Dependency Analysis Within Human Failure Events for Nuclear Power Plant: Comparison Between Phoenix and SPAR-H

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Abstract: Robust and realistic Human Error Probability (HEP) estimation within Human Reliability Analysis (HRA) relies upon, among other factors, appropriate consideration of the dependency between human failure events (HFEs). The approach for assessing dependency varies throughout HRA methods. The reasoning and cognitive basis behind the different approaches for dependency, their quantitative rationale, and their impact on the HEP are still subject to investigation from the HRA community. This paper aims to discuss the characteristics of HRA methodologies considering dependency through a comparison between two approaches: Phoenix, developed by the University of California, Los Angeles, and SPAR-H, developed by Idaho National Laboratorie. Their qualitative frameworks are compared through three elements: HRA variables, Performance Influencing Factors considered, and causal modeling methods. The factors used for estimating dependency, the guidance for assessing the dependency, and its impact on the HEP are further compared and discussed.

1. INTRODUCTION

Probabilistic Risk Assessments (PRAs) of nuclear power plants (NPPs) include Human Error Probability (HEP), estimated through Human Reliability Analysis (HRA) methods. Robust and realistic HEP estimation relies upon, among other factors, appropriate consideration of the dependency between human failure events (HFEs). Indeed, NUREG-1792 [1], Good Practices for Implementing HRA, emphasizes considering commonalities, similarities, and links among actions when assessing human performance. These links are at the roots of dependencies between actions and HFEs, such as actions involving the same crew members, occurring closely in time, crew sharing a common mindset, etc. Dependency is considered to occur when the success or failure of one action changes the probability of success or failure on a subsequent action [2] .

Despite its importance to HEP estimation and to PRA, the assessment of dependency and its impact on the HEP is still a challenge in HRA. Dependency assessment varies throughout HRA methods, and subjective determination of dependency between HFEs can lead to a difference in HRA and PRA results [3]. While many HRA methods estimate the impact of dependency using the THERP [4] dependency model as a basis, it has been argued that the model is highly subjective [4,5], and the foundations for its quantitative impact on the HEP are not clear. As a result, other approaches have been proposed, such as using Bayesian Belief Networks (BBNs) which models the relationship between environmental factors and HFEs [5]. A discussion on different definitions and a discussion on types of dependency can be seen at [6,7]

This paper aims to discuss approaches to dependency assessment in HRA by comparing two methods: Phoenix [8], developed by the University of California, Los Angeles, and SPAR-H [9], developed by Idaho National Laboratorie (INL). While SPAR-H uses the THERP model as a foundation for dependency assessment, Phoenix uses BBNs and Bayesian updating. First, their qualitative frameworks are compared through three elements: HRA variables, Performance Influencing Factors (PIFs) considered, and causal modeling. Then, their approaches for assessing dependency and its impact on the HEP are discussed. This paper is part of a larger study aimed at comparing HEPs generated by different methods and the impact of the different approaches for dependency assessment in the different HEPs.

This paper is structured as follows. Section 2 provides an overview of Phoenix and SPAR-H methods. Section 3 discusses their approach to dependency assessment, followed by the conclusions in Section 4.

2. OVERVIEW OF PHOENIX AND SPAR-H METHODS

At a high level, the HEP estimation procedures consist of three layers: HFE definition, assessment of PIFs, and calculation of the HEP with and/or without dependency between HFEs. Figure 1 presents Phoenix and SPAR-H main steps for HEP estimation.

SPAR-H was first developed in 1994 by the U.S. Nuclear Regulatory Commission (NRC) in conjunction with INL. It was initially called Accident Sequence Precursor Standardized Plant Analysis Risk Model (ASP/SPAR). In 1999, based on the experience gained in field testing, the method was updated and renamed to its current denomination. The complete and current version was published in 2005 by the U.S.NRC [9]. SPAR-H categorizes human activities as one of two general categories: action or diagnosis. Action tasks involve carrying out one or more activities indicated by diagnosis, operating rules, or written procedures. For example: operating equipment, performing line-ups, starting pumps, conducting calibration or testing, carrying out actions in response to alarms, and other activities performed during the course of following plant procedures or work orders. Diagnosis tasks concern tasks that rely on knowledge and experience to understand existing conditions, plan and prioritize activities, and determine appropriate action courses.

