An Approach to Dynamic Human Reliability Analysis Using the EMRALD Dynamic Risk Assessment Tool

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Abstract: There is a need for research into dynamic human reliability analysis (HRA) (i.e., simulation- or computation-based HRA), as many researchers have emphasized the importance of applying dynamic approaches to probabilistic safety assessments (PSAs). This study proposes the Procedure-based Investigation Method of EMRALD Risk Assessment – Human Reliability Analysis (PRIMERA-HRA), a dynamic HRA approach based on the Event Modeling Risk Assessment Using Linked Diagram (EMRALD) software developed by Idaho National Laboratory (INL). This study suggests how this software can be used to model human actions and evaluate error probabilities. The applicability of this approach is also be investigated in light of an extended loss of AC power (ELAP) scenario. This paper then discusses the major insights derived by comparing this dynamic HRA approach against the static one.

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1. INTRODUCTION

There is a need for research into dynamic human reliability analysis (HRA) (i.e., simulation- or computation-based HRA), as many researchers have emphasized the importance of applying dynamic approaches to probabilistic safety assessments (PSAs). Transitioning from static to dynamic HRA may be beneficial in realistically modeling and evaluating human actions that would actually be performed in a system. In static HRA, human actions are divided into components (e.g., diagnosis and execution), then quantified by summing the error probabilities of those components. However, this approach may overlook the dynamic characteristic of actual operations, with operators continuously diagnosing situations and executing proper actions based on relevant procedures. Furthermore, static HRA involves estimating the time windows for various human actions, based on structured interviews with knowledgeable experts (e.g., operators). It may also be challenging to specifically evaluate whether they can complete these actions in light of unexpected factors critical to system safety.

To treat these challenges, this study proposes the Procedure-based Investigation Method of EMRALD Risk Assessment – Human Reliability Analysis (PRIMERA-HRA), a dynamic HRA approach based on the Event Modeling Risk Assessment Using Linked Diagram (EMRALD) [1] software developed by Idaho National Laboratory (INL). This study suggests how the software can be used to model human actions and evaluate error probabilities. The applicability of this approach is also investigated in light of an extended loss of AC power (ELAP) scenario. This paper then discusses the major insights derived by comparing this dynamic HRA approach against the static one.

2. PREVIOUS EFFORTS REGARDING DYNAMIC HRA

In previous studies [2][4], two different approaches to dynamic HRA using the EMRALD software were developed. Table 1 summarizes the characteristics of these two different EMRALD modeling approaches to dynamic HRA. Procedure-based EMRALD modeling suggests how to specifically model procedural steps that describe the actions operators or plant personnel must perform in a given situation, while PRA/HRA-based EMRALD modeling makes the most of concepts and techniques that have used in existing PRA and HRA. These approaches were validated on an example scenario (see [2][4] for details).

These two approaches feature a couple of limitations. Procedure-based EMRALD modeling does not communicate with PRA parts such as equipment failure. In actual situations, the required operator actions may vary, depending on whether certain pieces of equipment remain operational. If the approach fails to consider components in PRA fault trees, it may be highly limited for evaluating various scenarios that lead to failure. Furthermore, the method was tested using only a small subset of procedures. A method of treating lots of procedural steps that could be used in a scenario is not explicitly suggested. In addition, this modeling approach does not consider performance shaping factors (PSFs), which influence human performance and are used to highlight error contributors and adjust basic human error probabilities (HEPs). For PRA/HRA-based EMRALD modeling, understanding how to assume the timeline uncertainty for each basic event and how to specifically model certain major HRA concepts (e.g., recovery opportunities) were pointed out as primary issues in a previous study.

Table 1: Characteristics of two different EMRALD modeling approaches to dynamic HRA [3]

	Procedure-based EMRALD Modeling	**PRA/HRA-based EMRALD Modeling**
Description	Specifically models procedural contexts	Models basic events and human failure events (HFEs) already considered in PRA and HRA
Characteristics	Useful in accounting for context uncertainties that complicate HEP determinations	Within PRA/HRA modeling, it could be used to validate timeline uncertainties not covered in existing PRA/HRA

3. THE PRIMERA-HRA METHOD

To complement the challenges posed by each approach, we suggest a more structured and systemic method of analyzing human actions in HRA and providing HEPs to existing PRA models. Our research team has developed the PRIMERA-HRA method, which combines the two EMRALD modeling approaches explored in the previous section. In existing HRA, human actions are modeled as backups against system, component, or equipment failures, but this method uses them as support for various scenarios and procedure paths, depending on the initiating event.

Figure 1 shows a conceptual design of the PRIMERA-HRA method, which models both equipment failure and procedural contexts representing human actions. In the figure, the heading events (i.e., Heading #0, #1, and #2) reflect initiating events, existing PRA headings modeled in event trees, or any event that contributes to the delay of a scenario. The procedure paths are combinations of procedural contexts that arise between different heading events or between a heading event and an end state (i.e., OK or Core Damage [CD]). The procedure paths all lead to different scenarios, mitigation strategies, and plant states, depending on the heading event involved. For example, if diesel generator availability is a heading event that follows the initiating event, success of this heading event may lead to an ELAP scenario, while failure of the event may lead to a station blackout scenario. Operators will apply a different set of procedures to each scenario. If the mitigation strategy is successful, the end state will be "OK." If not, the plant state will be "CD."

