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MODELING FLEX HUMAN ACTIONS USING THE EMRALD DYNAMIC RISK ASSESSMENT TOOL

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ABSTRACT

Most current efforts have modified and applied existing human reliability analysis (HRA) methods to treat human actions related to beyond-design-basis external events in which diverse and flexible coping strategies (FLEX) equipment would be deployed. However, many questions remain regarding the suitability of legacy HRA methods to address FLEX human actions, sparking the need for a new method of reasonably evaluating them. In this context, Idaho National Laboratory (INL) researched a relatively new approach to treating FLEX human actions via Event Modeling Risk Assessment Using Linked Diagrams (EMRALD) software. EMRALD was developed to support the increasing need for dynamic probabilistic risk assessment (PRA) models that can respond to evolving plant conditions during simulations. A couple benefits were identified when analyzing FLEX human actions through this software. In general, it is especially useful for evaluating a strategy's feasibility, including FLEX human actions that require a relatively long time to perform. In this paper, we suggest how FLEX human actions can be modeled using the EMRALD software. Two different HRA modeling approaches using EMRALD are introduced: (1) procedure-based modeling and (2) PRA/HRA-based modeling. The former approach was introduced in the authors' previous paper, whereas this paper mainly discusses how the latter approach works for an extended loss of AC power (ELAP) scenario with relevant procedures and PRA models. A hybrid method combining the two modeling approaches is introduced at the paper's conclusion.

Key Words: FLEX, Human Reliability Analysis, Dynamic Risk Assessment, Probabilistic Risk Assessment

1 INTRODUCTION

Most current efforts have modified and applied existing human reliability analysis (HRA) methods to treat human actions related to beyond-design-basis external events in which diverse and flexible coping strategies (FLEX) equipment would be deployed [1]. In this context, the Nuclear Energy Institute (NEI) provided guidance for analyzing FLEX human actions—based on the Cause-Based Decision Tree (CBDT) [2] and the Technique for Human Error Rate Prediction (THERP) [3]—in its NEI-16-06 report [4]. The U.S. Nuclear Regulatory Commission (U.S. NRC) attempted to analyze FLEX human actions through an expert elicitation method [5] as well as the Integrated Human Event Analysis System for Event and Condition Assessment (IDHEAS-ECA) [6, 7], an HRA method it recently developed.

However, many questions remain regarding the suitability of legacy HRA methods to address FLEX human actions. In fact, some FLEX human actions (e.g., deploying, installing, and executing FLEX equipment) possess characteristics quite different from tasks using main control room panels and local fixed equipment. These FLEX actions generally require a relatively long time to perform, have a high degree of timeline uncertainty, and are sensitive to environmental factors such as debris from natural disasters. Therefore, treating these actions solely by modifying existing HRA methods that focus on analysis of tasks using main control room panels and local fixed equipment may be of limited value.

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For this reason, Idaho National Laboratory (INL) has researched a relatively new approach within the Enhanced Resilient Plant (ERP) project under the Risk-Informed Systems Analysis (RISA) Pathway of the U.S. Department of Energy's (DOE's) Light Water Reactor Sustainability (LWRS) Program in order to treat FLEX human actions by using Event Modeling Risk Assessment using Linked Diagrams (EMRALD) software [8, 9]. EMRALD was developed to support the increasing need for dynamic probabilistic risk assessment (PRA) models capable of responding to evolving plant conditions during simulations. EMRALD is one of a growing number of tools that enable simulations to support plant state variations in order to better model realistic event progressions. Many dynamic PRA tools being used today are scripting methods, are difficult to use and debug, and lack a graphical user interface, whereas EMRALD is a robust platform that can generate probabilistic findings, process variables, and timing of events by fostering analysis via a drag-and-drop graphical user interface for creating models.

A couple benefits were identified when using EMRALD to analyze FLEX human actions. First, EMRALD supports realistic, dynamic HRA modeling that corresponds to FLEX actions as they would be performed in an actual plant. EMRALD allows for modeling the specific moment at which an action is performed, the time to perform the action, and the failure probability of that action—all modeled simultaneously, not as separate analytic activities. Second, it enables estimation of the time required to perform an action, as well as the evaluation of overtime failure by comparing the time required against the time window for that human action. Conventional static HRA mainly focuses on error probabilities rather than timeline feasibility in actual situations. Treating HRA with EMRALD is especially useful for evaluating a strategy's feasibility, including FLEX human actions that take a relatively long time to perform.

