A Model-Based Human Reliability Analysis Methodology

Ali Mosleh[a] , Song-Hua Shen[d], , Dana L. Kelly[c], Johanna H. Oxstrand[c], Katrina M. Groth[d]
[a]University of Maryland, College Park, MD, USA
[b]Sandia National Laboratories, Albuquerque, NM, USA
[c]Idaho National Laboratory, Idaho Falls, ID, USA
[d]US Nuclear Regulatory Commission, Washington, DC, USA

Abstract: This paper provides an overview of a comprehensive framework, corresponding set of techniques, and guidelines for performing HRA analysis in various nuclear power plant risk-informed applications such as full-power PRA and event assessment. The work on the methodology has been supported through a number of projects and grants sponsored by the US NRC. The qualitative analysis part of the approach introduces the "crew response tree" (CRT), providing a structure for capturing the context associated with the human failure events (HFE), including EOO and EOC. It also uses a team-centered version of the IDA model and "macro cognitive" abstractions of crew behavior, as well as other relevant findings from cognitive psychology and operating experience, in order to identify potential causes of failures and influencing factors during procedure-driven and knowledge-supported crew-plant interactions. The result of the analysis is a set of identified HFEs and the likely scenarios leading to each. The quantification methodology uses a conditional probability expression, associating the conditional probability of an HFE with probabilities of the contexts as given by PRA scenario, human failure mechanisms, and the underlying "performance influencing factors". Such mathematical formulation can be used to directly estimate HEPs using various information sources (e.g., expert estimations, anchor values, simulator or historical data), or can be modified to interface with existing quantification approaches. In addition a fully integrated BBN based quantification option is presented for more explicit accounting of causal dependencies of crew response (such as dependence between HFEs). The development envisions software-supported quantitative analysis, to build and analyse CRTs, identify Crew Failure Modes (CFMs), develop the human failure scenarios, and to support a number of quantification options, including the BBN based approach. Two other papers in this conference provide the details of the qualitative analysis approach and an example.

Keywords: Human Reliability Analysis (HRA), Crew Response Tree, crew failure modes, human error probability (HEP),

1. INTRODUCTION

Conceptual framework of the methodology was laid out in a paper at PSAM 10 conference (Mosleh et al, [1]). In this paper and the two companion papers [2] and [3], we provide an updated and more detailed methodology reflecting the work since PSAM 10. The methodology leverages lessons learned from empirical studies, embodies strong elements of current HRA good practices, and takes advantage of advances introduced through the second generation HRA methods, as well as emerging model-based approaches. The method formally incorporates relevant psychological and cognitive theories in its core human performance model on which the qualitative analysis tools and procedures are built. The overall structure of the approach is designed to support HRA in full-power internal events PRAs, low-power shutdown (LPSD) operations, event assessment and significance determination (SDP), as well as fire and seismic PRAs. What changes from one application domain to another are specific details of the analysis modules and techniques of the approach, and emphasis placed on aspects that are more relevant to the application at hand.

In this paper we highlight the core ingredients of the proposed model-based approach. The companion papers [2] and [3], provide more detailed sets of steps and examples on some key aspects of the methodology. Oxstrand et al. [2] have elaborated on the qualitative part of the methodology, providing models and guidance to support the analysts as they gather and organize the information needed for the follow-on quantitative portion of the HRA. Groth et al [3] further

advance the approach, particularly on how to integrate the various qualitative steps in preparation for quantification, and also demonstrate one quantification options (using Bayesian Belief Network, BBN) with the aid on an example. The example is based on a typical Steam Generator Tube Rupture (SGTR) scenario from nuclear plant probabilistic risk assessments (PRA). Section 2 of this paper provides an overview of the major steps of the proposed approach. Section 3 described the elements of the qualitative analysis methodology and refers to paper [2] for more details on some key features. Section 4 covers the quantification framework and refers to paper [3] for an example.