Figure 2 summarizes the PRIMERA-HRA method, which consists of four steps: (1) procedure-based task analysis, (2) task-unit analysis for procedures applied to a given scenario, (3) development of a procedure-based EMRALD model, and (4) model analysis and integration into the PRA model.

Regarding the first step, task analysis is the process of collecting and analyzing task-related information necessary for performing HRA [5]. In this step, we collect the input data required for modeling procedures and implementing the PRIMERA-HRA method. These data include PRA models, information (e.g., PSF data) related to HFEs, and relevant procedures. Then we develop an event sequence diagram such as that seen in Figure 1, and identify its actual timeline.

In the second step, procedure paths in the event sequence diagram are decomposed in the task-unit level. Basically, each procedure path consists of a couple of procedures, which in turn include many procedure steps. Each procedure step is also composed of a couple of task-units. The task unit refers to the procedure task type, as defined by the Human Reliability Data Extraction (HuREX) [6] framework and the GOMS-HRA method [7]. Time and HEP information are assigned per each task unit. In GOMS-HRA, the time information is assumed to follow a statistical time distribution with mean value, standard deviation, and 5th and 95th percentile values, depending on the particular task unit involved. The time data were collected through experiments involving actual operators at the Human Systems Simulation Laboratory [8][9] (i.e., INL's full-scope simulator), designed to conduct critical safety-focused human factors R&D. For the HEP calculation, it is credited only to task units critical to a failure of HFE. Depending on the general approach that has suggested in existing HRAs, HEPs are calculated based on the relationship between a basic HEP and the PSF multiplier values [5]. In this study, the basic HEPs for task units are derived from the HuREX database. Also employed are PSFs suggested via the Standardized Plant Analysis Risk-HRA (SPAR-H) [10] method.

In the third step, a procedure-based EMRALD model is developed. This model includes all the information obtained from the previous steps, and is used for evaluating HEPs and time information for HFEs. For the HEP evaluation, only those task units relevant to critical human actions are used, while the time evaluation is performed for all task units modeled in a given scenario.

In the final step, HFE failure paths, HEPs, and overtime failures for HFEs are evaluated. Those HFE failure paths that are based on cut sets generated from simulation logs explain why a given scenario is considered failed. These can be used to correct modeling errors in EMRALD. The HEPs generated are provided to support HEPs for the HFEs considered in static PRA models. Evaluation of overtime failures for HFEs only addresses whether the HFEs are completed within their allotted time windows. If not, this is considered a guaranteed failure (i.e., HEP = 1.0).