In this paper, we suggest how FLEX human actions can be modeled using the EMRALD software. Two different HRA modeling approaches using EMRALD are introduced: (1) procedure-based modeling and (2) PRA/HRA-based modeling. The former approach was introduced in the authors' previous paper [10], whereas this paper mainly discusses how the latter approach works for an extended loss of AC power (ELAP) scenario with relevant procedures and PRA models. Finally, a hybrid method combining the two modeling approaches is introduced as being currently under development.

2 TWO DIFFERENT HRA MODELING APPROACHES USING EMRALD

Table I. Differences between procedure-based modeling and PRA/HRA-based modeling approaches

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

Table I compares the differences between the initial procedure-based modeling approach and the subsequent PRA/HRA-based modeling approach. First, the procedure-based approach specifically models human actions at the procedure step level. Generally, procedures describe what operators or plant personnel should do in a given situation. Most tasks in nuclear power plants must be performed according to written procedures. In the proposed approach, major human actions are evaluated by modeling a combination of procedure contexts in EMRALD. This is useful to account for context uncertainties that complicate HEP determination. How to apply this approach is thoroughly covered in the authors' previous paper [10]. Second, PRA/HRA-based approaches primarily model basic events and HFEs already considered in PRA/HRA. Existing methods can integratively evaluate equipment and human failures by using the fault tree technique, but it remains challenging to determine the interactions among these failures over time. Furthermore, F

LEX actions generally take much longer to complete than human actions already considered in existing P RA/HRA. Within the PRA/HRA modeling approach, the proposed methodology could be used to validate timeline uncertainties not covered in existing PRA/HRA.

3 PRA/HRA-BASED MODELING USING EMRALD

3.1 Modeling Overview

This study assumed an ELAP scenario based on the event/fault trees introduced in Section 3.2 of IN L-EXT-19-53556 [11]. Figure 1 shows the ELAP scenario timeline, which includes two events, three HF Es, and failure of the FLEX diesel generators (DGs) and FLEX steam generator pumps (SGPs). The two e vents are (1) ELAP declaration and (2) debris removal, both of which take up time in the scenario but are guaranteed to succeed. These events were assumed in order to identify their impact on overtime failure of the following three HFEs: (1) operators fail to deploy and install FLEX DG, (2) operators fail to deploy a nd install FLEX SGP, and (3) operators fail to supply an alternative water source to condensate storage ta nk (CST), using FLEX SGP. Tables II and III summarize the timing information for the two events and th ree HFEs. In this information, the assumed time window and mean time values are based on the authors' previous research [12, 13], as well as on literature related to FLEX HRA [1, 4]. Due to data scarcity, to de rive the standard deviation and minimum/maximum values in these tables, this study assumed the followi ng:

- Standard deviation: 50% of mean value
- Number of samples collected: 4
- Minimum: 5% value within 95% confidence interval
- Maximum: 95% value within 95% confidence interval

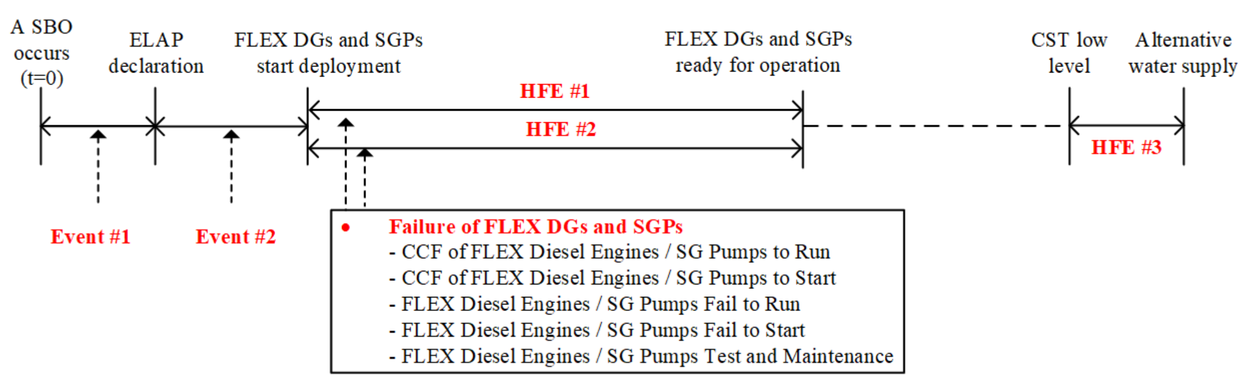

Figure 1. Timeline for the ELAP scenario.

