EVALUATION OF HRA METHODOLOGIES FOR APPLICATION IN SDP WORK

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ABSTRACT

This study critically evaluates human reliability analysis (HRA) methodologies applicable to regulatory probabilistic safety assessment (PSA) model, with a particular focus on their role in supporting the significance determination process (SDP) in nuclear safety assessment. Firstly, three widely utilized HRA methods—IDHEAS-ECA, SPAR-H, and ASEP/THERP—were qualitatively and quantitatively assessed. Qualitative assessments were conducted using attributes from the NEA/CSNI/R(2015)1 report, while quantitative evaluations employed regression and correlation analyses to compare predicted human error probabilities (HEPs) against empirical data. Results reveal distinct strengths, for example, IDHEAS-ECA's robust predictive accuracy and K-HRA's alignment with operational practices. In addition, dependency analysis and recovery analysis were critically evaluated. For dependency analysis, the methods' handling of inter-task dependencies and their impact on HEPs were examined, while recovery analysis highlighted strategies for mitigating failure events. Furthermore, strategies were proposed to evaluate performance shaping factors under conditions of reduced human performance, such as stress, fatigue, or cognitive overload, addressing specific challenges faced in SDP evaluations. Human errors from KINS's operational performance information system event reports were evaluated as a case study. This study identifies gaps and provides actionable insights to ensure their validity and applicability in SDP HRA applications. This paper is a part of research conducted by KINS, and it should be noted that this result does not represent the regulatory position of KINS.

Keywords: Human Reliability Analysis, Significance Determination Process, Qualitative and Quantitative verification, Recovery analysis, Dependency analysis

I. INTRODUCTION

In recent years, the Korea Institute of Nuclear Safety (KINS) has enhanced the Multi-purpose Probabilistic Safety Assessment (MPAS) model, originally developed as a regulatory PSA framework, to strengthen its capability in supporting the future application of Significance Determination Process (SDP) and other regulatory applications [1]. As a regulatory PSA model, MPAS is intended to provide independent and objective safety evaluations that are consistent with international standards and reflect plant-specific operational realities. However, one of the key limitations of the current MPAS model is that its human reliability analysis (HRA) adopts the same HRA methodology used by licensees [2]. This could compromise the independence and objectivity of the regulatory assessment. The objective of this study is to review suitable HRA methodologies for application in the MPAS model, to explore approaches for dependency and recovery analysis when applying the HRA method(IDHEAS-ECA), and to conduct a case study based on the selected methodology.

To address this issue, several HRA methodologies—including IDHEAS-ECA (Integrated Decision-tree Human Event Analysis System - Error Causal Analysis), SPAR-H (Standardized Plant Analysis Risk-Human Reliability Method), and ASEP (Accident Sequence Evaluation Program)/THERP (Technique for Human Error Rate Prediction)—have been reviewed. Among them, the IDHEAS-ECA method was selected as the most appropriate approach for human error probability quantification within MPAS. Despite this selection, there are still unresolved challenges associated with its practical application, especially in the context of regulatory PSA. In parallel, while a dependency analysis method has been developed and documented for MPAS, it lacks sufficiently detailed guidance for practical implementation. Moreover, a formal recovery action evaluation methodology has not yet been established. These gaps may limit the model's ability to accurately and transparently represent human performance under realistic accident scenarios.

This study aims to review and refine the application of HRA methodologies suitable for the MPAS model, with a particular focus on dependency analysis and recovery analysis. Furthermore, to validate the applicability of IDHEAS-ECA within a regulatory PSA context, a case study is presented using actual findings from a domestic nuclear power plant inspection. The outcomes of this study are expected to contribute to the advancement of a more robust and independent HRA framework tailored for regulatory PSA applications.

II. SELECTION OF HRA METHOD APPLLIED IN MPAS MODEL

We first reviewed three HRA methodologies: IDHEAS-ECA, SPAR-H, and ASE/THERP. The results of this review are summarized below. Subsequently, to select an HRA method for application in the MPAS model, qualitative evaluations were performed.

II.A. Review of HRA Methods

II.A.1. IDHEAS-ECA

IDHEAS-ECA, which provides a comprehensive framework for understanding and modeling human contributions to IDHEAS-ECA, was recently developed by U.S. Nuclear Regulatory Commission (NRC) staff [3]. This approach systematically considers the contextual conditions under which events occur, as well as the underlying cognitive and behavioral mechanisms that influence human performance. It evaluates both contextual factors and cognitive or organizational influences that may affect operator actions and decisions. Expert judgment plays a central role in conducting qualitative assessments, which are subsequently translated into quantitative estimates of HEPs. Designed to support both deterministic and probabilistic safety assessment, IDHEAS-ECA provides a comprehensive framework for understanding and modeling human contributions to risk.