2. METHODOLOGY OVERVIEW

The approach has two tightly coupled phases of analysis (1) Qualitative Analysis, and (2) Quantification. The backbone of the method is a three-layer methodology. The Crew Response Trees (CRT) forms the top layer of the methodology. The CRT is a crew-centric visual representation of the crew-plant interaction scenarios starting with the PRA initiating event and resulting in possible forms of Human Failure Events (HFE). Some branch points in the CRT are linked to their own instances of Crew Failure Modes (CFT) identified by applying a crew failure logic model in form of a set of fault trees (FT). These fault trees are based on the "embedded IDA architecture" of the IDAC Cognitive Model [4], enhanced through a comprehensive review of the psychological literature. The IDAC modeling framework and additional literature review provided the basis for the third layer of the methodology. This layer uses a particular from of influence diagrams known as Bayesian Belief Network (BBN) to model the context-specific effects of performance influencing factors (PIFs) on CFMs and consequently on HFEs identified in the CRT. The quantification process rides on this 3-layer model, by first assigning values to PIFs consistent with the qualitative information gathered in the process, and then generating estimates of the Human Error Probabilities (HEP) for the HFEs.

The analysis includes several key steps:

Qualitative Analysis Steps

1. **Construction of the CRT.** Oxstrand et al. [2] describe the methodology for constructing the CRT, which among other things provides a vehicle for task decomposition.
2. **Linking causal factors to the CRT branch points using fault trees.** Hendrickson et al [5] provides the basis for the FTs, which have been updated and included in [2]. The basic events in these FTs are called Crew Failure Modes (CFMs), defined in Section 3.2 of this paper.
3. **Linking PIFs to Crew Failure Modes.** A set of PIFs relevant to each CFM has been identified based on review of cognitive literature. A modeling approach for linking PIFs to CFMs using a Bayesian Belief Network (BBN) framework is presented in this paper. An example is given in [3]

Quantitative Analysis Steps

1. **Quantifying the bottom layer of the linked model (PIFs).** Groth and Mosleh [6] provide a quantified BBN built from HRA data. An example has been provided in [3] where the BBN from [6] has been modified to include links to the CFMs of an example HFE scenario.
2. **Solving the linked models to obtain CRT scenario cut-sets and quantify HEPs.** Ref [3] uses the Hybrid Causal Logic methodology [7] to solve the CRT /FT/BBN combination model and calculate HEPs of an example scenario.

In all steps, qualitative and quantitative screening of unlikely scenarios and contributing factors, and use of merge rules common in PRA, help limit the size of the models and the number of scenarios that need to be analyzed.

3. QUALITATIVE ANALYSIS APPROACH

The proposed approach uses two modeling vehicles: (1) A process and representational method for analyzing crew-plant interactions, focusing on identifying and quantifying HFEs and possible recoveries, and (2) A model of human response relating the observable crew failures modes (CFM), to "context factors". These are explained in this section.

3.1 Crew Response Tree (CRT)

The first modelling tool is a forward-branching tree of operator (crew) cognitive activities and actions (Crew Response Tree, CRT). We note that PRAs use event trees (ET) that define logical (and often temporal) sequences of binary events starting from an initiating event and resulting in plant End States (ES). Major functional responses of the plant and key operator actions constitute the various elements (top events) of the ETs. The sequences of ETs are typically the high level PRA scenarios (S). The details of how the plant functions fail as a result of failure of components or human actions are typically included in fault trees (FT) attached to various ET top events. The combinations of the events in these FTs, which are logically linked according to the ET scenarios, form the more detailed picture of the PRA scenarios (scenario cut sets). Such sets are defined in this paper as the PRA scenario context (S).

The CRT is a crew-centric visual representation of the crew-plant scenarios. CRT is also a roadmap and blueprint that supports performing and documenting HRA qualitative analysis. The branch points (BP) of the CRT can include (1) operator action options, (2) operator decision options, (3) crew member interactions (if the unit of analysis is each individual operator rather than the entire crew), and (4) relevant plant/system functional states that play a role in defining the context of the operator response. Time can be made an explicit parameter of the CRT sequence evolution by adding CRT branch points to differentiate between different operator or plant response times.