Figure 1. Conceptual design of the PRIMERA-HRA method

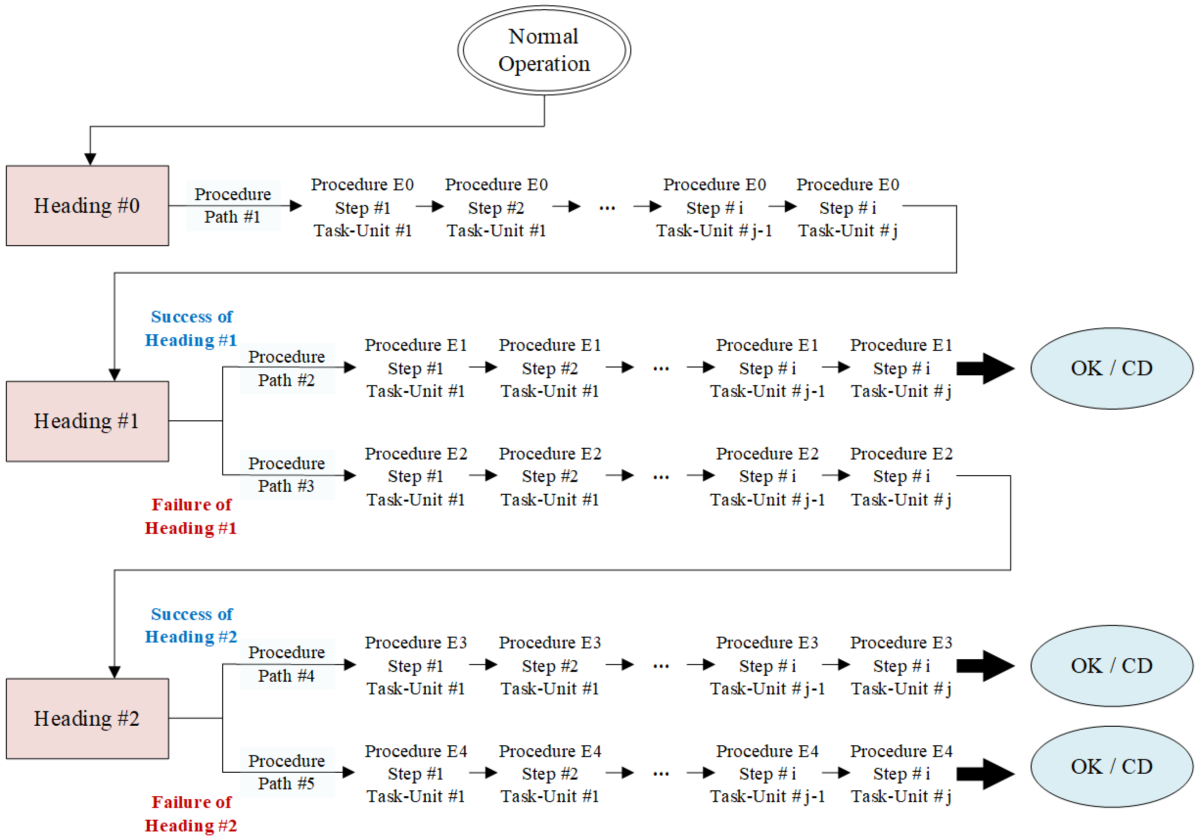
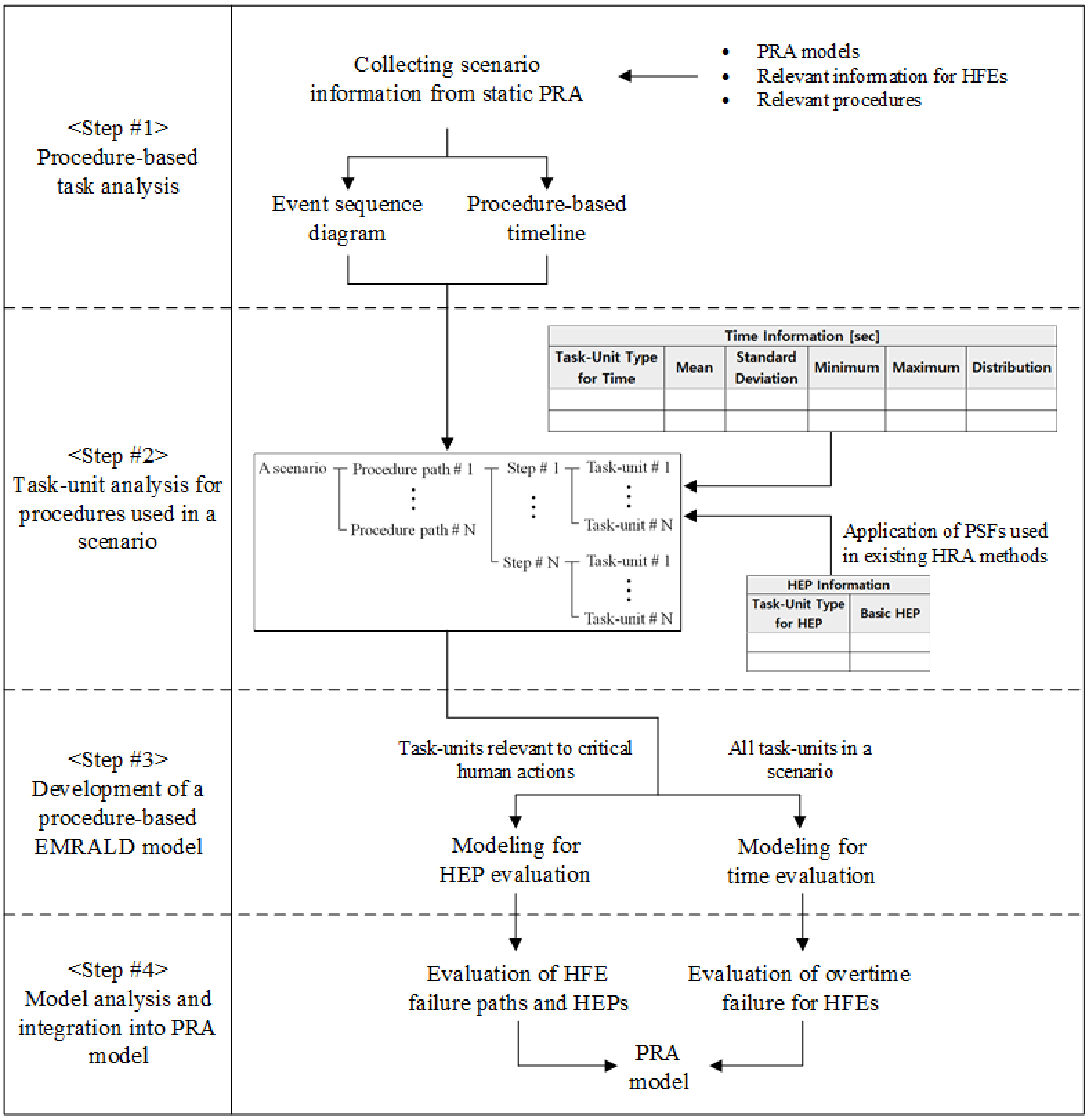


Figure 2. PRIMERA-HRA method



3. APPLYING THE PRIMERA-HRA METHOD TO AN ELAP SCENARIO

This study applied the PRIMERA-HRA method to an ELAP scenario. ELAP is a station blackout scenario in which offsite power, emergency diesel generators (DGs), and alternate AC DGs are all unavailable [11]. In this scenario, FLEX DGs are used to provide AC power in addition to aiding in the reactor cooldown. In this study, we specifically developed an ELAP scenario in which FLEX DGs were deployed and connected to the plant. This scenario was developed based on observations made during stress tests [12]. The scenario assumes that once the initiating event occurs, the main control room (MCR) panel indicators suddenly become unavailable due to a blackout. The operators are assumed to experience a high degree of disorientation and stress, and are not equipped with any flashlights. The battery power connection is delayed for 15 minutes. In other words, the battery power associated with the MCR indicators and emergency light functionality is automatically restored after 15 minutes. Also, operators find flashlights at a location outside the MCR and bring them inside the MCR. Once some of the indicators have been restored and the flashlights are available, the MCR operators can begin to perform procedures. First, they diagnose the initiating event. Following procedure, they evaluate whether the AC power sources will be difficult to restore. The outcome of this evaluation may be to declare an ELAP scenario, at which point two operator actions must then be performed almost simultaneously. First, the MCR operators must perform DC load shedding in collaboration with the local operators. Under this scenario, although the local operators are required to complete all their tasks onsite, they overlook a couple of manipulations. They notice the fault after coming back and communicating with the MCR operators, then leave to finalize the manipulations. Next, the MCR operators communicate with subcontractors to deploy the FLEX DGs. At this point, the subcontractor personnel move to the mobile equipment garage and deploy all relevant equipment to the designated place to connect them with the plant. During deployment under this scenario, some debris is in the way, and removing it is assumed to take 2 hours and 20 minutes. After that, the subcontractor personnel continue to deploy the equipment and connect the FLEX DGs to the plant. The scenario concludes when both operator actions are successfully carried out within the time window and are successfully reported to the MCR operators.

