The Phoenix HRA Approach: Method and Software Platform for Nuclear Power Plant PRA Applications

Ali Mosleh [a*], Marilia Ramos [a], Tingting Cheng [a], Wadie Chalgham [a]
[a] The B. John Garrick Institute for the Risk Sciences, UCLA, Los Angeles, United States

Abstract: This paper presents the underlying methodology and features of the Phoenix HRA software platform that has gone through nearly 10 years of research and development. Phoenix incorporates strong elements of current HRA good practices, leverages lessons learned from multiple empirical studies, and uses strong features of existing and emerging HRA methods. In addition, it formally includes relevant cognitive and psychological theories in its human performance model, namely the IDAC framework. Phoenix was developed to support Probabilistic Risk Assessments (PRA) of Nuclear Power Plants (NPP) including full-power internal events PRA, low-power shutdown (LPSD) operations, event assessment and significance determination processes (SDP), fire, and seismic PRAs. The methodology is generic and can be applied across different industries and environments, including oil & gas, aviation, power generation, and others. Phoenix framework includes qualitative and quantitative analysis steps. A summary of the steps and underlying method of Phoenix has been described in several papers by the authors of this paper and other co-authors. These publications provide the complete Phoenix HRA qualitative and quantitative analysis approach, detailed procedure, and data requirements. The aim of this paper is to present the key features of the Phoenix HRA software that greatly facilitates the application of Phoenix HRA by automating many of the qualitative and quantitative steps of analysis.

Keywords: PRA, HRA, Human Error, HRA Software

1. INTRODUCTION

Phoenix Human Reliability Analysis (HRA) methodology uses the Information, Decision and Action in a Crew context (IDAC) framework to model the response of operators to abnormal plant conditions [1-3]. It incorporates elements of current HRA good practices, leverages lessons learned from empirical studies, and strong features of existing and emerging HRA methods. It formally captures relevant cognitive and psychological theories in its human performance model. Phoenix was developed to support Probabilistic Risk Assessments (PRA) of Nuclear Power Plants (NPP) including full-power internal events PRA, low-power shutdown (LPSD) operations PRA, event assessment and significant determination processes (SDP), and fire and seismic PRAs. The methodology itself is generic and can be applied across different industries and environments, including oil & gas, aviation, power generation, and others [4-5].

Since its development in 2014, Phoenix has been applied to several case studies to test not only methodological features and assumptions, but also the practical aspects concerning its use by HRA analysts. These studies have resulted in several enhancements of the methodology and its implementation in the Phoenix 2.0 Web App developed by the UCLA B. John Garrick Institute for the Risk Sciences. The Phoenix Web App is a user-friendly software intended to minimize analyst effort in performing the complex qualitative and quantitative steps of the Phoenix HRA while maintaining its advanced features, resulting in a traceable and reproducible analysis.

This paper provides an overview of the Phoenix HRA methodology, and the Web App. Section 2 presents the Phoenix methodology and its main elements and steps, followed by a description of the Web App's main features in Section 3. Section 4 provides concluding remarks.

2. PHOENIX HRA METHODOLOGY

The Phoenix HRA methodology employs several layers of modeling as shown in Figure 1:

- Master Event Sequence Diagram (ESD): Connects Critical Functions (CFs) in a chronological sequence.
- Crew Response Tree (CRT): Models crew-plant interaction scenarios leading to Human Failure Events (HFEs).

- Human Response Model in from of a Fault Trees (FT), containing Crew Failure Modes (CFMs) within operator response phases of information gathering, decision making and action execution, in performing Critical Tasks (CTs) as identified in CRT.
- Causal Model - Performance Influencing Factors (PIFs), modeled using Bayesian Belief Networks (BBNs) to represent cognitive, emotional, and physical factors affecting human performance.