SPAR-H is a worksheet-based method: The evaluator fills in the analysis conditions on a worksheet, and the HEP is calculated using a multiplicative formula. Because it is worksheet-based, the calculation of HEP is simple, and the evaluation can be performed on-site and on time. Following the categorization of the HFE as diagnosis and/or action, the analyst assesses the performance drivers through the eight PIFs (Table 1) modeled by SPAR-H. The state of the relevant PIFs corresponds to multipliers that will either increase or decrease the HEP, i.e., degrade or enhance human performance. The analyst then calculates the PIF-Modified HEP, which can be modified using the dependency condition table, in case dependency is assumed.

Phoenix is a model-based methodology founded on previous works from different authors towards developing a model-based HRA methodology [10–12]. Phoenix was developed for supporting HRA of NPPs: full-power internal events PRAs, low-power shutdown (LPSD) operations, event assessment, significant determination processes (SDPs), and fire and seismic PRAs [8]. The methodology is generic and can be applied across different industries and environments, including oil & gas, aviation, power generation, and others [13,14].

Phoenix analyses human error and quantifies human error probability through three main layers. The first layer is the Crew Response Tree (CRT), which models the interactions between the crew and the plant through an Event Sequence Diagram (ESD). The Critical Tasks (CTs) identified in the ESD are further analyzed in the second layer, which models human performance through Fault Trees (FTs). The FTs lead to the identification of Crew Failure Modes (CFMs), further analyzed in the third layer. This layer models the influence of PIFs on the CFMs through BBNs. Phoenix makes use of the Information, Decision and Action (IDA) cognitive model, and categorizes an error as rooted in the information collection and processing, decision-making and situation assessment, or action taking – or a combination of those.