II.A.2. SPAR-H

SPAR-H method is a streamlined HRA approach designed to estimate HEPs in nuclear power plant operations [4]. It integrates both diagnosis error and action error and uses a set of predefined performance shaping factors (PSFs) to adjust base error rates. The method applies a relatively simple quantitative framework that enables consistent and rapid evaluations across a wide range of human tasks. Expert judgment is incorporated to assess task context and determine appropriate PSF multipliers. SPAR-H has been widely adopted in risk-informed applications due to its balance between usability and technical rigor.

II.A.3. ASEP/THERP

THERP is one of the earliest and most comprehensive HRA methods developed for nuclear power applications [5]. THERP provides a structured framework for identifying, analyzing, and quantifying human errors in complex systems. The methodology involves detailed task analysis, classification of potential human errors, and estimation of HEPs using empirical data. PSFs are applied to adjust base error rates, and dependency effects between tasks are explicitly modeled. THERP employs event trees to integrate human error probabilities into probabilistic risk assessments, making it a foundational method that has influenced many subsequent HRA approaches.

On the other hand, ASEP was developed as a simplified HRA approach to facilitate more efficient human error analysis during PSAs [6]. ASEP draws heavily on the THERP framework but streamlines the process to enable consistent application by analysts with limited HRA expertise. The method uses simplified decision trees to guide the estimation of HEPs for both pre-initiator and post-initiator human actions. Like THERP, ASEP incorporates PSFs to account for context-specific conditions but offers predefined multipliers and screening criteria to accelerate the quantification process. ASEP has been widely used for screening-level evaluations and as a practical tool in regulatory and industry applications.

II.A.4. Review Result of HRA Methods

NEA/CSNI/R(2015)1 published by OECD/NEA was used to review the HRA methods [7]. In NEA/CSNI/R(2015)1 report, desirable attributes of HRA methods were identified and defined. A total of twenty-seven attributes were developed and grouped into five categories: Construction validity, Content Validity, Empirical Validity, Reliability, and Usability. Table I is the example of evaluation criteria for rating scales on each attribute. IDHEAS-ECA, SPAR-H and ASEP/THERP were evaluated based on attributes in the NEA/CSNI/R(2015)1 [8].

TABLE I. Example Attributes, their Descriptions, and Rating Scales [8].

No.	Attribute	Description	Rating Scale
1	Availability of information relating to the technical basis of the method	Information is provided on the technical basis of the method, in terms of its scientific underpinnings and data, in order to allow a judgment on the validity of the method to be made.	High, Intermediate, and Low
2	The technical basis of the method (theory)	The technical basis of the method is based upon, and does not contradict, a relevant body of scientific knowledge.	High and Low
3	The technical basis of the method (data)	Where the technical basis of the method is based on a dataset, the source of the data/information and its relevance for application in the nuclear industry should be demonstrated.	High, Intermediate, and Low
4	Internal consistency of the method	The method demonstrates internal consistency between the technical basis, the error definition, the PSFs and the qualitative and quantitative method steps.	High and Low
5	Qualitative assessment	It is recognized as good practice that HRA quantification is supported by qualitative analysis to develop an understanding of operator performance within the scenario that is being assessed. This attribute considers the extent to which the qualitative analysis stages of the HRA (e.g. task analysis and error identification) is directed or prescribed by the HRA method, beyond providing a set of PSFs to be considered.	High, Intermediate, and Low
6	Adequacy of PSFs	The method requires qualitative assessment of a majority of accepted factors that affect human reliability.	High and Low
7	Qualitative sensitivity	The method is quantitatively sensitive to the effect of each individual PSF considered qualitatively.	High, Intermediate, and Low
8	Inter-dependency between PSFs	Typically, HRA methods adopt a linear multiplicative combination of PSFs. It is recognized that some PSFs may interact in other ways, e.g., a step change in the effect of one PSF once a threshold has been reached on a second PSF, or where the effect of the combination of two PSFs is far greater than multiplicative relationship would predict or where one PSF has a triggering effect on other PSFs in a causal chain.	High, Intermediate, and Low
9	Consideration of human error dependency	Modeling should include consideration of human error dependencies or common cause failures.	High, Intermediate, and Low
10	Consideration of deviations in accident sequences	The method should provide a capability to accommodate deviations from nominal accident scenarios due to plant conditions and human failure scenarios.	High, Intermediate, and Low
11	Consideration of fault progressions in accident sequences	Fault progressions including consequential faults and accident sequences encompassing Level 1 and Level 2 PSA which may involve extended time sequences and degraded operating environments should also be accommodated.	High, Intermediate, and Low

IDHEAS-ECA has the largest number of attributes rated as "High". On the other hand, SPAR-H and THERP show the second and third largest numbers in order. The following are the attributes for which IDHEAS-ECA was rated higher than at least one of the methods. IDHEAS-ECA is the latest version of the second generation HRA methods. The second generation HRA methods were developed for improving several challenges of the first-generation HRA methods. The list of attributes below indicates that IDHEAS-ECA considers the challenges of the first-generation HRA methods, especially for K-HRA

