, and σ_{TAv} and σ_{Req} their standard deviation. Then $P(Tcons)$ can be estimated through (for two normal distributions) (RIL-2020-02, 2020):

$$P(Tcons) = 1 - \phi\left[\frac{\mu_{TAv} - \mu_{TReq}}{\sqrt{\sigma_{TAv}^2 + \sigma_{TReq}^2}}\right]$$

The time constraint directly impacts the CT failure and, thus, the HEP. This impact is independent of the operators’ mental state and other conditions under which the tasks are performed. It represents the probability of human failure even if the operators correctly gather and pre-process information, perform situation assessment and decision-making, and take the correct action. Phoenix CT’s FT was modified to add an event concerning time constraint, which should receive as a value the *P(TConst)* (**Error! Reference source not found.**).

The perceived time constraint can be impacted by different aspects. More experienced operators, for instance, may have a more realistic feeling of time constraint, with their probability of perceiving time as inadequate to perform a task being very close to the *P(Tconst)*. We initially consider that operators are well trained and experienced, and the perceived time constraint is sufficiently close to the real time constraint for *P(TConst)* to be directly used in the PIFs assessment.

Phoenix assesses the level of PIFs, i.e., their probability of being in a state that degrades human performance, through questionnaires. These questionnaires have been modified for explicit consideration of perceived time constraint.

In this preliminary version, two Level 1 PIFs are considered to be impacted by perceived time constraint. The perception that time is insufficient for completing the tasks increases the operators' stress level, modeled by the PIF Stress (Level 2: Stress due to Situation Perception; Level 3: Perceived Situation Urgency). The time pressure also increases the complexity of the tasks: it hinders cognition and decision-making and also affects operators’ abilitiy to correctly execute tasks, modeled by the PIF Task Load (Level 2: Cognitive Complexity, Level 3: Cognitive Complexity due to External Factors; and Level 2: Execution Complexity, Level 3: Execution Complexity due to External Factors).

For the PIF Stress, two questions concern stress related to the perception of time:

1- Is the crew likely to be under pressure / tensed due to their assessment of the situation's urgency, i.e., their perception that they should act rapidly to prevent the situation from escalating?
2- Is the crew likely to be under pressure / tensed due to the perception that the available time is inadequate to complete the task, i.e., their perception that required time for completing the task is higher than the available time?

Additional questions on stress include aspects related to the severity of the situation and the consequences of the decision.

Instead of assessing the level of stress due to time pressure through the questions above, they are removed and the contribution of time-related stress is assessed by *P(TConst)*. The following

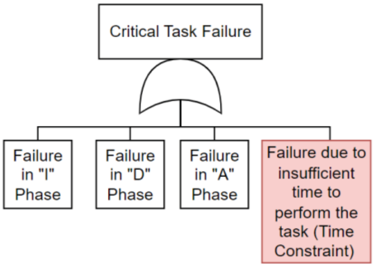

Fig. 1. Modified CT Failure FT for including of Time Constraint

Table 1: Sample of mapping of Phoenix PIFs and the Error Causes from the Cause Analysis Guide (Nuclear Regulatory Authority, 2019)

Causes of Error			**Phoenix PIFs**	**Comment**
Primary Item	Secondary Item	Tertiary Item		
3.Working Environment Characteristics Factors	3.1 Insufficient HMI	3.1.4 Inappropriate structure and layout of machines and control panels	Level 1 – Resources Level 2 – Workplace Adequacy	The physical layout of the work environment – control room, field operations, are modeled by the workplace adequacy. They refer to the design of the space, decided by the organization.
3.Working Environment Characteristics Factors	3.1 Insufficient HMI	3.1.1 Inadequacy of display, etc. (alarms, gauges, nameplates, etc.)	Lebel 1 – Human-System Interface	The HSI PIF models the display used for interacting with the plant. This may refer to the presentation of information (output) or to the buttons, control, for the system to receive a command or control of the crew (input)
3.Working Environment Characteristics Factors	3.1 Insufficient HMI	3.1.3 Inappropriate work tools, etc.	Level 1 – Resources Level 2 – Tool Quality	The work tools are necessary tools for the crew to perform their tasks.

formula was adopted in this initial exercise:

If $P_{TConst} < 0.5$,
Level (Stress) = 0.5*(total of yes / total of yes and no) + P_{TConst}
If $P_{TConst} \geq 0.5$,
Level = 1

For the PIF Task Load, two questions are related to increased complexity due to external factors:

1- Are there external situational factors and conditions that would induce cognitive demands on the crew?
2- Are there external situational factors and conditions that would induce physical demands on the crew?