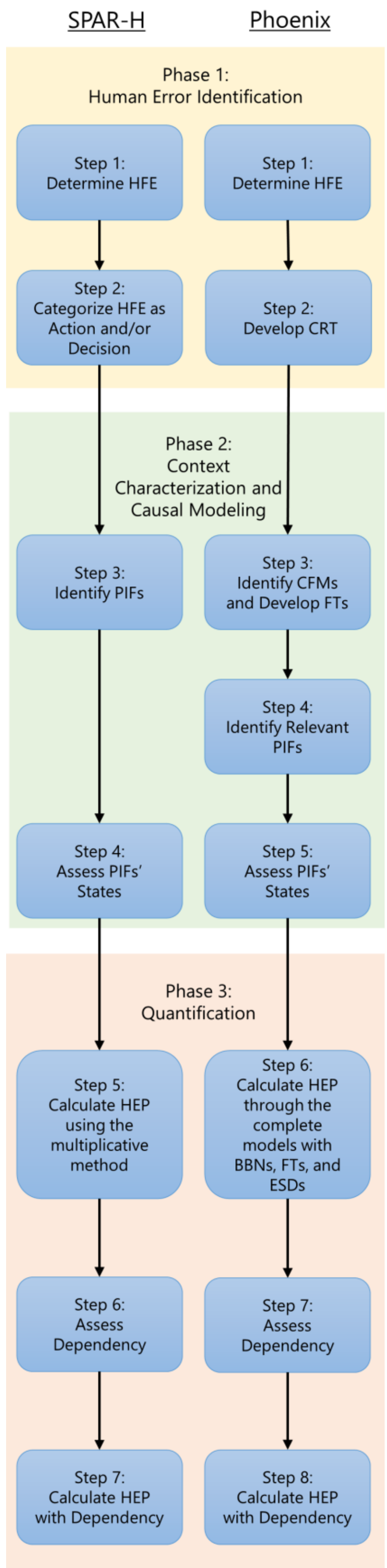


Figure 1 Analysis steps for SPAR-H and Phoenix

Phoenix is a software-based method. It can be applied through generic software that models and quantifies ESDs, FTs and BBNs, or the dedicated Web-App developed by the Garrick Institute for the Risk Sciences at UCLA. The development of the CRT leverages a flowchart, from which the CRT is developed through "yes/no" responses of the analyst about the scenarios and crew-plant interactions. In addition to crew critical tasks, the analyst can add events to the CRT corresponding to equipment failures. The analyst then identifies the relevant CFMs for the crew's critical tasks, and the PIFs for each CFM. Finally, the state of each PIF is assessed through a questionnaire that comprises questions about the condition of the PIF. The state of the PIF is translated into the probability of the PIF being in a state that will 'degrade' human performance and is used to update the node's marginal probability in the BBN. The CFMs' probabilities are then calculated through the BBNs and used in the critical tasks failures' FTs. The Critical Task failure probability then propagates to the ESDs, resulting in cutsets' probabilities and the HEP. For dependency assessment, the sources of dependency among common PIFs, and the CFMs probabilities are re-calculated through the Bayesian updating process (section 2.1).

3. DEPENDENCY ASSESSMENT IN SPAR-H AND PHOENIX

Dependency between HFEs or crew tasks may exist due to common factors, such as actions performed by the same crew, use of the same procedures, or safety culture. In addition to the different methods for quantifying the impact of dependency in the HEP (multiplicative method or Bayesian updating), SPAR-H and Phoenix's different approaches to dependency also arise from their distinct elements, including the PIFs and a causal model. Section 3.1 presents an overview of these differences, followed by the methods' approaches to dependency in Section 3.2.

3.1. Methods Elements and PIFs

Phoenix and SPAR-H model and quantify human error through different elements, as shown in Figure 1. Phoenix causal model, using FTs and BBNs, introduce the mid-layer containing CFMs. As such , the PIFs' impact on the HEP is not direct, such as in SPRA-H, but indirect, through the BBNs and FTs layers.

SPAR-H contains 8 PIFs (Table 1), and models the impact of these PIFs at different levels. Stress/Stressors, for instance, can be assessed as Extreme, High, Nominal, or Sufficient Information. Each level corresponds to a multiplier that will modify the nominal HEP, which is different for action or diagnosis tasks.

Table 1: SPAR-H PIFs [15]

PIF	Description
Available Time	Refers to the amount of time available relative to the time required to complete the task.
Stress / Stressors	Refers to the level of undesirable conditions and circumstances that impede the operator from completing a task. Stress can include mental stress, excessive workload, or physical stress such as that imposed by environmental factors.
Complexity	Refers to how difficult the task is to perform in the given context; it considers both the task and the environment. Complexity also considers the mental effort required and refers to the physical efforts required.
Experience / Training	Refers to the experience and training of the operator(s) involved in the task. Included in this consideration are years of experience of the individual or crew, and whether or not the operator/crew has been trained on the type of accident, the amount of time passed since training, the frequency of training, and the systems involved in the task and scenario

Procedures	Refers to the existence and use of formal operating procedures for the tasks under consideration.
Ergonomics / HMI	Refers to the equipment, displays and controls, layout, quality, and quantity of information available from instrumentation, and the interaction of the operator/crew with the equipment to carry out tasks. Aspects of the human-machine interface (HMI) are included in this category.
Fitness for duty	Refers to whether or not the individual is physically and mentally suited to the task at hand.
Work Processes	Refers to aspects of doing work, including inter-organizational, safety culture, work planning, communication, and management support and policies.

Phoenix PIFs are organized on a hierarchical structure containing three levels (Table 2). Level 1 PIFs directly impact the CFMs, while Level 2 PIFs impact Level 1 PIFs, and Level 3 PIFs impact Level 2. Phoenix has 8 Level 1 PIFs. The CFMs possess a probability for when all the PIFs are in a nominal state, which are the leak factors in the Noisy-OR Leak BBN [16]. This probability would be equivalent to the nominal HEP of SPAR-H, but at a CFM level rather than a task level. The impact of the PIFs is then estimated by considering both their marginal probability, which corresponds to the state in which the PIFs are, and their conditional probability, which corresponds to the “strength” of the impact of that PIF on the CFM.