For many of the applications of the proposed methodology, it is assumed that the customary steps of building a PRA model starting with development of ETs for various initiating events have been taken (the ETs can be modified if in the process of constructing CRTs new HFEs are identified. In some PRAs the process starts with developing a set of event sequence diagrams (ESD) based on which ETs are developed. Either of the two diagrams can be used to help make CRT development consistent with the PRA scenarios being considered.

The conceptual relation between CRT and typical PRA events tree is shown in Figure 1. The top tree (above the time arrow) is the plant event tree for an initiating event with system failures and HFEs. The CRT (the tree below the time arrow) is a supporting tree, providing a causal explanation of the HFEs. Symbolically these links are shown as dashed lines in Figure 1. The link is for "bookkeeping" purposes to help analysts keep track of the relation between the CRT scenarios and event tree scenarios; no formal logical or mathematical link is proposed. Both the ET and corresponding CRT start at the initiating event (for full power applications). The role of the CRT is to ensure a systematic coverage of crew-plant interactions consistent with the scope of the analysis.

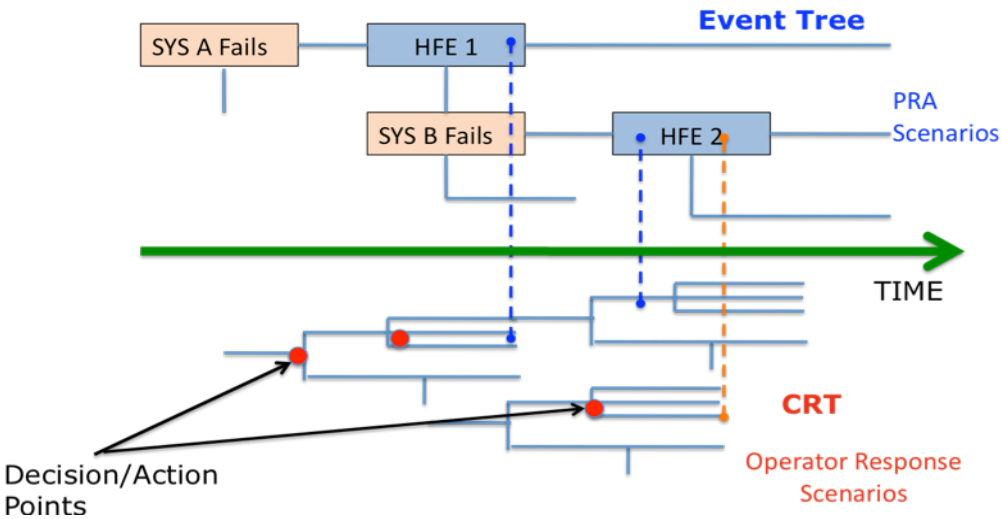

Figure 1 Plant and Crew Interaction Modeling Through CRTs

An interdisciplinary team of PRA analysts develops CRT, as it requires knowledge of plant behavior and human response. We note that event trees in principle play a similar role in PRA, although the level of resolution is normally inadequate for HRA analysis. CRT is an analysis aid but is also envisioned as an HRA work product, a means of documenting and reporting the qualitative analysis.

Referring to Figure 1, the "context" of an HFE to be captured by the qualitative analysis through CRT and other layers of the methodology includes:

- The portion of the specific PRA event tree scenario(s) that leads to the HFE of interest
- The corresponding time from the start of the scenario
- The portion of the specific CRT scenario that leads to the HFE of interest
- All other relevant plant and crew "factors" not shown in ET and CRT, including:
    - Relevant plant physical parameter displays, alarms, and indicators
    - System and component functional states
    - External conditions such as harsh environment
    - Other human and organizational performance-influencing/shaping factors

In developing the CRT and using it to describe the various scenarios leading to each HFE, all context factors are considered, and most will have an explicit representation in the CRT or supporting information and sub-modes (see Section 4).

CRT can be devoted to find paths to predefined HFEs and possible recoveries, or used as a vehicle to also identify new HFEs. The process can cover both Errors of Omission and Errors of Commission. CRTs can be constructed for crew response situations that are procedure-driven (PD), knowledge-driven (KD), or a hybrid of both (HD). Ref [2] provides a procedure and generic flowchart for developing CRT. The methodology covers a case where HFE is associated with a specific safety function in in the context of a defined PRA scenario. As a practical approach to building larger, more comprehensive, CRTs such "function-level" CRT modules can be assembled through simple merge rules (Figure 2).