Since the questions above include additional aspects unrelated to the time pressure/time constraint, their contribution to the Task Load level is not completely replaced by *P(TConst)*.

The following formula was adopted in this initial exercise:

If $P_{TConst} < 0.5$,
Level = (total of yes / total of yes and no) + p (time constraint). [*if level > 1, then level = 1*]
If $P_{TConst} > 0.5$,
Level = 1

5. Assessing Phoenix for digital control room operations

Digital control rooms can relate to different aspects. For instance, it may concern digital displays only or digital procedures. It is also associated with more automated plants. The modernization of NPP control rooms, resulting in advanced control rooms (ACRs), includes modern digital HSIs. The conventional paper-based procedures, hard-wired indicators and analog controls are being replaced by digital (on-screen, computer-based) procedures, integrated information systems and soft controls.

The changes in the HSI can impact the work of the operators in several ways and thus potentially affect plant safety (Porthin et al., 2019). Most of the HRA methods used today were developed before the introduction of ACRs and digital HSIs. They may not properly account for the changes in the operators' work induced by the new features of ACRs.

Phoenix elements, namely CRT, CFMs, PIFs, and quantitative aspects, were assessed for digital control room operation. Phoenix elements have been reviewed according to i) completeness – i.e., are all aspects involved in human performance / human error during digital control room operations represented in Phoenix? and ii) adequacy – i.e., how well do Phoenix elements reflect human performance / human error in these operations? The assessment leveraged peer-reviewed articles and public reports on digital control rooms and impact on human performance/ human failure and human reliability. Due to size constraints, this section summarizes the main findings but does not provide a review of all sources used and a full description of the analysis.

The first element assessed was the CRT. As stated by Kim et al (Kim et al., 2019), digital control rooms change task types at the interface operation level and keystroke level. They conclude that there are no significant differences in the task type level. Therefore, no changes in Phoenix CRT structure should be needed.

The following summarizes additional points raised by researchers and how they are modelled through Phoenix:

- Operator possibities to transfer to other computerized or paper backup procedures if computerized system crashes

Phoenix: Phoenix proposes a Phoenix flowchart to build the CRT, which includes recovery tasks. The CRT includes a branch point concerning the use of other cues or procedures in case the main procedures is not available. The same flowchart question / branch point would apply in this situation.

- The importance of “mode error, a failure related to recognizing or selecting the mode of operation for automated controls” (Presley et al., 2022)

Phoenix: The mode error can have different aspects. One is a failure related to recognizing the mode of operation. This can be modelled through CFMs in the I phase, such as Data Incorrectly Processed. This can also have roots in the D phase, in which the operator misdiagnoses the Plant / System State, i.e., thinking the plant is in one mode when it is in another one. This aspect can thus be modelled by these two Phoenix CFMs.

Indeed, as pointed by (Wright & Bye, 2022), “Mode confusion errors do not have a direct counterpart in existing taxonomies but are considered within modes/mechanisms such as the ‘Wrong Data Source Attended To’ or Right/Wrong Action on Wrong Object’”

Concerning PIFs, authors have discussed aspects mainly related to workload, task complexity, and HSI:

Workload:

- Higher automation may lead to higher workload in emergencies. While the digitized interface requires less movement around the control room, operators perceive higher workload and higher physical demands” (Medema et al., 2019)

Phoenix: these points are associated with the states of the PIF workload (i.e., its probability of being in a state that degrades human performance). They are thus covered by Phoenix Task Load PIF. Additional questions can be added to assessing workload concerning aspects specific to automation.