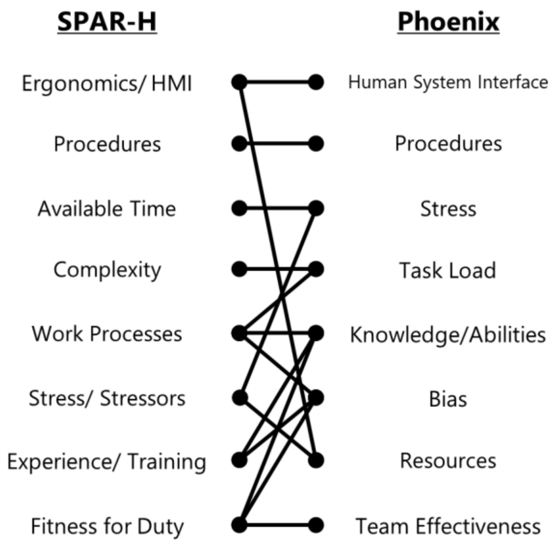
Correspondences between Phoenix and SPAR-H’s PIFs can be found, as illustrated in Figure 2. Indeed, Phoenix development, including establishing its PIF set, leveraged SPAR-H and other HRA methods.

Table 2: Phoenix PIFs

Level 1 PIF	**Description and Level 2 and 3 PIFs**
HSI	Refers to the ways and means of interaction between the crew and the system. *Level 2: HSI input, HSI output*
Procedures	Refer to the availability and quality of the explicit step-by-step instructions needed by the crew to perform a task. *Level 2: Procedure Quality, procedure Availability*
Resources	Refers to the availability and adequacy of the required resources necessary to aid the crew in completing their assigned task. *Level 2: Tools. Level 3: Tool Availability, Tool Quality* *Level 2: Workplace Adequacy*
Team Effectiveness	Refers to the experience and training of the operator refers to the degree of harmonization and synchronization of crew members' contribution to the team's overall goals and tasks. *Level 2: Communication Level 3: Communication quality, Communication Availability* *Level 2: Team Coordination. Level 3: Leadership, Team Cohesion, Responsibility Awareness, Team Composition, Team Training*
Knowledges/ Abilities	Refers to the adequacy of knowledge and abilities of the crew. *Level 2: Knowledge / Experience / Skill (content) . level 3: Task Training* *Level 2: Knowledge / Experience / Skill (access). Level 3: Attention* *Level 2: Physical Abilities and Readiness*

Bias	Refers to the crew's tendency to make decisions or reach conclusions based on selected pieces of information while excluding information that doesn't agree with the decision or conclusion. *Level 2: Morale/ Motivation/ Attitude, Safety Culture, Confidence in Information, Familiarity with of Recency of Situation, Competing or Conflicting Goals*
Stress	Refers to the tension/pressure induced on the crew by their perception of the situation, including the perception of available time, or by the awareness of the consequences and responsibility that comes along with their decisions. *Level 2: Stress due to Situation Perception, Level 3: Perceived Situation Urgency, Perceived Situation Severity* *Level 2: Stress due to Decision*
Task Load	Refers to the load induced on the crew by the actual demands of the assigned task in terms of the complexity of the task, quantity, importance, accuracy requirements per unit of time. *Level 2: Cognitive Complexity. Level 3: Inherent Cognitive Complexity, Cognitive Complexity due to External Factors* *Level 2: Execution Complexity. Level 3: Inherent Execution Complexity, Execution Complexity due to External Factors* *Level 2: Extra Work Load, Passive Information Load*