Table II. Timing information for Events 1 and 2

Event No.		Event 1	Event 2
Event		ELAP Declaration	Debris Removal
Time Information [min]	**Mean**	5.00	60.00
	Std.	2.50	30.00
	Min.	2.55	30.60
	Max.	7.45	89.40

Table III. Timing and HRA-specific information for HFE 1, 2, and 3

HFE No.			HFE # 1	HFE # 2	HFE # 3
Description			Operators Fail to Deploy and Install FLEX DG	Operators Fail to Deploy and Install FLEX SGP	Operators Fail to Supply Alternative Water Source to CST Using FLEX SGP
Cue			ELAP Declaration	ELAP Declaration	FLEX DG/SGP ready to start
Diagnosis	**Actor**		MCR Operators	MCR Operators	MCR Operators
	Work Device		MCR Boards	MCR Boards	MCR Boards
Execution	**Actor**		Subcontractor	Subcontractor	Local Operators
	Work Device		FLEX DG	FLEX SGP	FLEX SGP
Time Information [min]	$T_{Time\ Window}$		240.00	240.00	1320.00
	T_{Delay}	**Mean**	0.00	0.00	1200.00
		Std.	-	-	600.00
		Min.	-	-	612.00
		Max.	-	-	1788.00
	$T_{Diagnosis}$	**Mean**	10.00	10.00	5.00
		Std.	5.00	5.00	2.50
		Min.	5.10	5.10	2.55
		Max.	14.90	14.90	7.45
	$T_{Execution}$	**Mean**	120.00	120.00	60.00
		Std.	60.00	60.00	30.00
		Min.	61.20	61.20	30.60
		Max.	178.80	178.80	89.40

Table IV shows the HEP information for the three HFEs. These are assumed based on the authors' previous research [12], which estimates the HEPs using the Standardized Plant Analysis Risk-Human Reliability Analysis method [14], as well as observations and experience from stress tests performed in South Korea.

Table IV. HEP information for the three HFEs

HFE No.	Type	HEP for Diagnosis or Execution	Final HEP
HFE #1	Diagnosis	4.8e-2	5.0e-2
	Execution	2.0e-3	
HFE #2	Diagnosis	4.8e-2	5.0e-2
	Execution	2.0e-3	
HFE #3	Diagnosis	4.8e-2	6.0e-2
	Execution	1.2e-2	

For failure of FLEX DGs/SGPs, the model considers 10 random equipment failure events, including common-cause failure (CCF) events. A list of these events and their failure probabilities is shown in Table V, based on the fault trees introduced in Section 3.2 of INL-EXT-19-53556 [11].

Table V. Equipment failure information on FLEX DGs/SGPs

Equipment Type	Equipment Failure	Failure Probability
FLEX DGs	CCF of FLEX DGs to Run	2.826e-4
	CCF of FLEX DGs to Start	5.750e-5
	FLEX DGs Fail to Run	3.536e-2
	FLEX DGs Fail to Start	2.860e-3
	FLEX DGs Fail Due to Testing and Maintenance	1.500e-2
FLEX SGPs	CCF of FLEX SGPs Fail to Run	2.826e-4
	CCF of FLEX SGPs Fail to Start	5.750e-5
	FLEX SGPs Fail to Run	3.536e-2
	FLEX SGPs Fail to Start	2.860e-3
	FLEX SGPs Fail Due to Testing and Maintenance	1.500e-2

3.2 Model Details

The PRA/HRA-based FLEX HRA model was developed using the inputs discussed in Section 3.1. No recovery human action or equipment recovery is credited in the model. For each HFE, overtime failure is evaluated by comparing the available time window with the total time required for operators. The model consists of one main model and five component models, as listed below:

- One Main Model for PRA/HRA-based FLEX HRA Model
- Component Model Describing Equipment Failure Related to FLEX DGs/SGPs
- Component Model Describing Operator Failure Related to HFE #1
- Component Model Describing Operator Failure Related to HFE #2
- Component Model Describing Operator Failure Related to HFE #3

Figures 2, 3, and 4 show representative examples of the main and component models describing equipment and operator failure. The main model (Figure 2) summarizes the sequence of the ELAP scenario. Figure 3 includes the basic events modeled in the static fault tree introduced in Section 3.2 of INL-EXT-19-53556 [11]. Lastly, the HFE model (Figure 4) reflects a general process for calculating HEPs within HRA, as well as a diagram for evaluating operator overtime failure.