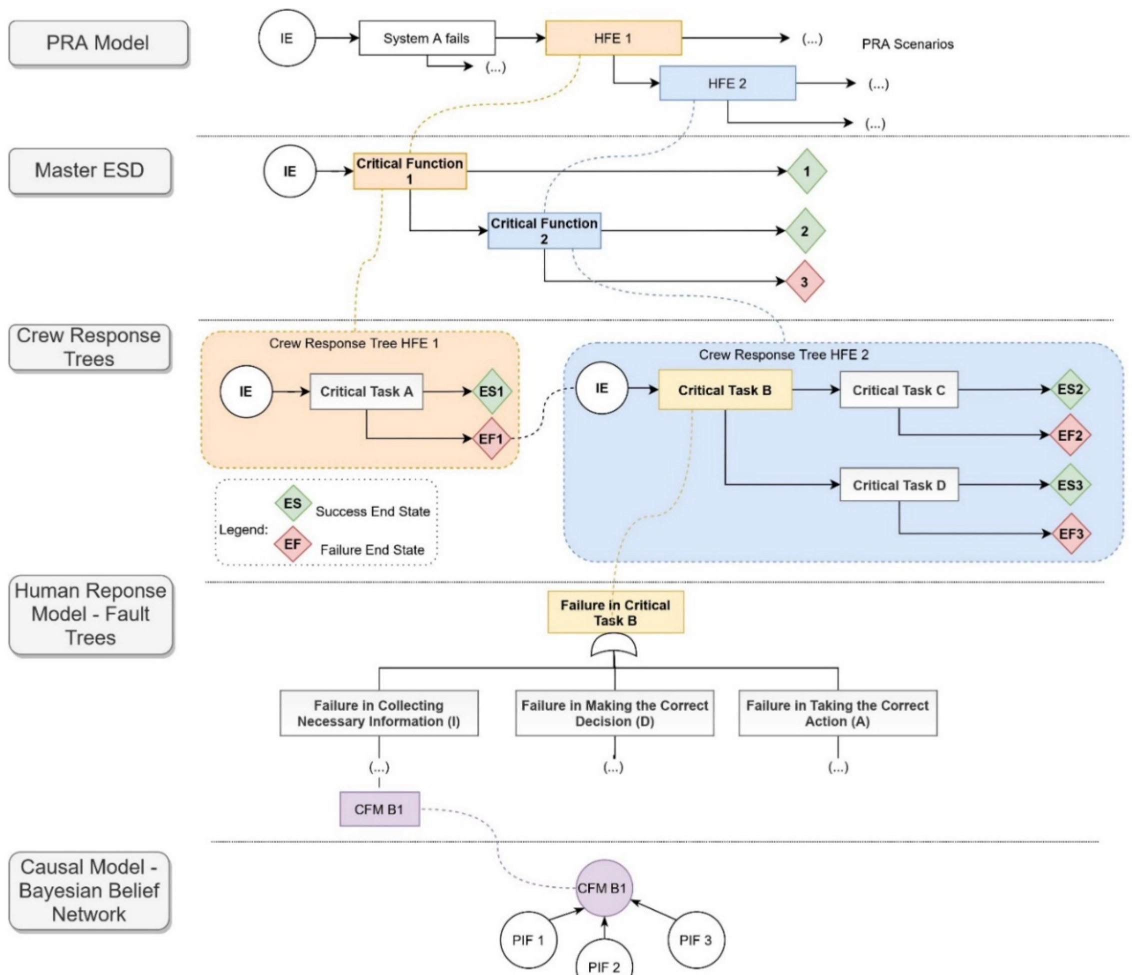

Figure 1. Phoenix Modeling Layers and Relation to PRA ET Model

The qualitative part of Phoenix involves developing CRTs using a guiding flowchart and answering structured questions to identify CTs and CFMs. This helps in understanding crew actions, potential errors, and their impacts. The quantitative part involves using causal FTs and BBN model of PIFs to calculate Human Error Probabilities (HEPs) by considering the impact of PIFs on CFMs. Details can be found in [6-7].

The modeling and calculation process of Phoenix methodology is shown in Figure 2, and further summarized in the following:

- Developing Master ESD:
  - Identify CFs from PRA models or develop PRA models concurrently.
  - Connect CFs through ESD, considering human and system events.
- Creating Crew Response Tree (CRT):
  - Use CRT construction flowchart to model interaction scenarios and identify CTs.
  - Focus on critical procedural steps to achieve CFs.
- Human Response Model – Causa Fault Trees:
  - Model CT failures using FTs.
  - Identify relevant CFMs for each phase of Information Gathering, Decision Making, and Action Execution (I, D, A)

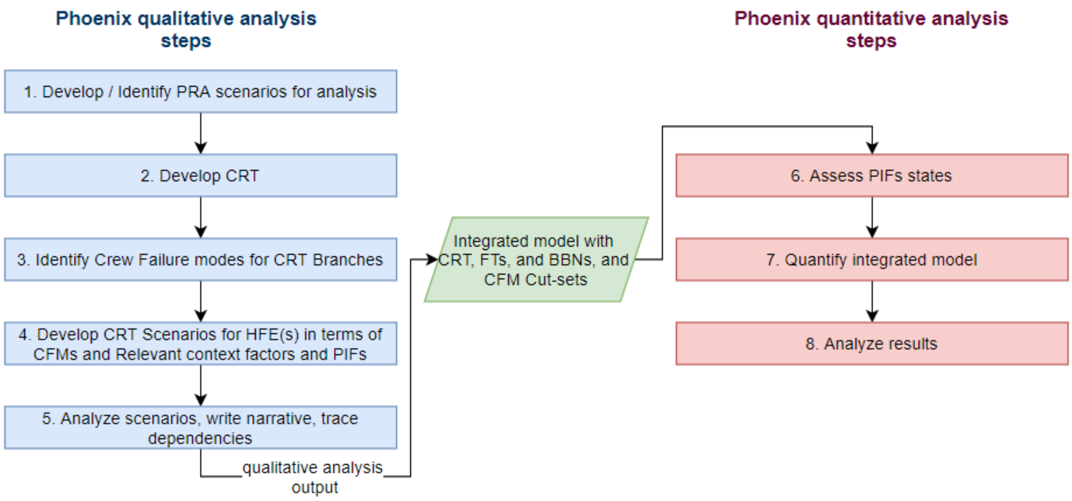

Figure 2. Phoenix Qualitative and Quantitative Analysis Steps

- Selecting Crew Failure Modes (CFMs):
  - Use guiding questions to identify relevant CFMs for the context defined by CRT scenarios.
  - Ensure CFMs are mutually exclusive to avoid double-counting.
- Causal Model - Bayesian Networks (BN):
  - Identify PIFs and their influence on CFMs through BBNs.
  - Determine the probability of PIFs being in “nominal” or “degraded” states.
- Quantification:
  - Use BNs to quantify probabilities of CFMs and HEPs.
  - Perform dependency quantification.

3. PHOENIX HRA SOFTWARE

The Phoenix Web App has been developed to aid the analyst in conducting qualitative and quantitative steps of the Phoenix HRA methodology. The following is a step-by-step overview of the software in the modeling and calculation process, covering key elements such as ESD, CRT, FT, CFM, PIF, BBN, and final human error probabilities. Model elements are shown in the second rectangle in Figure 3.

3.1 Master ESD Screen - Modeling Master ESD

In this panel, users can add an image, e.g., the PRA Event Tree or Even Sequence Diagram, define Critical Functions (e.g., Feed & Bleed operation in PWR PRA), and build a sequence of CFs (master ESD). Two CF analysis types are available: Phoenix Model and Probability-Based, which means the failure of the CF will be modeled and quantified with Phoenix steps or with user-assigned failure probability, as shown in Figure 3. The Critical Functions can be linked as the Master ESD to follow the PRA ETs (Figure 4).

3.2 Crew Response Trees (CRT) Screen - Building CRT

Users can follow a flowchart and answer scenario-specific questions that define Branch Points (BPs). CT events are then generated by responses to questions, and are linked to form the CRT, corresponding End States or Master ESD End States finally. Figure 5 shows the CRT Screen:

1. Master ESD view
2. Flowchart: The CRT is built using a flowchart. The flowchart contains questions (DPs) and BPs. The questions concern the scenario under analysis and the operators’ interaction with the system. They can be answered as “Yes” or “No / Does not Apply”. The response to the questions will trigger the creation of BPs, which may be system events (e.g. Pump Availability) or human events (e.g. Crew Follows Procedure). The flowchart in progressively built according to the response to questions.
3. Copy from: this function allows copying the responses given when building a previous CRT. It can be used in case the CFs have the same CRT structure.
4. Questions: Questions /Answers are displayed. Users can add a description to document the basis of the answer.