For the initial step of the PRIMERA-HRA method, this study performed a procedure-based task analysis, based on the scenario outlined above. Figure 3 and Figure **4** show an event sequence diagram and procedure-based timeline for the ELAP scenario. These figures simplify and summarize the stages of this ELAP scenario.

Figure 3. Event sequence diagram for an ELAP scenario

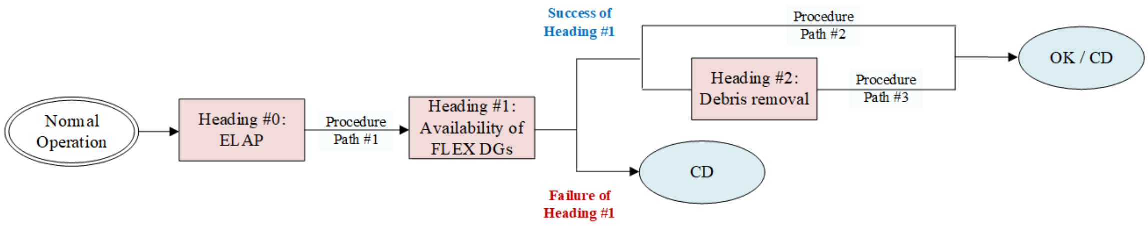
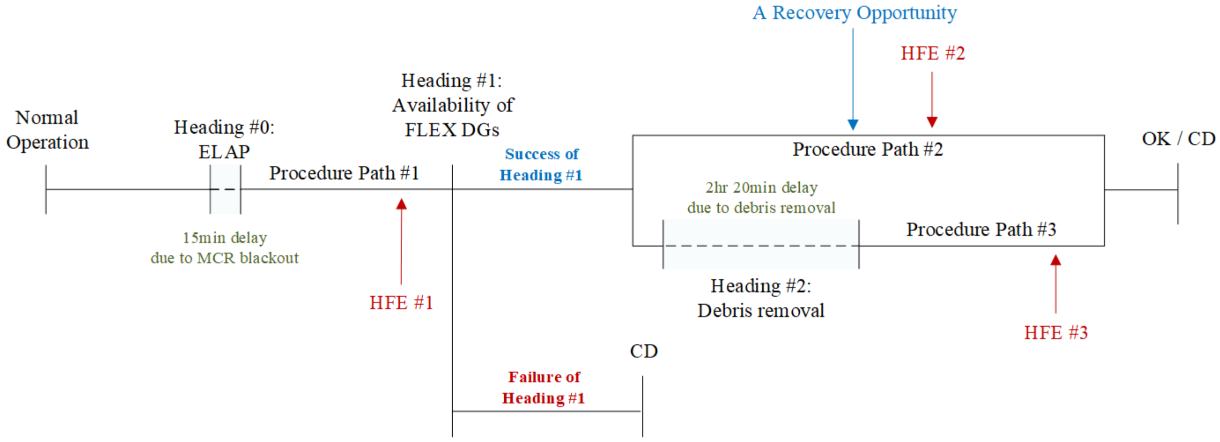


Figure 4. Procedure-based timeline for an ELAP scenario



Regarding the three heading events (i.e., Heading #0, #1, and #2), the first is the initiating event, which causes 15 minutes of delay due to the MCR blackout. The second event splits into two branches: success or failure of the FLEX DGs. FLEX DG unavailability is assumed to lead to the CD state. Failure of this heading event is determined by the static fault tree logic developed in a previous report [13]. The logic is also modeled within the EMRALD software. The third heading event causes 2 hours and 20 minutes of delay for debris removal.

In this scenario, three procedure paths (i.e., Procedure Path #1, #2, and #3) are considered. The first consists of post-trip action procedures, which extend from the occurrence of the initiating event up to the procedural step for checking FLEX DG availability. It may include emergency operating procedures (EOPs), such as “EOP-E-0” in Westinghouse-type nuclear power plants (NPPs) and the Standard Post Trip Action and Diagnosis Action procedures in Combustion-Engineering-type NPPs. The early stage of FLEX Support Guidelines is also involved in the path. The second and third procedure paths mostly consist of specific FLEX Support Guidelines on DG load shedding and FLEX DG deployment/installation.

Furthermore, the procedure paths involve three HFEs that are considered critical events in static FLEX HRA [14]. Table 2 summarizes the HFE information collected from static HRA. It includes the SPAR-H PSF evaluation results and the time window for each HFE. These are assumed based on the relevant literature [12][14].