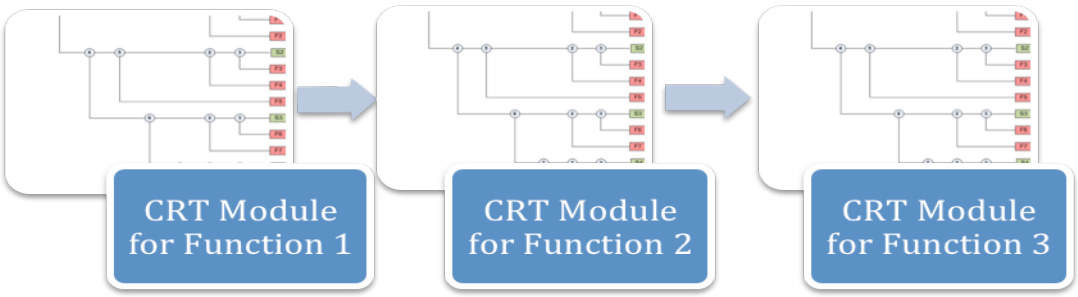

Figure 2 Modular Construction of large CRTs by Linking Function Level Sub-CRTs

3.2 CREW PERFORMANCE MODEL

CRT sequences and branches capture some (but not all) of the context factors and causes of operator responses. To simplify the analysis and modeling process the branches of CRT are defined mainly at the functional level and do not cover the "human failure mechanisms" or their causes. This aspect is delegated to a set of supporting models of crew behavior in the form of causal trees. The overarching human cognitive response model adopted for this purpose is essentially a human information processing model. An implementation of this modeling concept is the IDAC [4] approach, which has provided a basis for developing the proposed framework. According to IDAC, given incoming information, the crew model generates a response, linking the context to the action through explicit causal models. Failure mechanisms are linked to the possible human failures identified within the CRTs on the basis of the IDAC cognitive model. The stages of the IDAC cognitive model are:

- *Information.* This stage focuses on the operator's perception of the environment and the cues presented to him/her. Cognitive processing of the information is limited to the task of perceiving the information, but limited processing of the information is done at this stage.
- *Diagnosis/Decision.* This stage is internal to the operator. At this phase, the operator uses whatever information was perceived in the previous stage, along with stored memories, knowledge, and experience, to develop a mental model of the situation. Following this situational assessment, the operator engages in decision-making strategies to plan the appropriate course of action.
- *Action.* In this final stage, the operator puts the chosen course of action into play.

These stages of the IDA model cover similar subdivisions of information processing such as Detecting/Noticing, Sense-making/Understanding, Decision Making, Coordination /Communication, and Action. Within each of the IDA elements, a nested I-D-A structure may exist [4]; that is, each phase of the IDA model may be decomposed into further I-D-A structures as needed during task analysis and parsing of different human activities into 'sub-events" or sub-tasks. For instance, I-in-I explains the information being perceived and recognized, D-in-I involves deciding what to do with the perceived information (e.g., discard it or keep it), and A-in-I involves any actions stemming from this decision. For the application described within this paper, only the nested structure for the primary I phase is used. Error is defined in terms of the operator failing to meet a plant need. The focus is on the functional impact of operator actions, which may be identical to HFEs defined in PRA, or it could be one of the corresponding causes.

Using the information-processing model, HFEs (errors defined based on mismatch between the operator's action and a plant need) can be traced through the I-D-A chain. An error could therefore be rooted in (1) action execution failure (A) given correct decision; (2) failure in situation assessment, problem solving and decision making, given correct information (D); or (3) failure in the information-gathering stage. In this view, failures in I, D, or A are "minimal cut-sets" of the human failure events. A fault three representation of this logic is shown in Figure 3.