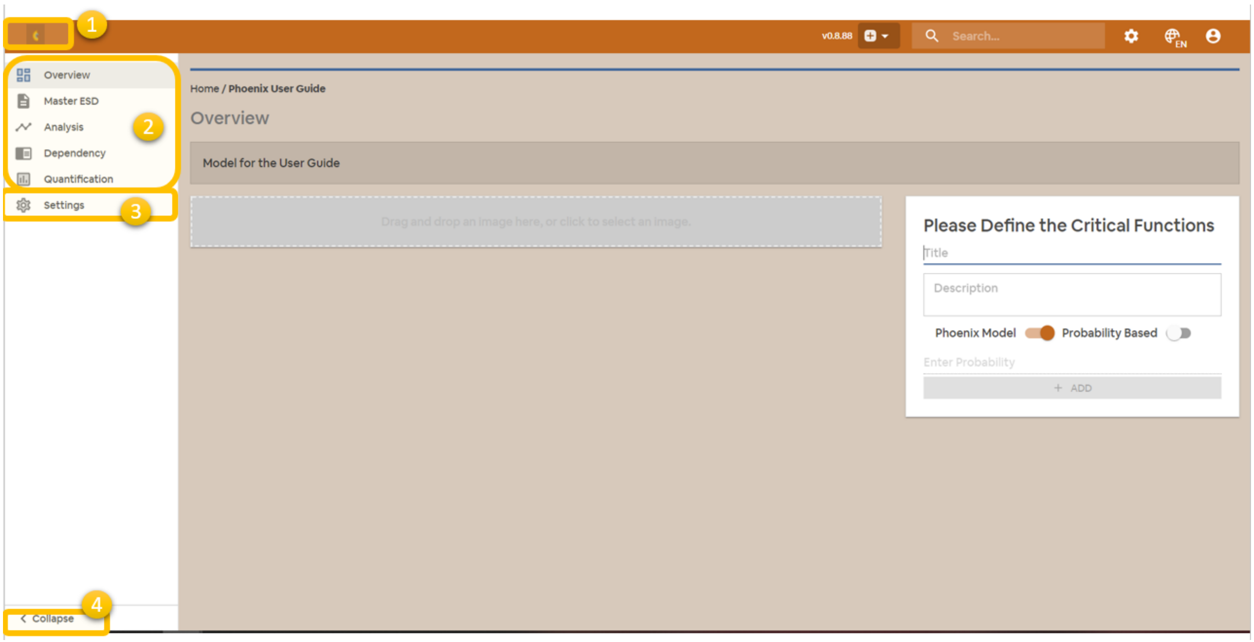

Figure 3 Phoenix Overview Screen - Definition of Critical functions (1: return to initial page, 2: model elements, 3: model settings, 4: collapse menu)

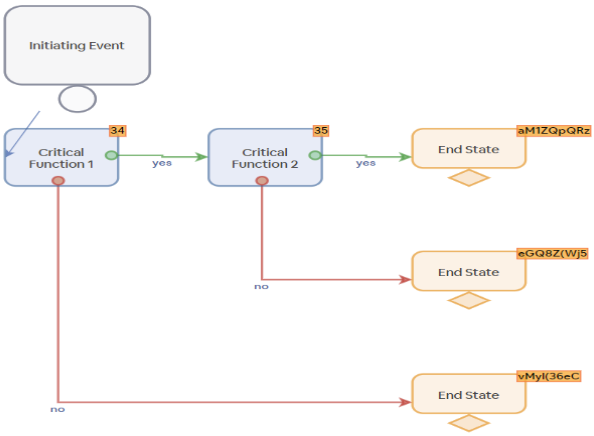

Figure 4 An Example of Master ESD in Phoenix Software

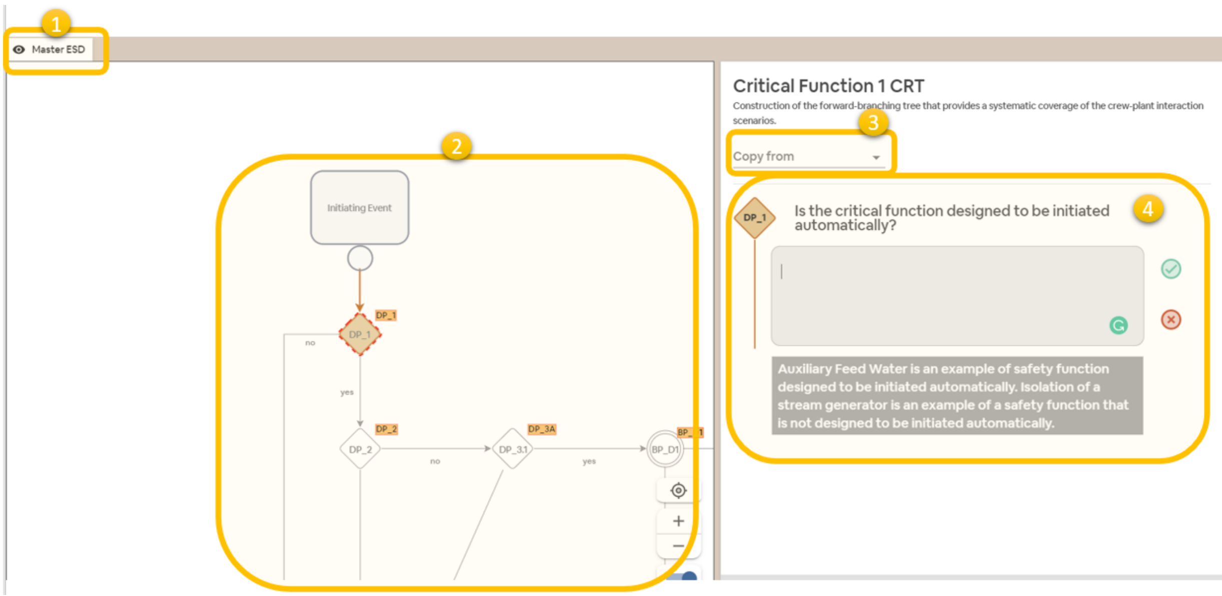

Figure 5 CRT Construction Screen

3.3 Analysis Screen

Analysis Screen pathways to the following functions: building fault trees (FTs), users navigate to select relevant CFMs and basic events; selecting CFM, users answer guided questions to select appropriate CFMs for each BP; Calculating HEPs. Figure 6 shows the elements in the Analysis page: 1. Name of the CT, 2. CFMs and Basic Events selected for that CT, 3. CT options: Fault Tree view (available once the CFMs are selected), editing (selecting CFMs), quantification, CFMs view, 4. CF options: view the CRT and quantify the CRT (once CFMs and PIFs are assessed).