- The technical basis of the method (Data) (#3)
- Qualitative assessment (#5)
- Consideration of deviations in accident sequences (#10)
- Consideration of fault progressions in accident sequences (#11)
- Consideration of cognitive error (#12)
- Consideration of process factors (#15)
- Statistical evidence (#16)
- Qualitative outputs (#23)
- Use of Limiting Values (#26)
- Resources (#27)

As a result, we selected IDHEAS-ECA method for application in the MPAS model. Nevertheless, the IDHEAS-ECA methodology has certain limitations, particularly the lack of concrete guidelines for dependency analysis and the absence of recovery analysis. Therefore, in the following chapter, alternative methodologies for dependency analysis and recovery analysis that can be used in conjunction with the IDHEAS-ECA HRA method have been investigated

II.B. Review of Dependency Analysis Method

Dependency analysis refers to the process of identifying and evaluating the extent to which the performance of one human action is influenced by previous or concurrent actions. This includes considering factors such as shared personnel, similar tasks, time pressure, or common cues that could increase the likelihood of human error if one action fails. Dependency analysis helps assess the realistic probability of multiple related human errors occurring, which is critical for accurate risk modeling.

As part of the dependency analysis, we conducted a comparative evaluation of the EPRI dependency method suggested in NUREG-1921, SPAR-H, and IDHEAS-DEP methodologies. On the other hand, THERP was excluded from the list. It's because, as mentioned in Table 21, THERP is used for quantification as a part of most dependency methods but does not provide specific guidance to determining a dependency level.

II.B.1. EPRI Dependency Method in NUREG-1921

The dependency analysis method described in NUREG-1921 provides a structured approach for assessing dependencies between human actions within HRA. It uses eight qualitative factors – intervening success, crew, cognitive, cue demand, manpower, location, sequential timing, stress – to determine the overall dependency level between two or more human actions. Based on this assessment, the dependency is categorized into one of five levels : zero, low, moderate, high, complete [9].

II.B.2. SPAR-H Dependency Method

The guidance on the SPAR-H methodology includes a structured approach to dependency analysis by defining five levels of dependency : zero, low, moderate, high, and complete. These levels are determined based on four qualitative factors : crew, time, location, and cues. For each factor, guidance is provided to qualitatively assess the dependency between two human actions. After a dependency level with the previous HFE (Human Failure Event) is determined, each equation for the dependency levels is applied to adjust the HEP for the HFE using the THERP dependency equations [4].

II.B.3. IDHEAS-DEP Method

IDHEAS-DEP has been updated as a framework for modeling dependency in HRA, particularly within the IDHEAS-G framework. This model emphasizes a more context-driven and evidence-based approach, moving beyond traditional categorical levels. It incorporates key factors such as functions or system similarity, time proximity, same personnel, location similarity, procedure similarity to assess the likelihood of dependency between human actions. Unlike earlier methods that rely on fixed multipliers, the model supports a graded assessment, encouraging the use of expert judgment and scenario-specific information to derive conditional probabilities. This allows for more nuanced and realistic treatment of dependencies in complex operational contexts [10].

II.B.4. Review Result of Dependency Analysis Method

NEA/CSNI/R(2015)1 published by OECD/NEA was used in order to review dependency analysis methods [7]. Some attributes that are less significant or irrelevant to dependency analysis were excluded from the original list proposed in the NEA/CSNI/R(2015)1 report. Among twenty-seven attributes, nine attributes were used to review dependency analysis methods as follows.

- Availability of information relating to the technical basis of the method
- The technical basis of the method (theory)
- The technical basis of the method (data)
- Internal consistency of the method
- Qualitative assessment
- Adequacy of PSFs/dependency factors
- Application/maturity
- Traceability
- Resources

The results of the analysis indicated that, despite the distinct advantages of each methodology, the evaluation outcomes were largely similar. However, the EPRI dependency method provides HRA analysts comprehensive information and its application is required for understanding the method and analyzing dependencies between HFEs. The method operates a relevant dependency model of human performance or system safety which has scientific acceptance. The qualitative and quantitative component parts of the method are theoretically compatible and form a coherent consistent whole. The dependency method contains or prescribes a process for qualitatively selecting a dependency level. Also, the EPRI method provides a procedure to ensure easy and complete traceability of dependency assessments, such that an independent reviewer could trace back how dependency levels are evaluated. In addition, although there are a lot of dependency candidates generated from cutsets, the method itself (i.e., evaluating a dependency level) may not require the huge amount of time and cost, if all the relevant information is ready [11].