A preliminary set of CFMs is proposed to further specify the possible forms of failures in each of the IDA phases (Table 2). CFMs are generic functional modes of crew failure in its interactions with the plant. They can be mapped to psychological and physiological causes and

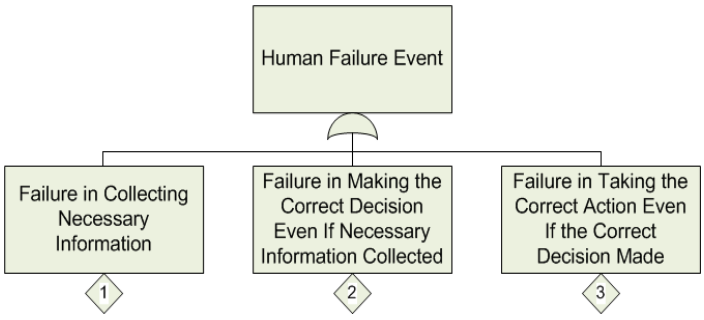

Figure 3. "Logic of HFE" in Terms of IDA Stages

their contextual factors or reasons. CFMs cover different modalities in operator response including procedure driven, (PD), knowledge driven (KD), or a hybrid of both (HD).

Table 1 CFMs for Various Phase of Crew Response

Crew Failure Mode in I Stage	Crew Failure Mode in D Stage	Crew Failure Mode in A Stage

• Data Not Obtained (International)
• Data Collected but Dismissed
• Key Alarm Not Responded To
  • Intentional
  • Unintentional
• Data Incorrectly Processed
• Decision to Stop Gathering Data
• Data Incorrectly Processed
  • Wrong Indicator Used
  • Procedure Reading Error
  • Indicator Reading Error
	• Skip Procedure Step (Intentional)
	• Postpone Procedure Step
	• Deviate from Procedure (e.g. Transfer to Another Procedure)
	• Plant/System State Misdiagnosed
	• Decide to Wait for More Information
	• Decide to Delay Action
	• Decide to Take Alternate Action
		• Unintentional Delay
		• Incorrect Operation of Component or System
		• Select Wrong Component or System
		• Skip Action on One or More Components

In the PD mode, CFMs are tailored to the various sub-tasks that can be identified for procedure-driven crew interactions in nuclear power plants.

All CFMs are potentially relevant to each CRT branch point and therefore to each HFE. However, when analyzed in the context of a scenario, and depending on the I-D-A phase, only a subset of CFMs may apply. For example, if there is no reliance on an alarm, then the CFM related to alarms will not apply. For this reason, a set of fault trees has been introduced to help analysts select the relevant CFMs for each branch point within each scenario. These fault trees are presented in [2].

A "linked trees" approach (similar to FT-ET linking) can help identify CRT scenario "causal cut-sets." This will result in a more explicit identification of sources of HFE dependencies. Qualification models can also use such "causal cut-sets" as their starting point in quantifying the HFE probabilities. As an example,