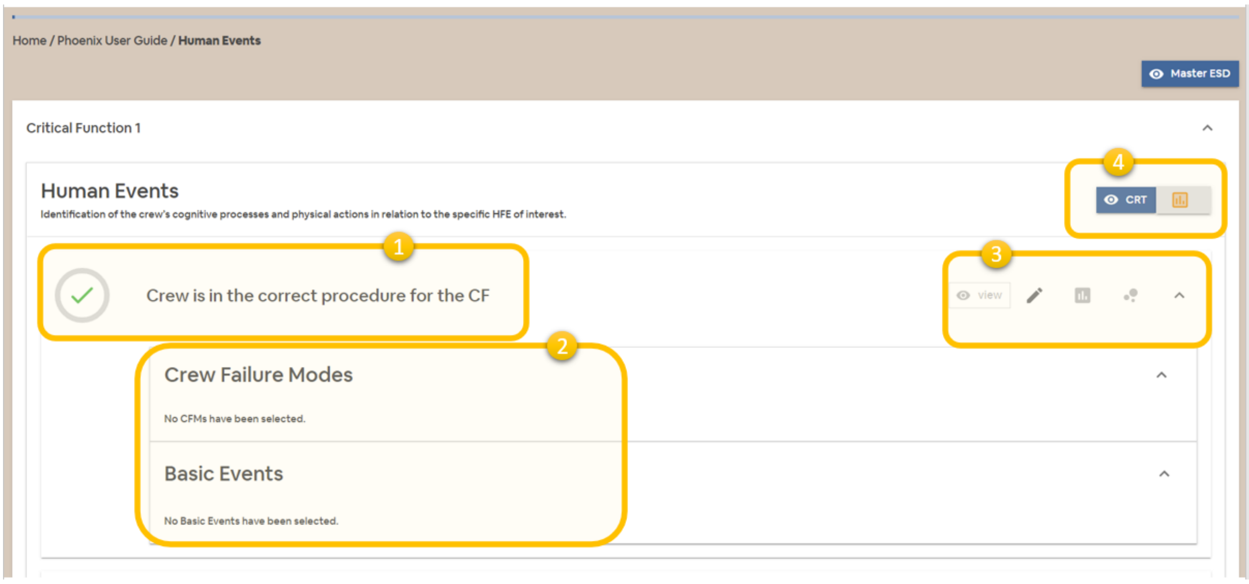

Figure 6 Analysis Screen

3.4 Crew Failure Modes Screen

The CFM page presents the FT and guides the analyst in selecting the appropriate CFMs, as illustrated in Figure 7 (1. Fault Tree view ; 2. CRT view; 3. Name of the BP for which the CFMs are being selected ; 4. Questions for selecting the CFMs).

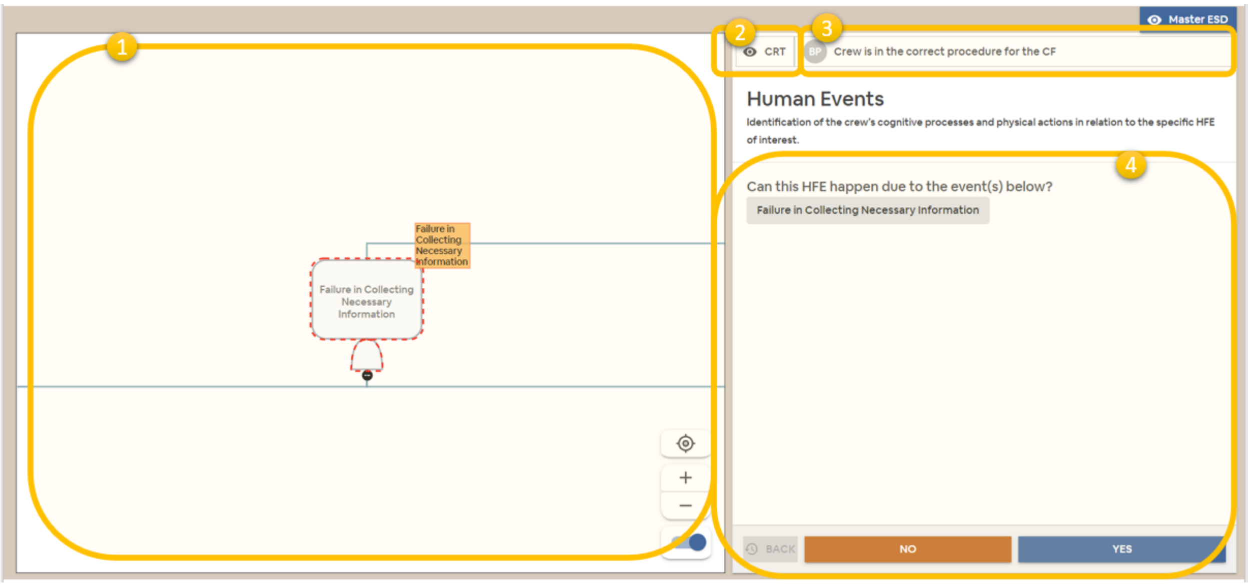

Figure 7 Crew Failure Modes Screen

An example of selecting CFM is shown in Figure 8. The questions posed guide the selection of the appropriate CFMs for the event. Responding <YES> or <NO> to the questions directs to the relevant branches of the CFM FT, leading to CFMs concerning the IDAC three phases of response namely Information, Decision, and Action. More than one CFM may be relevant for any given BP.