Table 2: Summary of HFE information from static HRA

		HFE #1	HFE #2	HFE #3
Description		Operator fails to declare ELAP	Operator fails to perform FLEX DC load shedding	Operator fails to deploy and connect FLEX DGs
SPAR-H PSFs	Available time	Extra time	Extra time	Extra time
	Stress/stressor	Extreme	High	High
	Complexity	Moderately complex	Nominal	Nominal
	Experience /training	Nominal	Low	Low
	Procedures	Nominal	Nominal	Nominal
	Ergonomics /human-system interface	Nominal	Nominal	Nominal
	Fitness for duty	Nominal	Nominal	Nominal
	Work process	Nominal	Nominal	Nominal
Time window		1 hour	1.5 hours	6 hours

Using the information above, this study performed task-unit analysis—the second step of the PRIMERA-HRA method. Figure 5Figure 6 show some of the results of this analysis. In the figures, six task units (i.e., E0_S3_TU1, E0_S3_TU2, E0_S3_TU3, E0_S3_TU4, ECA_S1_TU1, and ECA_S1_TU2) are included in Procedure Path #1. The description, actor, work device, time information, and HEP information for each task unit are also summarized in the figures. As mentioned in the previous section, the time and HEP information were determined using the HuREX database [6] and GOMS-HRA method [7], respectively. The task units that start with "EO" are the procedure contents belong to EOP post-trip action procedures, while those that start with "ECA" relate to the EOP that specifically pertains to the loss of all AC power sources. In the analysis, only one task unit (i.e., "EO_S3_TU2") was identified as being critical to the failure of HFE #1.

Figure 5. Example of the task-unit analysis: time information

Procedure Path	Relevent HFE	Diagram Name in EMRALD	Action	Actor	Work Device	Time Information [sec]					
						Task-Unit Type for Time	Mean	Standard Deviation	Minimum	Maximum	Distribution
#1	-	E0_S3_TU1	Verify vital AC buses have electrical power	MCR Operator	MCR Board	T-M-Check	2.14	0.76	2.44	29.9	Lognormal
#1	HFE#1	E0_S3_TU2	Verify at least a vital AC bus has electrical power	MCR Operator	MCR Board	T-M-Check	2.14	0.76	2.44	29.9	Lognormal
#1	-	E0_S3_TU3	Connect at least a vital AC bus. If at least a vital AC power is not available, go to ECA-0.0 (Loss of All AC Power).	MCR Operator	MCR Board	T-M-Action	2.23	1.18	1.32	65.3	Lognormal
		E0_S3_TU4				T-M-Action	2.23	1.18	1.32	65.3	Lognormal
#1	-	ECA_S1_TU1	Check if RCS is isolated	MCR Operator	MCR Board	T-M-Check	2.14	0.76	2.44	29.9	Lognormal
#1	-	ECA_S1_TU2	PRZR PORVs - Closed	MCR Operator	MCR Board	T-M-Check	2.14	0.76	2.44	29.9	Lognormal

Figure 6. Example of the task-unit analysis: HEP information

Procedure Path	Relevent HFE	Diagram Name in EMRALD	Action	Actor	Work Device	HEP Information			
						Task-Unit Type for HEP	Basic HEP	PSF muliplier	Final HEP
#1	-	E0_S3_TU1	Verify vital AC buses have electrical power	MCR Operator	MCR Board	-	-	-	-
#1	HFE#1	E0_S3_TU2	Verify at least a vital AC bus has electrical power	MCR Operator	MCR Board	H-M-Indicator	2.30E-03	1.0	2.30E-03
#1	-	E0_S3_TU3	Connect at least a vital AC bus. If at least a vital AC power is not available, go to ECA-0.0 (Loss of All AC Power).	MCR Operator	MCR Board	-	-	-	-
		E0_S3_TU4				-	-	-	-
#1	-	ECA_S1_TU1	Check if RCS is isolated	MCR Operator	MCR Board	-	-	-	-
#1	-	ECA_S1_TU2	PRZR PORVs - Closed	MCR Operator	MCR Board	-	-	-	-

In the third step of the PRIMERA-HRA method, this study developed the procedure-based EMRALD model. This model consists of three parts: the (1) main model, (2) heading model, and (3) procedure model. The main model, which is developed based on the event sequence diagram, gives an overview of the scenario, along with heading events. Figure 7 shows the main model for the ELAP scenario. The heading model includes a logic for determining the success or failure of heading events. If a heading does not split into branches, it need not be modeled (e.g., Heading #0 and #2 in Figure 3). The heading model is developed based on static fault tree logics. Figure 8 indicates the heading model for Heading #1. In that figure, the following five basic events are reflected in the heading model. Each basic event contributes to the failure of Heading #1, and its failure probability is assumed from [13].

- DGs_Fail_CCF_Run: CCF of FLEX DGs to Run
- DGs_Fail_CCF_Start: CCF of FLEX DGs to Start
- DGs_Fail_Run: FLEX DGs Fail to Run
- DGs_Fail_Start: FLEX DGs Fail to Start
- DGs_Fail_TM: FLEX DGs Fail Due to Test and Maintenance.

Lastly, the procedure model reflects all the information obtained from the task-unit analysis. Figure 9 shows the procedure model for Procedure Path #2. In that figure, the dotted red boxes are the task units critical to failure of HFE #2, while the solid red boxes, which are diagrams for HFE #2 and its overtime failure, visually combine the task units. The dotted blue boxes indicate the task units relevant to recovery failure, and the solid blue box is a diagram that visually combines the task units.