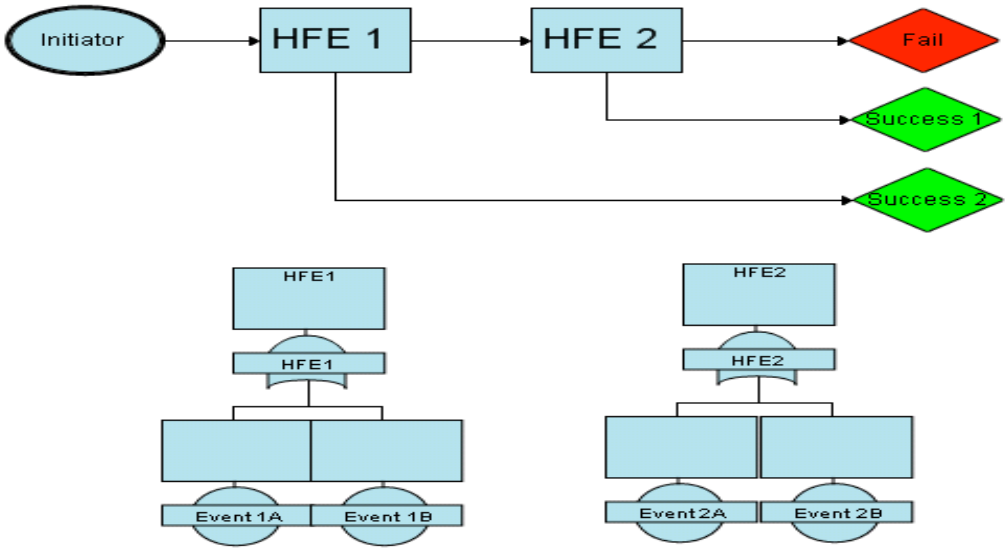

Figure 4. A Simple CRT Involving Two HFEs and Corresponding CFM Fault Trees

consider the simple CRT shown in Figure 4 which includes two HFEs both needed to cause a failed state of the plant. We have included two HFEs to facilitate the discussion of treatment of dependencies later in the paper. The branch points of this simple CRT include HFEs as an outcome.

Let us assume that the qualitative analysis at each branch point has produced FTs in terms of applicable CFMs. Events 1A and 1B are possible CFMs for HFE1, while 2A and 2B are CFMs for HFE2. The failure scenario cut sets in terms of these CFMs, obtained by linking the HFE FTs, are: {1A, 2A}, {1A, 2B}, {1B, 2A}, and {1B, 2B}. Therefore the failure scenario has 4 different versions: S_1 = IE*1A*2A; S_2=IE*1A*2B; S_3=IE*1B*2A; and S_4=IE*1B*2B.

As the third layer of the qualitative analysis, the CFMs are linked to the set of relevant PIFs. PIFs proposed by Groth and Mosleh [6] are used for this purpose. These PIFs were developed based on an analysis of all HRA methods, IDAC model, review of psychological literature, and actual operational events. The PIFs are organized under six major categories of factors related to System, Situation, Stressors, Person, Team, and Organization.

There are various ways that the effect of additional context factors typically represented by a set of PIFs can be included in the qualitative analysis. Ample examples can be found in various HRA approaches. The following option provides significant technical advantages in realism and rigor both in the qualitative and quantitative phases of the analysis. According to the proposed method, the set of PIFs and their context-specific influences on CFMs can be modelled through the use of influence diagrams, particularly a class known as Bayesian Belief Network (BBN).

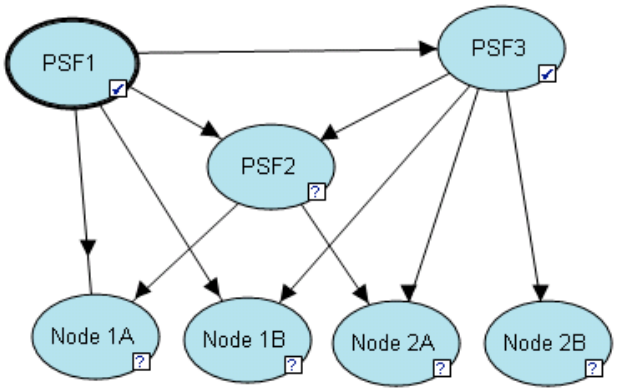

Figure 5. A Simple BBN for Modelling the Effects of PIFs on Multiple CFMs

Figure 5 is an example of this modelling option, where nodes represent the states of PIFs (or PSFs) and CFMs influenced by them. Arrows indicate the presence of some level of influence between the nodes. In BBNs the degree of influence of one node on another is measured by a conditional probability, which can vary depending on the context of the scenario and the nature of the CFMs in the scenario. The figure shows the path of influence of a set of 3 PIFs on each other and also on the various CFMs of Figure 4. According to this simple model, PIF2 influences only CFMs 1A and 2A. PIF3 directly influences CFMs 1B, 2A, and 2B. It also influences CFM 1A through PIF2. We can see that the issue of CFM-to-CFM or HFE-to-HFE dependencies can be easily addressed by adopting the BBN approach to PIF modelling. The CFM nodes on the BBN diagram and the CFM basic events in the FTs associated with branch points of the CRT are obviously the connection between the PIF model and the rest of the qualitative analysis modules. The HFE scenarios identified through CRT and CFM fault trees are now extended to include the last layer of "causal factors" i.e., the BBN of PIFs.