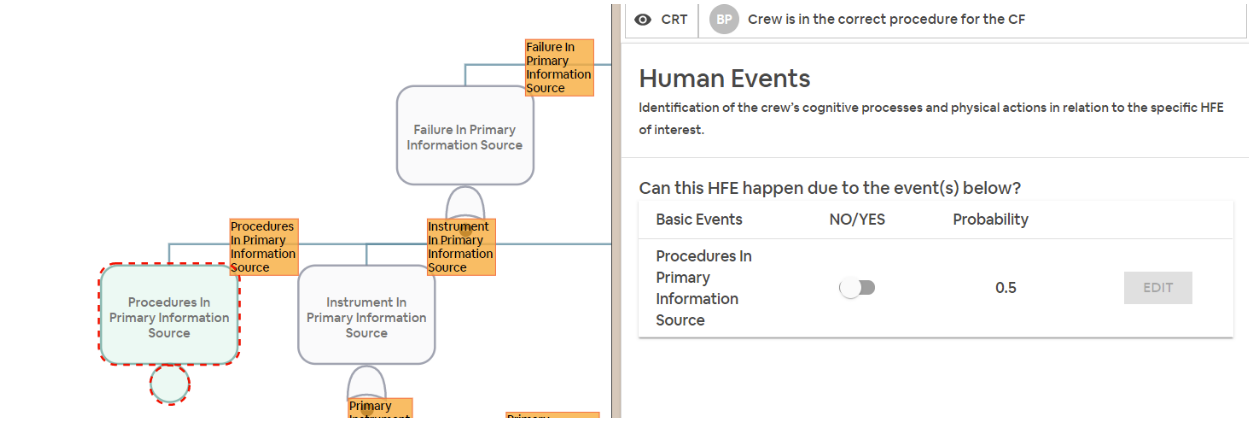

Figure 8 Selecting CFMs in the fault tree

Once users scan through the three parts of the CFM FT, a summary of the selected CFMs and Basic Events will be displayed. Users can return to a previous branch of the FT by clicking <BACK>. Otherwise, by clicking <NEXT> the user will be directed to directed to the Analysis page. CFMs will appear in the Analysis Page under the event's name, with options for editing and quantifying (available after PIFs have been selected). By clicking Edit, the user can select the PIF for a given CFM, at which point the user can record the assessed PIF states by inputting scores or by answering detailed questions.

Figure 9 shows the elements of PIF page elements which include:

1. BP being analyzed.
2. View the HFE (Fault Tree)
3. CFM for which the PIFs are being selected.
4. List of PIFs (organized hierarchically, with the sublevel PIFs shown in grey).
5. Selecting PIFs (user can the toggle to select applicable relevant PIFs).

Once the PIFs have been selected, users will be directed to the Analysis page, where they will find the PIFs under the CFM (Figure 10).