In the last step of the PRIMERA-HRA method, we analyze the EMRALD model and integrate the major results into static PRA models. In this step, we also evaluate whether the HFE failure paths and HEPs are reasonable, and whether all the HFEs have been completed within the allotted time windows. Figure 10 represents the results of the EMRALD model simulation featuring 100,000 trials. The number of failures of HFEs, recovery human actions, and components are shown in the figure. In regard to failures of HFEs, two types are counted: (1) failure due to task-unit failure, and (2) failure due to overtime. The former carries the same definition of HEP as used in existing static PRA and HRA methods, while the latter occurs when the total time required for completing a HFE exceeds the time window.

As shown in Table 3, this study compared the HEPs from the EMRALD model with those obtained via a static HRA method (i.e., Integrated Decision-Tree Human Event Analysis System for Event and Condition Assessment [IDHEAS-ECA]) [15]. IDHEAS-ECA is the latest HRA method endorsed by the U.S. Nuclear Regulatory Commission, who issued a technical report [14] analyzing FLEX-related actions by using the IDHEAS-ECA method. In this study, we investigated the extent to which the HEPs from the EMRALD model differ from those obtained via the IDHEAS-ECA method. As shown in the table, the HEP for HFE #1 from the EMRALD model is included in the range of HEPs obtained via the IDHEAS-ECA method. On the other hand, the HEPs for HFE #2 and #3 from the EMRALD model indicate higher values than those calculated via the IDHEAS-ECA method. The recovery failures and overtime failures of HFE #1, #2, and #3 are not compared with each other, since they are only estimations generated by the EMRALD model.