Clearly the use of BBN is an option among a number of alternatives such as tables (as it is done in many HRAs) or binary decisions trees (BDT) as used in the CBDT method. In other words the CRT/FT formalism does not in itself require the use of BBNs for PIF modeling. But the proposed option addresses a number of outstanding HRA issues, such as modeling various dependencies in an elegant and effective way**.**

4. QUANTIFICATION FRAMEWORK

Since an HFE is the result of one or several sequences of events or conditions (overall context) for a given plant PRA scenario (S) according to the CRT and corresponding linked causal models, the HEP can be calculated as follows:

The quantification framework consistent with a "scenario-based" approach is as follows:

$$p(HFE \mid S) = \sum_{i=1}^{I} p(\, HFE \mid FM_i) \left[\sum_{j}^{J} \mathrm{p}\,(FM_i \mid \mathrm{F}_{j1}, \mathrm{F}_{j2}, \ldots\ldots, \mathrm{F}_{jn}; \mathrm{S}) \times p(\mathrm{F}_{j1}, \mathrm{F}_{j2}, \ldots\ldots, \mathrm{F}_{jn} \mid S) \right]$$

- The summation in the brackets is the probability of i-th CFM considering all possible CRT scenarios (j = 1,2,…, J) that lead to the HFE of concern. Each scenario is characterized by a set of n factors (or different instances of a fixed super set of factors). The set $\{F_{j1}, F_{j2}, \ldots, S\}$ includes the usual PIFs and everything else in the scenario context that affect the probability of HFE.
- The term $p(FM_i \mid F_{i1}, F_{i2}, \ldots)$ is the probability of i-th CFM for a given CRT scenario, and $p(F_{i1}, F_{i2}, \ldots \mid S)$ is the probability of that scenario in the context of the PRA scenario S.
- One can define CFM's in such a way that $P(HFE \mid FM_i) = 1$ for all "i". In this case the aim of the HRA quantification model is to assess the values of $p(FM_i \mid F_{j1}, F_{j2}, \ldots)$ and $p(F_{j1}, F_{j2}, \ldots \mid S)$ for each sub-context j.

While in theory all PIFs need to be considered in estimating p (FM_i | F_{j1} ,F_{j2} , …) and p(F_{j1} ,F_{j2} , …| S) for each CRT scenario j and for each CFM_i , the crew response modelling methodology outlines in previous sections provides a basis for down-selecting those PIFs that are most relevant to each CFM. The PIF-CFM mapping provides a layer of simplification in applying the above quantification scheme.

The above formulation symbolically requires that in quantifying p(FM_i | F_{j1} ,F_{j2} , …) and p(F_{j1} ,F_{j2} , …| S) one should take into account the collective effect of the set of relevant PIFs for each CFM. A consensus is emerging that contrary to the assumption made in many popular HRA methods, PIFs are in fact interdependent. Such interdependencies should be explicitly acknowledged in quantification of p(FM_i | F_{j1} ,F_{j2} , …) and p(F_{j1} ,F_{j2} , …| S). This motivates the use of influence diagrams (BBN) to, as a minimum, capture in a qualitative way the PIF interdependencies.

The following qualitative/quantitative approach for estimating HEPs avoids oversimplification of the HRA model at the cost of realism and rigor. The use of software is proposed to significantly reduce complexity in routine applications.

Qualitative Steps (Model Integration):

- Develop qualitative map between the PIFs and CFMs in form of a set of PIF-CFM influence diagrams (BBNs) that represents the interdependencies among the PIFs and also their relation to each CFM.
- Merge the PIF-CFM influence diagrams into a single BBN that explicitly accounts for the effects of PIFs that are common to multiple CFMs.
- For most general formulation, add another layer to the combined BBN that relates the CFMs to HFEs. This is to allow for the case where, (a) multiple CFMs are needed for HFE to concur, and (b) relaxing the assumption that P(HFE | CFM_i) =1. This step may be unnecessary in some applications, but could be important in other cases, all depending on how CFMs are defined.
- Link the root PIFs of the combined BBN to the corresponding set of observable or inferable metrics. The set of observable or inferable metrics is a derivative of the qualitative analysis methodology including the underlying crew response model and the theoretical and empirical bases of the set of PIFs. This step links the qualitative analysis results with the elements of the quantification model.