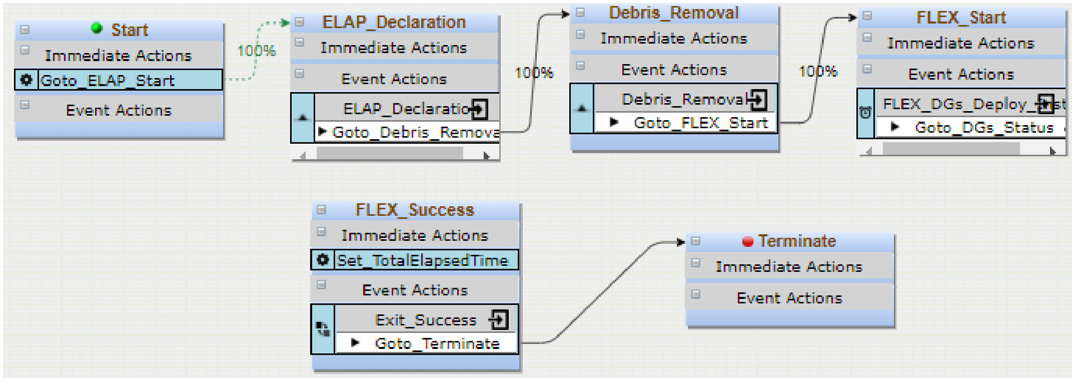

Figure 2. Main model for PRA/HRA-based FLEX HRA model.

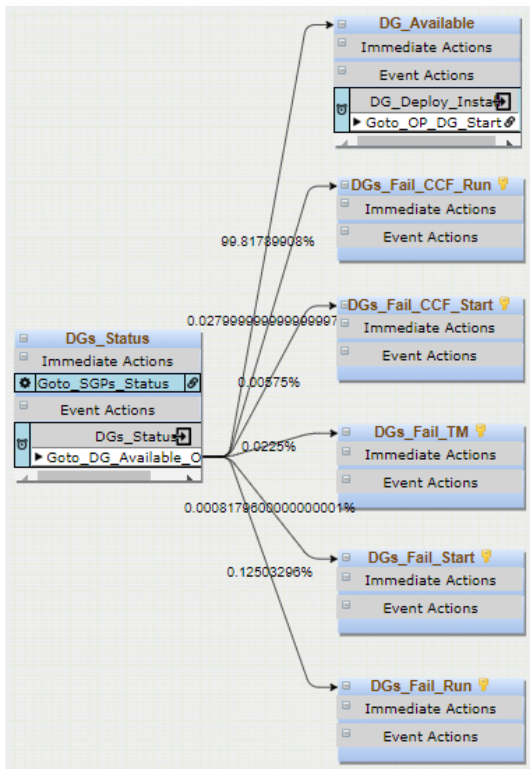

Figure 3. Component model describing equipment failure related to FLEX DGs.

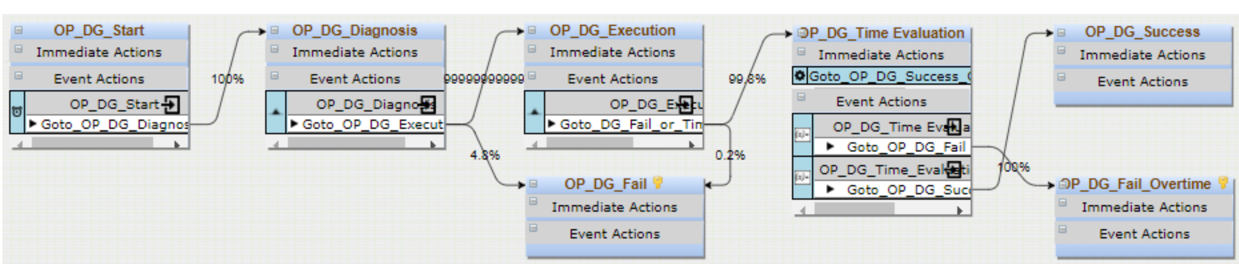

Figure 4. Component model describing operator failure related to HFE #1.