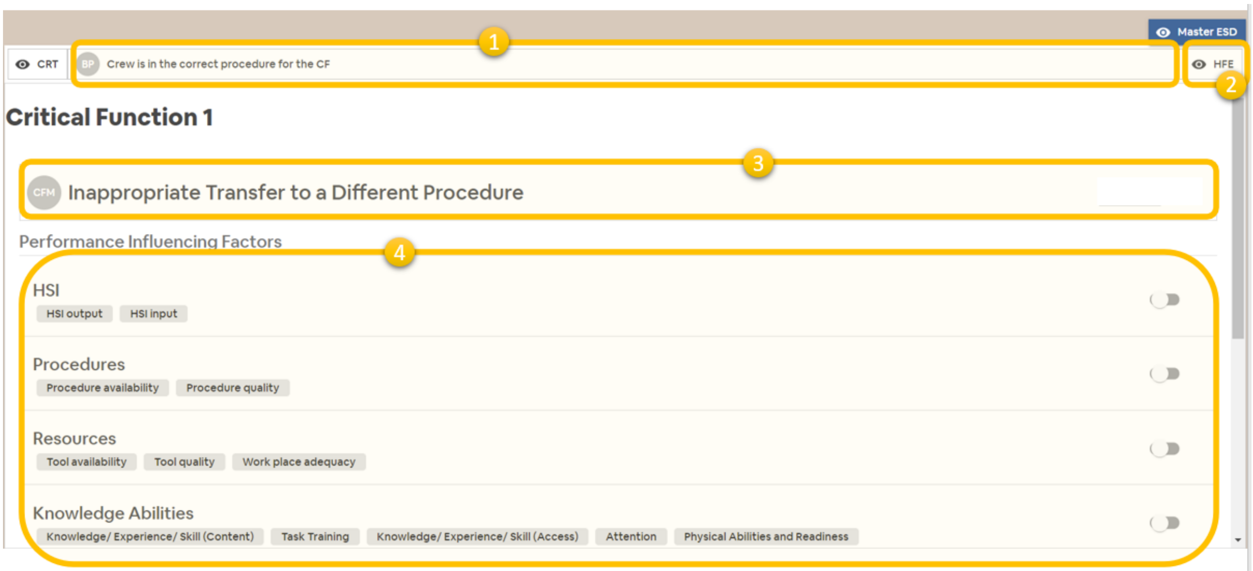

Figure 9 PIF Selection/Assessment Screen

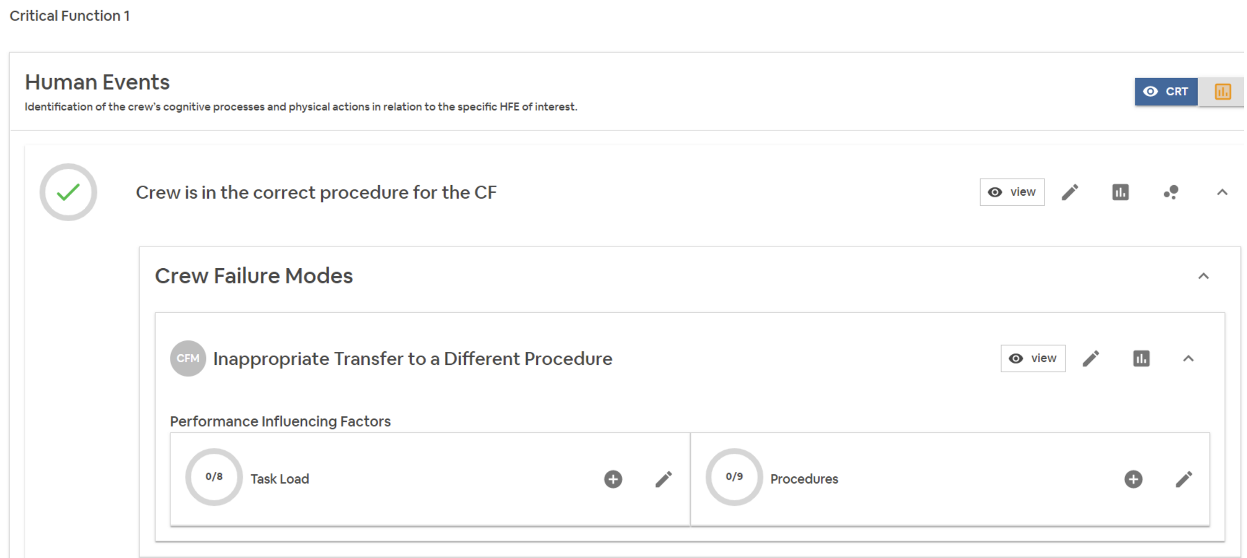

Figure 10 PIFs in the Analysis Screen

Two options are available for assessing the state of the PIFs : input score or edit the PIFs. When inputting a score, users will directly enter a probability (score). This is the probability that the PIF is in a state that will degrade human performance, contributing to that CFM (increasing the likelihood of human error). PIF assessment through answering the related questions is preferred for enhancing the traceability of the analysis. The input score can be used if a PIF has been assessed for another CFM and is in the same state (does not change with scenario progression). A justification for the score must be added, as shown in Figure 11.

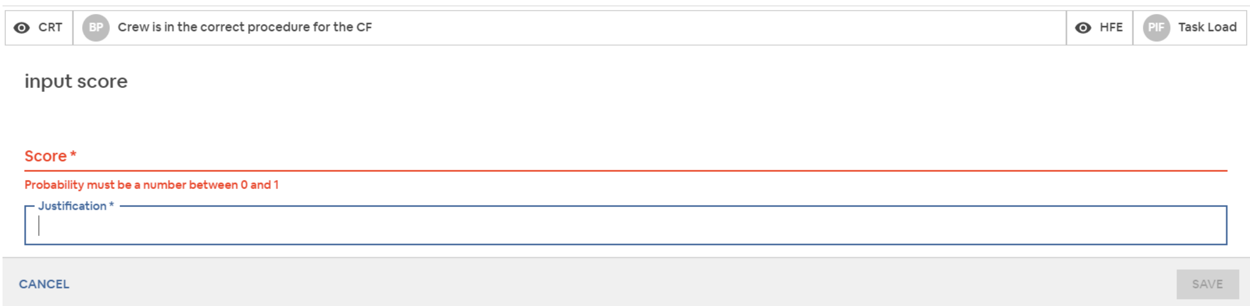

Figure 11 Documentation of Basis for Scores and Justification of PIF States

When editing the PIFs, users will respond to questions concerning the state of the selected PIF. The options are Yes/No, or N/A. Users can justify their own responses, as shown in Figure 12.

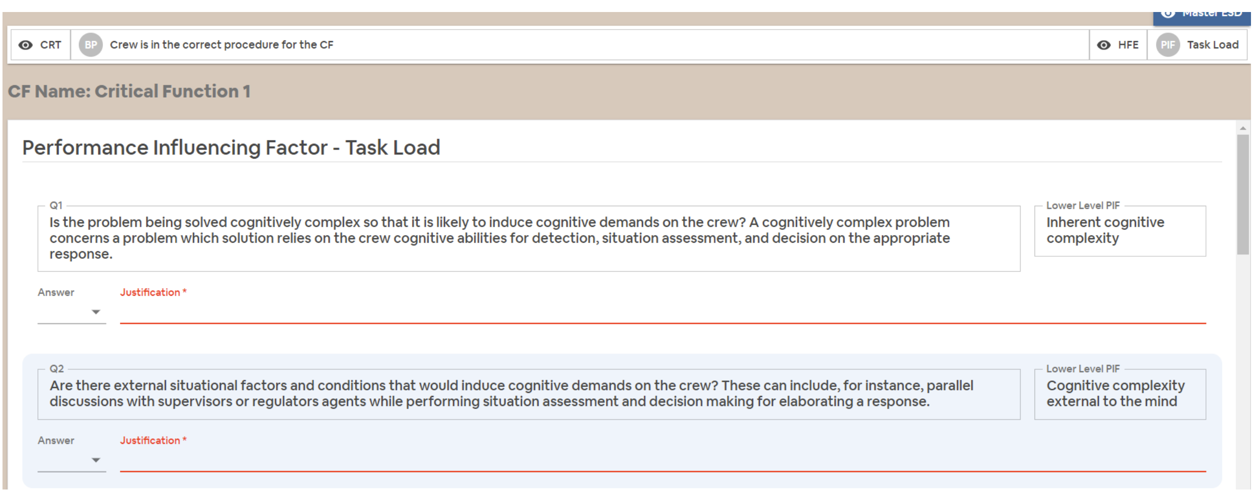

Figure 12 Questionnaire for Assessing PIF States

Once the responses to questions are completed, the PIF score (the probability that the PIF is in a state that would degrade human performance) is displayed. By going back to the analysis page, users can click on the score and "override" this probability if desired (e.g., for performing sensitivity analysis). Figure 13 presents the Analysis Page with the CFMs and PIFs selected, with their respective states. The green label concerns PIFs assessed through Phoenix questionnaires, whereas the red label concerns PIFs for which the probability was directly input by the user. Once the model is complete with CFMs, PIFs, and PIFs' states, the user can quantify the CFM probability, which will quantify the BBN (3), the CT failure probability, which will quantity the FT (2), and the CRT, which will quantify the ESD (1).