Figure 7. Main model for the ELAP scenario

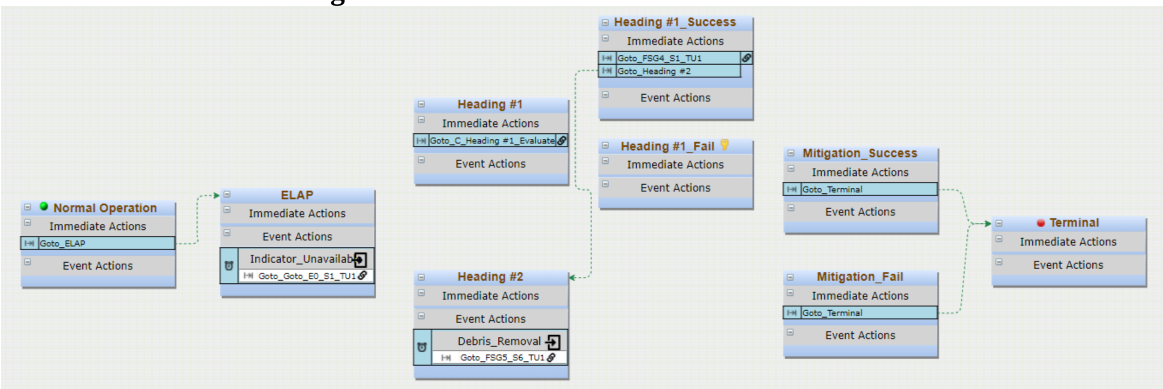


Figure 8. Heading model for Heading #1

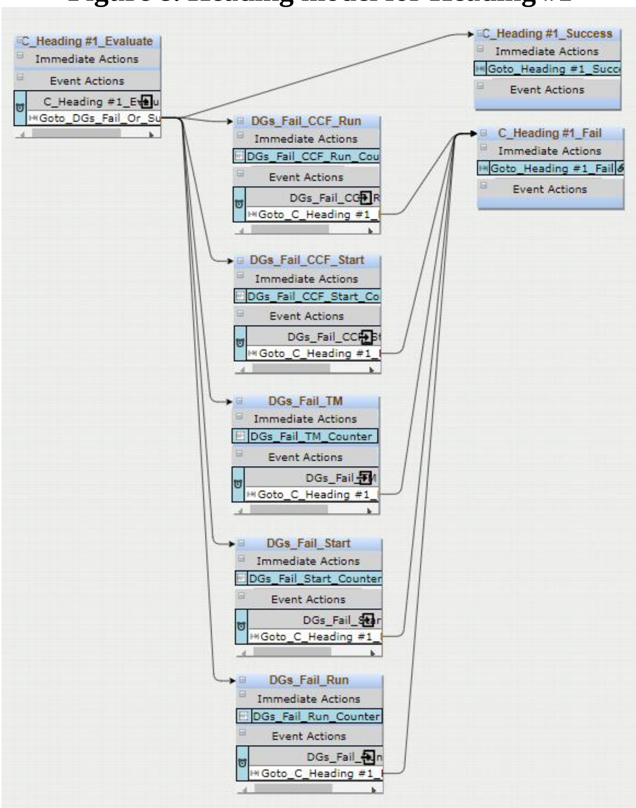


Figure 9. Procedure model for Procedure Path #2

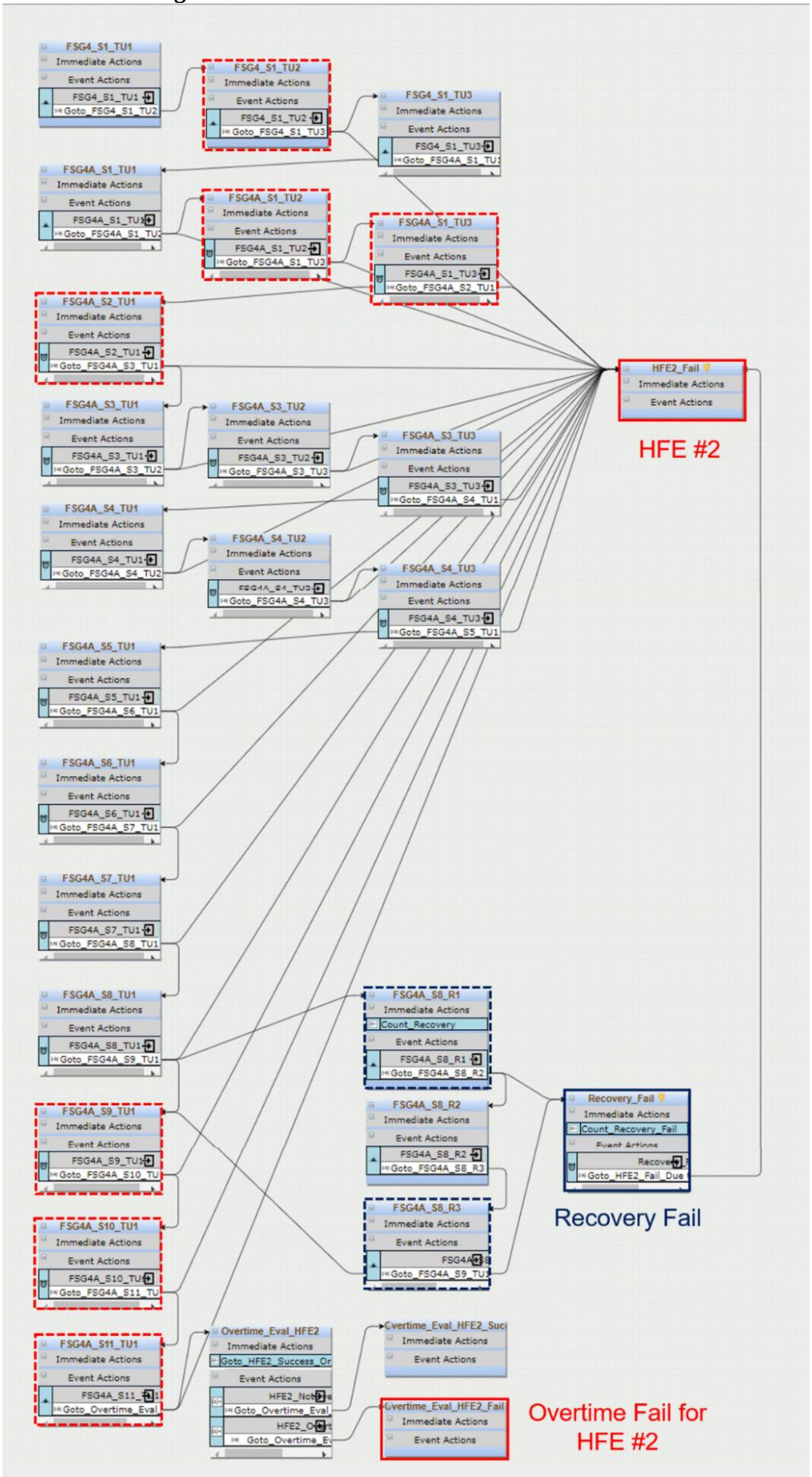


Figure 10. Results of the EMRALD model simulation featuring 100,000 trials

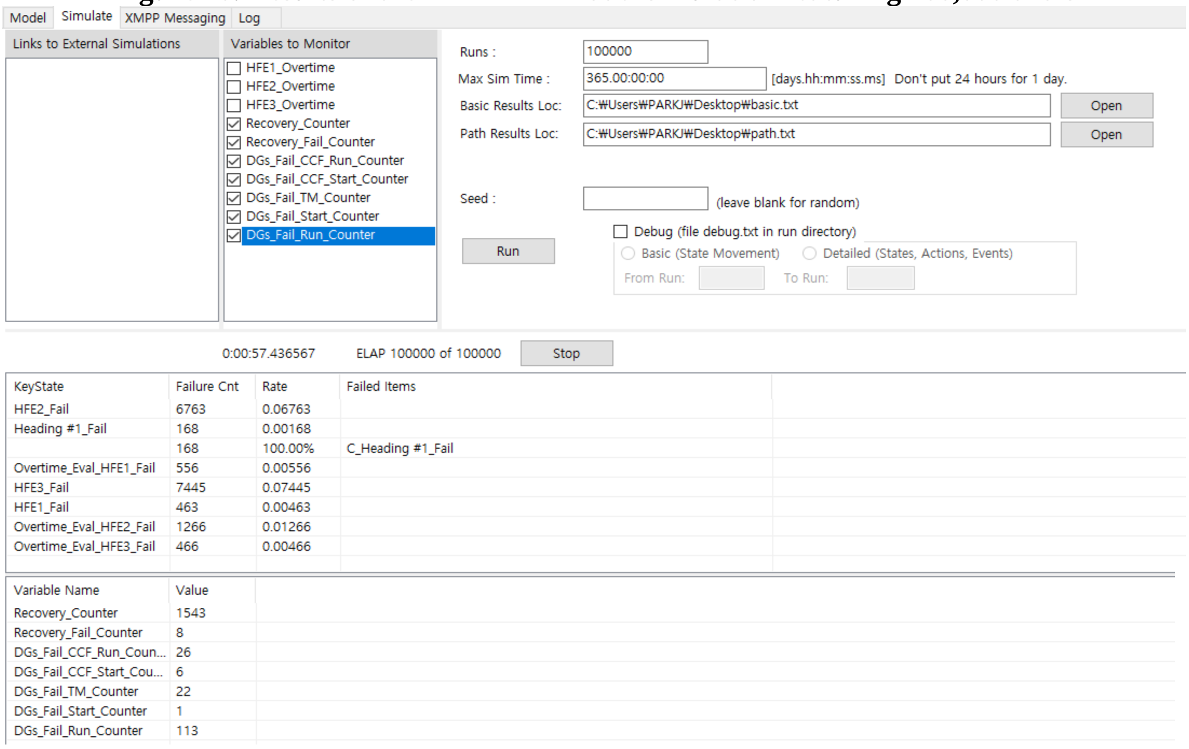


Table 3: Comparison of HEPs from the EMRALD model against those obtained via the IDHEAS-ECA method [14]

	HEPs from EMRALD Model	**HEPs from IDHEAS-ECA**
HFE #1 (ELAP Declaration)	4.6e-3	1.1e-3 ~ 1.1e-1
HFE #2 (DC Load Shed)	6.8e-2	2.0e-3 ~ 6.0e-3
HFE #3 (Deploy and Connect FLEX DGs)	7.4e-2	1.3e-3 ~ 1.2e-2
HFE #1_Overtime Failure	5.6e-3	N/A
HFE #2_Overtime Failure	1.3e-2	N/A
HFE #3_Overtime Failure	4.7e-3	N/A
Recovery Failure	5.2e-3	N/A

4. DISCUSSION

This study attempted to develop an enhanced approach to dynamic HRA by using the EMRALD software. This approach was upgraded by complimenting a couple of the limitations seen in the previous methods, such as the procedure-based and the PRA/HRA-based EMRALD modeling approaches. This study also assumed an ELAP scenario that included detailed assumptions based on observations made during stress tests [12], then applied the PRIMERA-HRA method to this scenario. As a result, this study observed that the HEPs from the EMRALD model are similar or a little bit higher than those obtained via the IDHEAS-ECA method. A new category of human error not specifically considered in existing HRA (i.e., overtime failure) was also enabled by the EMRALD model. In addition, this study's method of estimating recovery failure probabilities differed from that used in existing HRA.

The approach suggested in this study may prove beneficial for providing stronger background information and more concrete evaluation criteria to estimate HEPs. In the existing HRA, the process of defining analytical subjects and dividing a HFE into the level that the analysis is available has been a challenge that varies HRA results depending on the analysts [5]. A couple of HRA methods (e.g., Technique for Human Error Rate Prediction [16] and K-HRA [17]) decompose a HFE into subtasks to estimate HEPs, while other HRA methods (e.g., SPAR-H) do not. On the other hand, the EMRALD software approach involves procedures that may be more objective, as the assigned values are determined from the HuREX database [6] and via the GOMS-HRA method [7], thus providing the latest version of HRA data in the most effective manner.