Figure 2: Correspondence between SPAR-H and Phoenix PIFs



3.2. Dependency Treatment and Dependency Value Estimation Methods

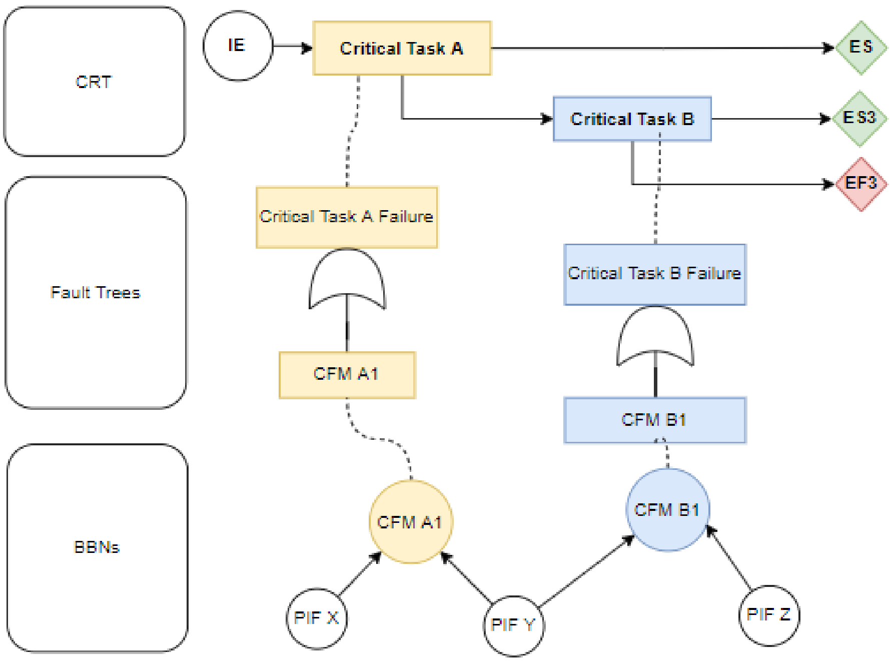
Dependency between HFEs may occur due to different factors. A functional dependency, for instance, occurs when the existence of an event is dependent on the outcome of a previous one. When discussing dependency in HRA, the main focus is the "causal dependency", generated by commonalities between tasks.

As previously stated, the SPAR-H approach to dependency is based on THERP. SPAR-H has adapted the THERP model of dependence at the HFE level, versus the subtask level at which THERP uses it. In determining the level (i.e., degree) of dependency, SPAR-H adapts from THERP the factors of same person/crew, close/not-close in time, same/different location, and presence/absence of additional cues [17]. If two tasks are performed by the same crew, close in time, is the same location and with no additional cues, the dependency is assessed as "complete", and the probability of failure of the second task is assigned the value of 1, when considering that the crew failed in the first task. In contrast, if the tasks are performed by different crews, not close in time, at different locations and with additional cues, the tasks are assumed to be independent. The probability of failure in the second task is the same as the probability calculated without considering dependency. Depending on these factors, then, the dependency can be further assessed as high, moderate, low, or zero.

Phoenix models direct causal dependency through Bayesian updating. The marginal probabilities of the PIFs, i.e., their state, represent the analyst's knowledge about the PIF. Once it is known that the PIF has impacted the previous crew's failure, the analyst's knowledge about the state of the PIF increases [17].