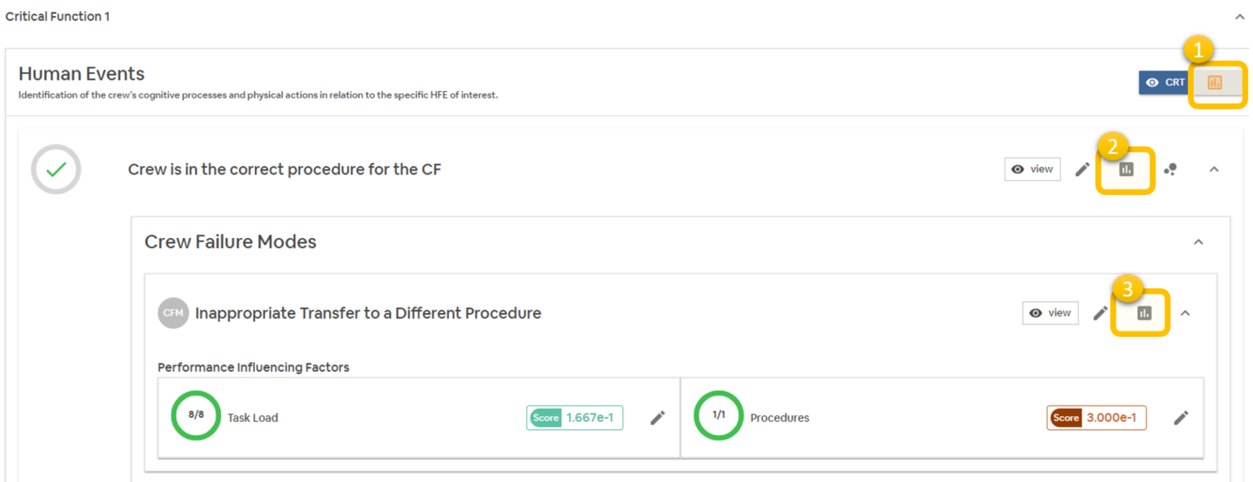

Figure 13 Analysis Page with PIFs states

3.4 HEP Quantification and Treatment of Dependencies

Once the assessment of all relevant PIFs is completed, the analysis of dependencies is initiated. Users can establish dependencies between CFMs using common PIFs, and group CFMs to manage dependencies. A hierarchical list will present all the included CFs and events. When the PIF has been selected as relevant for a CFM under the event, the CFM will appear on the list (in blue, as shown in Figure 14):

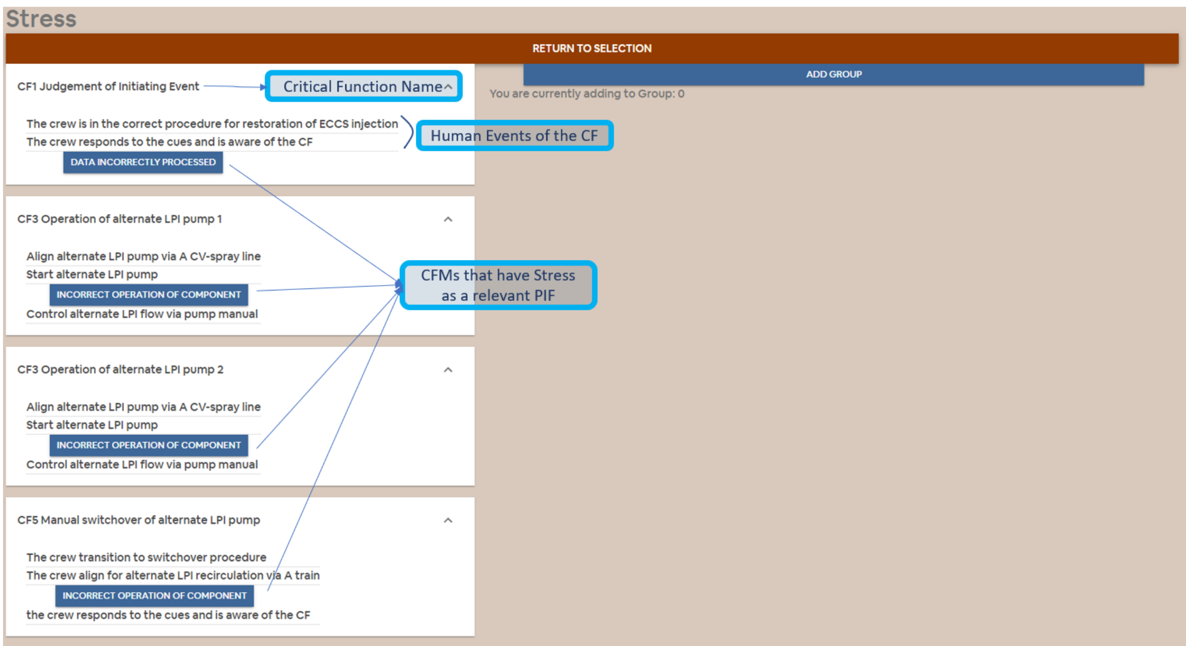

Figure 14 Dependency Assessment Screen

In case the CFMs are dependent on the PIF, the user needs to click on <ADD GROUP> and select the CFMs to add them to the same group, as shown in Figure 15.