3.3 Insights from the Model

This study simulated the PRA/HRA-based FLEX HRA model for 100,000 trials. Table VI shows the number of cases—along with the ratio of success/error types—in regard to human error and equipment failure over all 100,000 trials. Out of all the cases, 71.2% failed, either due to human error (69.8%) or equipment failure (0.4%). The remaining 29.8% represents the success of the FLEX strategy. In the human error category, “OP_SGP_FI_Fail_Overtime” (which indicates overtime failure of HFE #3) constitutes the highest number of cases (25,892 [37.1%]), whereas “DGs_Fail_Run” ranks the highest (126 [32.4%]) in the equipment failure category.

Table VI. Number of cases—along with the ratio of success/error types—in regard to human error and equipment failure over 100,000 trials

Category	Error Type		Number of Cases	Ratio
	Event ID in EMRALD	Description		
Success (29.8%)	FLEX_Success	The FLEX Strategy Succeeds	29,845	100.0%
	Sum		29,845	100.0%
Human Error (69.8%)	OP_DG_Fail	HFE #1 Fails	4,977	7.1%
	OP_SGP_Fail	HFE #2 Fails	3,785	5.4%
	OP_SGP_FI_Fail	HFE #3 Fails	3,543	5.1%
	OP_DG_Fail_Overtime	HFE #1 Fails Due to Overtime	19,189	27.5%
	OP_SGP_Fail_Overtime	HFE #2 Fails Due to Overtime	12,380	17.7%
	OP_SGP_FI_Fail_Overtime	HFE #3 Fails Due to Overtime	25,892	37.1%
	Sum		69,766	100.0%
Equipment Failure (0.4%)	SGPs_Fail_TM	FLEX SGPs Fail Due to Testing and Maintenance	12	3.1%
	SGPs_Fail_CCF_Run	CCF of FLEX SGPs Fail to Run	53	13.6%
	SGPs_Fail_Run	FLEX SGPs Fail to Run	80	20.6%
	SGPs_Fail_CCF_Start	CCF of FLEX SGPs Fail to Start	25	6.4%
	SGPs_Fail_Start	FLEX SGPs Fail to Start	21	5.4%
	DGs_Fail_Run	FLEX DGs Fail to Run	126	32.4%
	DGs_Fail_CCF_Start	CCF of FLEX DGs to Start	14	3.6%
	DGs_Fail_TM	FLEX DGs Fail Due to Testing and Maintenance	26	6.7%
	DGs_Fail_Start	FLEX DGs Fail to Start	1	0.3%
	DGs_Fail_CCF_Run	CCF of FLEX DGs Fail to Run	31	8.0%
	Sum		389	100.0%

In Figure 5, the mean values of the time required for HFE #1, #2, and #3 are compared with the time window values for the HFEs. For example, the time required for HFE #1 is calculated at 195 minutes by allotting 5 minutes to declare ELAP, 60 minutes to remove debris, and 130 minutes to perform HFE #1, then comparing the total sum with the time window for HFE #1 (i.e., 240 minutes). In summary, all comparisons indicate the “time required” values to be lower than the time windows. However, the EMRALD model’s analysis (i.e., Table VI) identified additional human errors caused by overtime (i.e., “OP_DG_Fail_Overtime,” “OP_SGP_Fail_Overtime,” and “OP_SGP_FI_Fail_Overtime”). These indicate much higher error probabilities than the human failure types (e.g., “OP_DG_Fail,” “OP_SGP_Fail,” and “OP_SGP_FI_Fail”) considered in existing HRA.

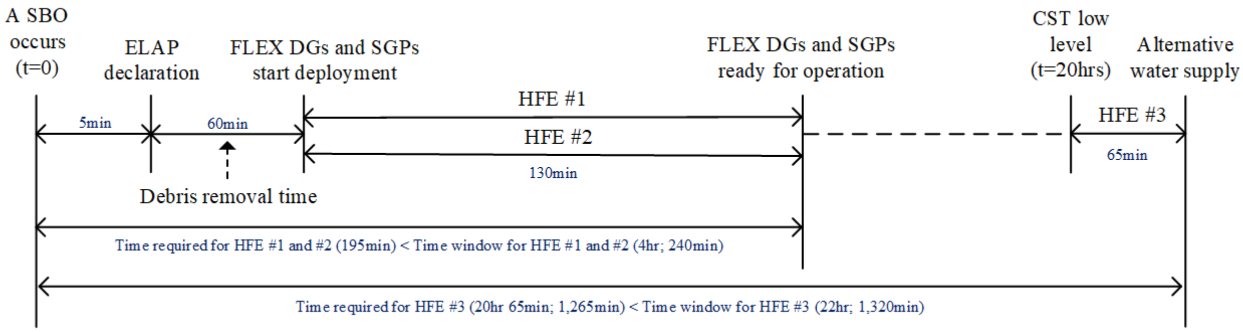

Figure 5. Comparison between the time window and time required, with mean value.