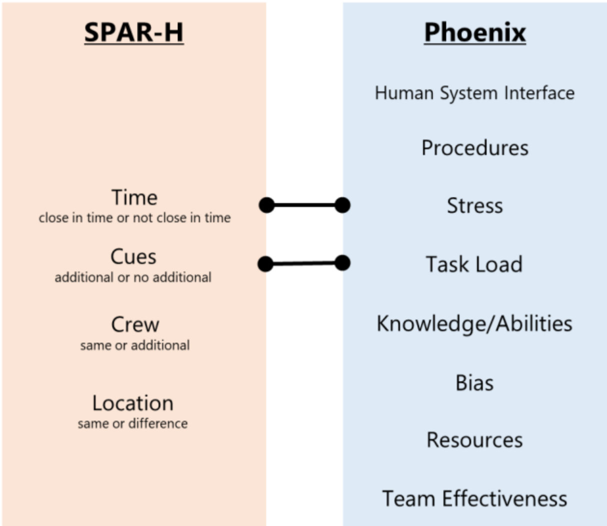
Consider, for instance, a CRT with two Critical Tasks, A and B (Figure 3). For simplicity, assume that each task is associated with one CFM only, i.e., their FTs have only one basic event each.The CFMs are further analyzed with the BBNs: consider that PIFs X and Y impact CFM A1, and CFM B1 is impacted by CFMs Y and Z. A dependency is created due to PIF Y, which may be any of the PIFs presented in Table 2. The HEP calculation will be performed in two-time steps. At the first time- step, the probability of CFM A1 is calculated, considering PIFs X and Y. In the second time step, the likelihood of the CFM B1 is calculated considering the complete BBN. An evidence of “degraded” is added to CFM A1, indicating that the crew has failed in the Critical Task A. The evidence back-propagates to the parent nodes (PIFs), including PIF Y, which, in its turn, modifies the probability of the CFM B1. In short, the likelihood of CFM B1 is calculated P(CFM B1| CFM A1=1). This calculation is automatically performed by Phoenix Web-App. Note that having a common PIF *type* is not sufficient for assuming dependence. For instance, if two tasks are dependent on procedures but not *the same* procedure, they are not dependent.

Figure 3: Direct causal dependency



The framework for calculating the HEP with dependency on SPAR-H or Phoenix is similar: 1) determine the dependency factors, 2) assess the dependency impact (through the dependency table ; clacification system of dependency condition considering the relationship within two tasks, or through the BBN), and 3) quantify the HEP. Both SPAR-H and Phoenix have a traceable method for assessing dependency, in which the analyst needs to identify commonalities between tasks or HFE. Yet, the quantification of the HEP with dependency in Phoenix using Bayesian updating allows tracing precisely the reason for the HEP modification when the dependency is considered. In contrast, SPAR-H uses a formula, published in THERP method, that could benefit from further investigation.The coefficience of that foemula changes depending on five dependency level. For instance, the probability of 1 in case of complete dependency implies that the crew could not use any other resources to not fail in the second task in a sequence. Furthermore, Phoenix assesses dependency through the direct use of its PIFs, while the factors considered by SPAR-H indirectly correspond to its PIFs (e.g., when the analyst states that the same crew performs the tasks, they are indirectly using the PIFs Fitness for Duty and Experience/ Training) , which leads to the deference in PIF considered elements for dependency analysis (Figure 4) Time and Cues in SPAR-H can convert into Phoenix Stress PIF and Task Load PIF, in respectively, yet other PIFs difficult to replace for each methods.

Figure 2: Factors considered for assessing dependency by SPAR-H and Phoenix



4. CONCLUSION

The issue of dependency and its impact on the HEP is still a subject of research within the HRA and PRA communities. While many methods use the THERP-inspired dependency table, recent methods propose other modeling approaches, such as BBNs. A benchmark exercise for comparison between different approaches should consider not only the different methods for modeling and quantifying dependency, but also differences between other elements of the methods.

Phoenix possesses many differences compared to SPAR-H, among which:

1) a causal model (CFMs rooted in the IDA model); Phoenix can estimate an errors combinated information gathering, decision−making and situation assessment, or action taking, while SPAR-H assess action HEP and decision HEP separately
2) the PIFs modeled; Phoenix PIFs consists of three layers which leads to CFMs probabilities, while SPAR-H PIFs are modeled in one layer,
3) the quantitative framework (ESD, FTs and BBNs against the multiplicative method); Phoenix modified CFM probabilities considering PIFs states using BBN updating, and links all related HFEs by ESD and FTs.

These differences may contribute to possibly different HEPs that may be obtained when using the two methods for quantifying a HEP with dependency between HFEs. However, it is possible to “translate” elements of one method to the other (e.g., the PIFs) for a solid comparison study. This study is the first step of a larger initiative aiming to compare Phoenix and other methods, including its qualitative framework and guidance, quantitative methodology, and the assessment of dependency.

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