In ref [3] we demonstrate the process of constructing CRTs, identification of relevant CFMs for the CRT scenarios using the proposed fault tree approach, and linking the BBN model of the relevant PIFs to CFMs. The linking of the three layers (CRT, FTs, and BNs) was made using the Hybrid Causal Logic (HCL) methodology [7], which is also used to quantify HFPs of the scenarios in the integrated model.

Quantification Steps:

In principle, the HEPs that appear at the top of the combined BBN should be quantified as a function of the diagram structure (using Bayesian inference engine) and based on context-specific values of PIFs, and generic conditional probability tables covering the relation among PIFs, between PIFs and CFMs, and between CFMs and HFEs. However, such probabilities are currently unknown and their direct assessment in a credible way is not within reach until such time that a targeted data collection effort provides the necessary statistical basis. For now, expert judgment is the only practical source for such estimates.

The approach that can be explored is to develop the BBN conditional probabilities based on "anchor values" obtained from expert assessment of a selected set of HFEs (alternatively CFMs). This can be done in a three-step process:

(1) define reference CRT scenarios to be used for expert-estimated HFEs (CFMs) as anchor values,

(2) elicit expert opinions (minimum of 5 per reference HFE/CFM),

(3) use the expert-estimated anchor values to back-calculate BBN conditional probabilities. The fully quantified BBN can then be used for quantification of HEPs for other contexts

(4) Link BBNs of multiple HFEs for calculating conditional HFE probabilities for interdependent HFEs.

Step 4 offers a cause-based explicit treatment of dependencies among HEPs. The BBN model contains the context-specific causal factors common among multiple HFEs and uses such dependencies to determine the individual conditional probabilities of the those HFEs.

7. PRACTICAL CONSIDERATIONS

Automation can remove virtually all of the computational and analytical complexities of the proposed quantification model. In fact software can be developed such that the analysis could complete the quantification in three relatively simple steps:

1. The analyst answers a series of questions via software user-interface. These questions aim to
    a. determine the credible set of specific context factors for the HFE,
    b. assess the values/states of PIFs for the context,
    c. identify the relevant CFMs (in the context of CRT scenarios)

    The specific sub-set of questions that an analyst would see in analyzing a particular HFE is determined dynamically depending on the answers to preceding questions, reducing the analysis workload. This reflects the fact that situational factors and context characteristics are interdependent.

2. Software then generates the HEP (and corresponding uncertainty distribution) based on the analyst's response to questions (BBN inference engine runs in the background).

3. For multiple HFEs in the same PRA scenario, the analyst follows step 1 for each HFE in the sequence they appear in the PRA scenario. The software then calculates the corresponding conditional HEPs.

In these steps the analyst only answers questions and is not required to see or modify the BBNs, FTs, or probabilistic operations on CRT sequences and corresponding cut sets.

7. APPLICATIONS

The proposed framework, its conceptual building block, and many of the specific techniques are designed to support HRA in full-power internal events PRAs, low-power shutdown (LPSD) PRAs, event assessment and significance determination (SDP), as well as PRAs of external events such as fire and seismic. What changes from one application domain to another are the specific details of the analysis modules and emphasis on aspects that are more relevant to the application at hand. The authors have developed examples of the application of the methodology for LPSD operations and SDP. These will be described in several upcoming technical reports and papers.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contributions of the late Dr. Dana Kelly to this work. This work was partially funded by the U.S. Nuclear Regulatory Commission (USNRC) at . Idaho National Laboratory (INL) and the University of Maryland. INL is a multi-program laboratory operated by Battelle Energy Alliance for the United States Department of Energy. This work was also supported by the Laboratory Directed Research and Development program at Sandia National Laboratories. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the US Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. This paper was prepared in part by employees of the USNRC. It presents information that does not currently represent an agreed-upon staff position. NRC has neither approved nor disapproved its technical content.

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