4 HYBRID EMRALD HRA METHOD

The two approaches discussed in the previous sections feature a couple of limitations. The initial procedure-based modeling does not communicate with PRA parts such as equipment failure. In actual situations, required operator actions may vary, depending on whether certain equipment works or not. If components in PRA fault trees are not considered in the approach, the method 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 for treating lots of procedure steps that could be used in a scenario is not explicitly suggested. In addition, this modeling approach does not consider performance shaping factors, meaning factors that influence human performance and were used to highlight error contributors and adjust basic HEPs. For PRA/HRA-based modeling, two main issues must be considered. The first is how to assume timeline uncertainly for each basic event. As mentioned in Section 3.1, due to data scarcity, this study assumed the standard deviation and minimum/maximum values that are inputs in the EMRALD software. How to derive and use those values based on empirical evidence is a primary challenge of this approach. The second issue is how to specifically model certain major HRA concepts (e.g., recovery opportunities).

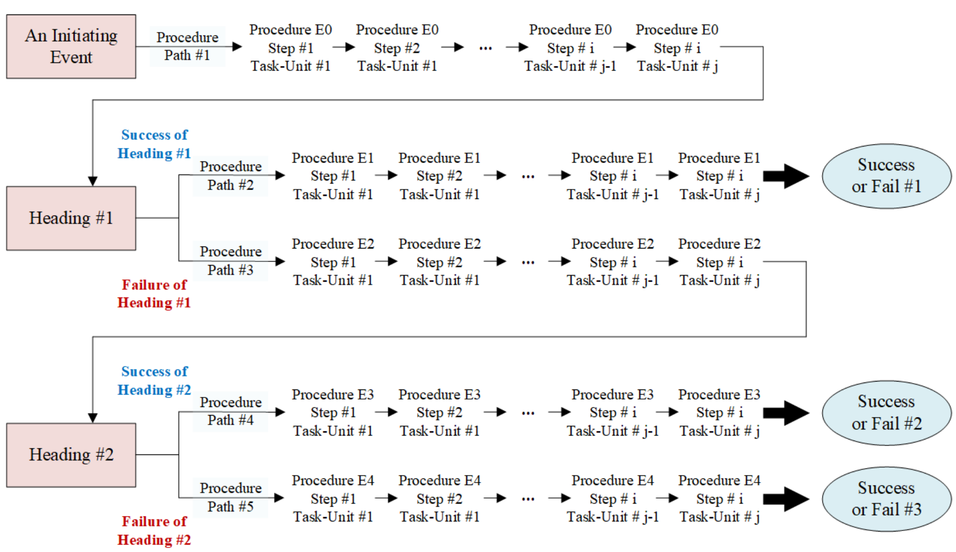

Figure 6. Conceptual design of the hybrid method.

For those reasons, our research team has developed a hybrid method by combining the two EMRALD HRA modeling approaches. This method was designed to complement the challenges that each approach faces, suggesting a more structured and systemic way to analyze human actions in HRA and provide HEPs to existing PRA models. Figure 6 shows a conceptual design of the hybrid method, which models both procedure contexts representing human actions as well as equipment failure. In existing HRA, human actions are modeled as backups for system, component, or equipment failure, whereas this method uses them as support for various scenarios and procedure paths, depending on the initiating event.

5 CONCLUSIONS

This paper introduced two different HRA modeling approaches using EMRALD (i.e., procedure-based modeling and PRA/HRA-based modeling), a method of applying the PRA/HRA-based modeling approach to an ELAP scenario with relevant procedures and PRA models, and the conceptual design of the hybrid method combining the two modeling approaches. The hybrid method is still under development. Details on the process and the analysis results of using this new hybrid method are planned for future papers.

6 A DISCLAIMER

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