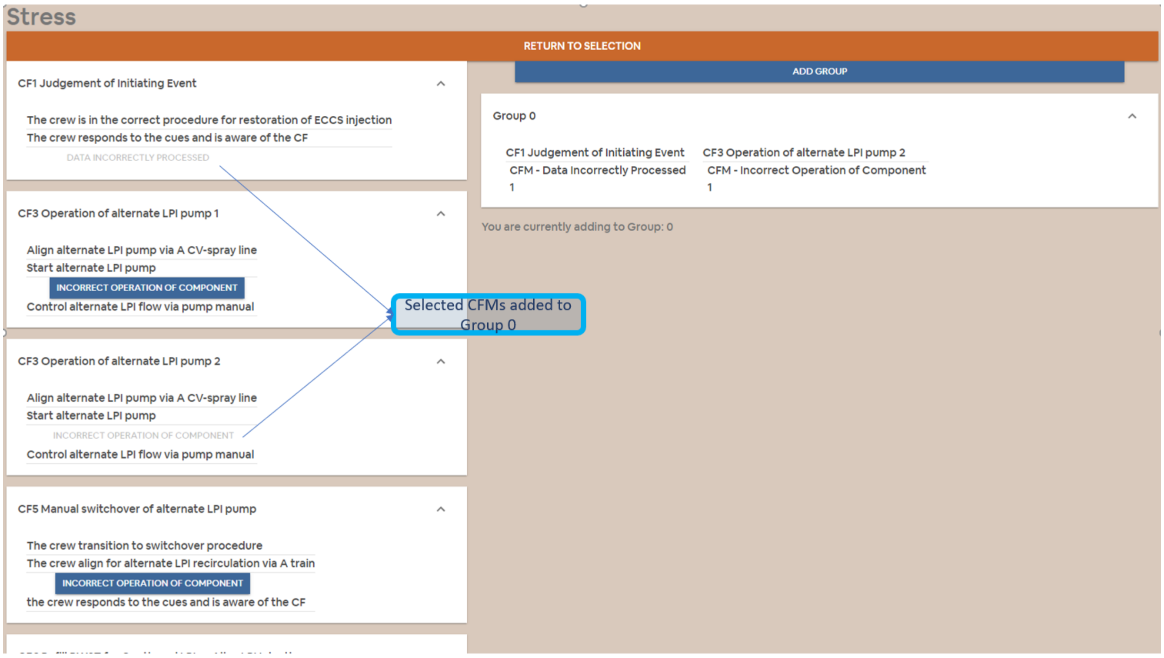

Figure 15 Establishing Dependency Among CFMs

To create another dependency group, the user can click on <ADD GROUP> once more. As an example of when multiple grouping might be needed, consider two actions A and B that are performed by the same team (Team 1), having stress as a common PIF affecting their CFMs. Now consider two other actions C and D that are performed by a different team (Team 2). While actions A, B, C, and D may have CFMs that are impacted by the PIF Stress, the dependency needs to be treated separately between actions A and B and between C and D. The user's input on dependency is used for quantifying the CFMs through a Bayesian updating process [8].

After dependency analysis is completed, the user can go to the Quantification screen, where the HEPs for various CFs and the Master ESD are displayed (Figure 14). Also, past quantifications can be seen at "Quantification History," with the dates the quantification was performed.

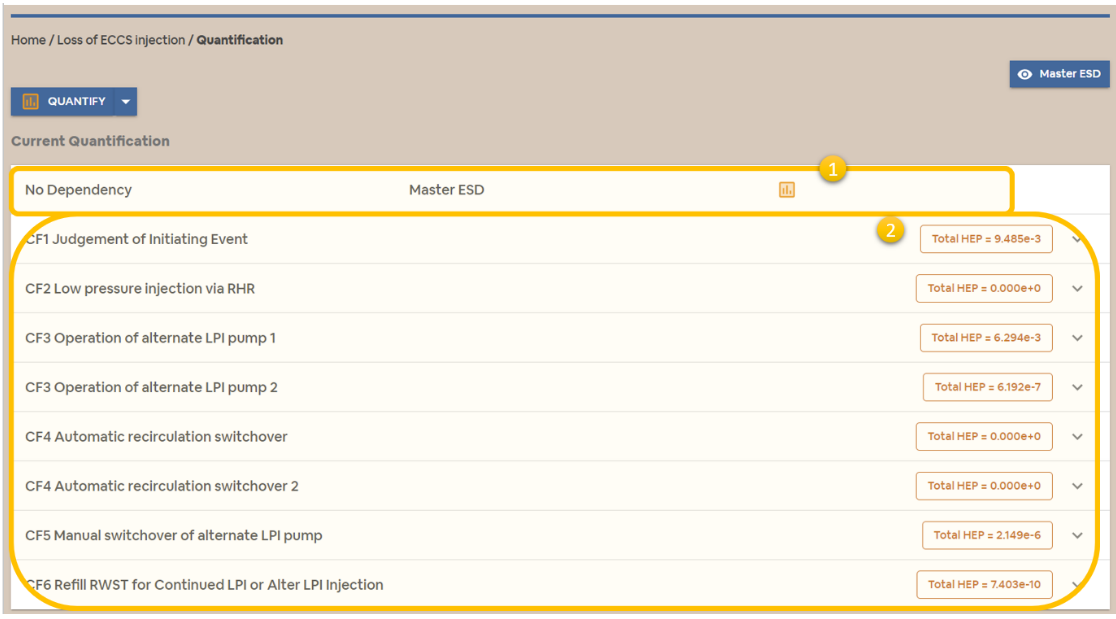

Figure 14 Quantification Screen

4. CONCLUDING REMARKS

This paper briefly describes the underlying methodology and features of the Phoenix HRA software platform that has gone through nearly 10 years of research and development. Phoenix's framework includes qualitative and quantitative analysis phases. A summary of the steps and underlying method of Phoenix qualitative analysis has been provided in papers by the authors of the present paper. These publications provide the complete Phoenix HRA qualitative and quantitative analysis approach and the detailed procedure and data requirements. The present paper discusses the Phoenix analysis process, and key features of the Phoenix HRA software that automates the generation of crew-plant interaction scenarios through CRTs, enables the analyst to construct causal models (through fault trees of crew failure modes, CFMs, and relevant PIFs), and to quantify probability of resulting HFEs (both commission and omission errors) and quantify dependencies among HFEs through corresponding PIFs. The Phoenix software greatly facilitates the process of conducting an NPP HRA, while maintaining the features of an advanced method, resulting in a traceable and reproducible analysis.

Numerical HEP values from conducting HRA in nearly 20 detailed scenarios with Phoenix software have been compared with several other HRA methods such as SPARH and IDHEAS producing consistent, order of magnitude, results and also ranking of HEPs. However, the results for dependent HFEs are markedly different. A future paper by the authors will focus on these results and explore the reasons.

The aforementioned trial applications identified areas of methodological and software implementation improvements which were fully addressed resulting in Phoenix 2.0. Two challenges that are worth mentioning were: (a) keeping proper balance between automation of alanyls steps and transparency and traceability, and (b) user experience in terms of speed of processing large models in an online Web App.

Acknowledgements

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