This study counts overtime failures—never specifically considered in the existing HRA—and may be of use in supporting human factors engineering programs. In the human factors engineering program outlined in NUREG-0711 [18], there was originally a HRA process to identify whether the time required for HFEs made it feasible to complete them within the allotted time windows. ("Time required" refers to the duration of time needed by operators to perform a task, while "time available" is the duration of time in which the operators must perform the task.) If the time required for a HFE exceeds the time window, this is considered a guaranteed failure (HEP = 1.0), and the plant state is assumed to be irreversible. To date, time windows have been calculated using thermo-hydraulic analysis, which produces accurate values based on simulations. On the other hand, determining the time required relies on structured interviews with instructors, operators, and other knowledgeable experts, not on actual data or simulations. To put it simply, estimation of the time required is made complicated because so many factors can affect it. Therefore, only depending on the experience may be challenging for getting reasonable time-required values, considering all the variables that must be considered in NPPs. In this regard, the EMRALD-based HRA method may be useful for estimating time-required values and supporting the HRA aspect of human factors engineering programs by evaluating overtime failure HEPs or whether an overtime failure is counted or not.

This study may be useful for specifically evaluating human action recoveries. The existing HRA considers recovery to be a successive action. For example, when estimating a final HEP, a recovery probability is multiplied by the HEP of an HFE. However, the recovery action does not always occur. There should be any cue that makes the person recognize his fault. Nevertheless, it is rare to happen. Furthermore, the different mechanisms behind the post-recovery mitigation activities are not sufficiently explained in the existing HRA. In this regard, the EMRALD-based simulation approach may represent a breakthrough. The ELAP scenario explored in the previous section includes the local operators' fault that very specifically accounts for a recovery opportunity that is feasible in NPPs. It will be further researched at INL to afford a method of reasonably reflecting recovery opportunities when estimating HEPs in HRA.

5. CONCLUSION

This paper introduced the PRIMERA-HRA method, an approach to dynamic HRA that uses the EMRALD software developed by INL. This paper suggests how the software can be used to model human actions and evaluate error probabilities. The applicability of this approach was investigated in light of an ELAP scenario. This paper then discussed the major insights derived by comparing this dynamic HRA approach against the static one.

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