Task Complexity

- Park et al. (Park et al., 2022) analysed the effect of task complexities on the occurrence of errors of omission (EOOs) and errors of commission (EOCs) in an analog and digital environment. They observed that for proceduralized tasks relatively easy or moderate level of the task complexity, MCR operators in the analog environment can be more likely to make EOOs. For more complex proceduralized tasks, “the occurrence probability of EOOs in the digital environment drastically increases compared to that of the analog environment. Finally, they state that the probability of EOOs in a digital environment seems to largely depend on the task complexity, while it is less impactful for analog environment. EOCs, on the other hand, seems to be significantly affected by the task complexity in both environments.

Phoenix: these observations indicate that the conditional probability of failure in certain tasks given task complexity can be different for analog and digital environments. Future work includes cross-referencing the errors analysed by Park et al. and Phoenix CFMs. Phoenix may differentiate the CFMs as happening in analog or digital environments, each with their own BBn with different CPTs.

Human-System Interface

- “HMIs with up-to-date digital technologies can be regarded as a double-edged knife because they are effective for preventing EOOs but they can provide more chance to cause EOCs than that of analogue HMIs.” (Park et al., 2022)
- Experiments pointed that digital control systems can enable operators to perform more efficiently than with conventional analogue HSI (Wright & Bye, 2022)

Phoenix: Similarly to the points related to task complexity, it may be that the conditional probability of certain CFMs given the HIS state differs for digital and analog HSIs, leading to two instances of some CFMs’ BBNs.

The following points were raised by Presley et al. (Presley et al., 2022) as potential new aspects for HRA concerning digital control rooms:

- Automation under-reliance
- Automation over-reliance

These aspects are related to operators’ bias, included in Phoenix Level 1 PIF Bias through, e.g, Confidence in Information or Recency of Situation. Additional questions to assess these factors’ state can be added to cover issues specific to automation over and under-reliance.

Concerning HEPs, Park and Kim (Park & Kim, 2022) performed an analysis using Hurex framework. They identified differences in the HEPs for EOOs and EOCs for different task types. However, their work uses HEPs based on tasks, rather than a causal analysis of the errors. Since Phoenix uses a causal model through the BBN-FTs layers, the use of this data is not straightforward. Before integrating Park and Kim conclusions, a “translation” between Hurex task types and Phoenix is necessary.

6. Discussions and concluding thoughts

Phoenix framework is sufficiently flexible to be applied to contexts and NPPs configurations for which it was not initially developed. Indeed, this flexibility has been demonstrated before with adaptations to the downstream oil and gas processing (M. A. Ramos et al., 2020).

The exercises summarized in this paper shows that the framework is also applicable to inspections and the new digital control rooms. Some of the PIFs need to be reassessed to investigate if we are providing sufficient guidance to analysts to consider aspects related to, e.g., digitalization and other contexts. Likewise, the impact of certain PIFs on the CFMS may mean that we need different instances of the CFMs’ BBNs. Some of Phoenix CFMs are already differentiated considering the context. For instance, Phoenix CFM include “Plant/System Misdiagnosed by Following Procedure” and “Plant/System Misdiagnosed by Following Own Knowledge”. The conditional probabilities of these CFMs concerning the PIFs Procedures Knowledge are different, as we expect that inadequate procedures will have a higher impact on misdiagnosing a plant when following the procedures than when following operators’ knowledge, and vice-versa.

The following summarizes the main conclusions of the exercises described in this paper:

1. <u>The use of Phoenix with DPRA tools:</u> Preliminary application to Loss of Secondary Cooling and Station Blackout have been performed and resulted in adequate HEPs. Further analysis is being performed to assess the impact of Time Constraint on the HEP through a sensitivity analysis.
2. <u>Inspection activities using the Cause Analysis Guide and Phoenix:</u> All the error causes could find correspondence with Phoenix PIFs. Further investigation include assessing how well some organizational factors are represented by Phoenix PIFs.
3. <u>The use of Phoenix for digital control rooms:</u> Recent studies suggest that cognitive-based HRA methods such as Phoenix cover the failure modes related to digital control rooms (Bye et al., 2022). Similarly, most of the discussions about the PIFs revolve around PIFs that are covered in Phoenix. These impact of some PIFs seem to be higher or lower in digital control rooms compared to analog ones, which may lead to different instances of Phoenix CFMs with specific conditional probabilities.

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