II.C. Review of Recovery Analysis Method

Recovery analysis within HRA refers to the evaluation of the potential for operators to successfully detect and correct an error or prevent its consequences after the initial failure has occurred. Key factors influencing recovery include the availability of cue, time available for recovery, operator training, procedures, and system feedback. Recovery analysis is essential for ensuring realistic estimation of human error probabilities, as it accounts for the defense-in-depth strategies inherent in many operational contexts. Despite its importance, formalized methodologies for recovery analysis remain limited, and are often implemented based on expert judgment or simplified assumptions. As part of the recovery analysis, we reviewed THERP and CBDT (Cause-Based Decision Tree) methods. IDHEAS-REC is a recovery method for supporting IDHEAS-ECA. In the current IDHEAS-ECA, recovery probabilities are assumed as 1.0, because an approach to recovery analysis within IDHEAS-ECA was not developed yet.

II.C.1. THERP

The THERP incorporates recovery analysis as a critical component of human error evaluation. In THERP, recovery is modeled explicitly as a branch in the event tree, representing the probability that an operator detects and corrects an error before it leads to undesirable consequences. The recovery probability is typically estimated based on contextual factors such as checking routine tasks with written materials, alerting factors, checking by reader/checker of the task performer. This approach allows for quantifying the likelihood of successful recovery and integrating it into the overall HEP calculations [5].

II.C.2. CBDT

The CBDT incorporates recovery analysis by evaluating the potential for operators to detect and correct errors based on the underlying cognitive causes of failure. CBDT determines recovery failure probabilities such as self-review, extra crew, shift technical advisor review, or shift change [12].

II.C.3. Review Result of Recovery Analysis Method

NEA/CSNI/R(2015)1 published by OECD/NEA was used in order to review recovery analysis methods [7]. Some attributes that are less significant or irrelevant to dependency analysis were excluded from the original list proposed in the NEA/CSNI/R(2015)1 report. Among twenty-seven attributes, fifteen attributes were used to review dependency analysis methods as follows.

- Availability of information relating to the technical basis of the method
- The technical basis of the method (theory)
- The technical basis of the method (data)
- Internal consistency of the method
- Qualitative assessment
- Adequacy of PSFs
- Quantitative sensitivity
- Inter-dependency between PSFs
- Consideration of statistical uncertainty
- Statistical evidence
- Application/maturity
- Traceability
- Qualitative outputs
- Qualitative uncertainty and quantitative conservatism
- Resources

The results of the analysis indicate that THERP demonstrated a higher level of performance across a greater number of evaluated attributes than the CBDT methodology. Notably, THERP received higher ratings than CBDT in key attributes, including the adequacy of its treatment of PSFs and the extent of supporting statistical evidence [11].

III. CASE STUDY

Human errors from KINS's operational performance information system (OPIS) event reports were evaluated as a case study. This study identifies gaps and provides actionable insights to ensure their validity and applicability in SDP HRA applications. In the SDP evaluation, PSFs were assessed to estimate the delta HEP resulting from human errors. As previously mentioned, the IDHEAS-ECA methodology was employed for this purpose. However, since the dependency analysis method and recovery analysis method have not yet been finalized, these factors were not considered in the current evaluation. Three OPIS event reports are as follows.

- An automatic start of a standby diesel generator at Wolseong Unit 2 on April 5, 2023 (OPIS No. 230405W2)
- An automatic reactor trip at Hanul Unit 6 on July 19, 2020 (OPIS No. 200719HU6)
- A manual reactor trip and actuation of auxiliary feedwater system at Hanbit Unit 1 on May 10, 2019 (OPIS No. 190510HB1)

III.A. OPIS No. 230405W2

The event occurred during testing protection relays installed on 13.8kV BUB (Bus Under Breaker) bus. The nuclear utility failed to manage test and maintenance procedures that can cause loss of voltage with the high probability. An inlet circuit breaker for the BUB bus was activated due to loss of voltage when operators performed the procedures. Accordingly, a standby diesel generator was automatically activated. This action is related to human factors degradation, especially for procedures. An action CFM (Cognitive Failure Mode) can be credited. The relevant PSFs, i.e., task complexity, procedures and guidance, and training and experience, can be evaluated using the following options [11].

- C5: Cues for detection are not obvious
- PG3: Procedure lacks details
- TE5: Operator is inexperienced

As a result of HEP evaluation, assuming a nominal HEP (all HSI work successfully) of 1.00E-04, the HEP under degraded PSF conditions was estimated to be 2.10E-01. Accordingly, the delta HEP was calculated as 2.10E-01.

III.B. OPIS No. 200719HU6

After the reactor tripped, operators determined to stop a main feedwater pump to prevent steam generators from overcharging and reactor coolant from overcooling. Due to HSI errors (indicators for main feedwater pumps and booster pumps showed that these were still working), operators failed to recognize the actual status of the pumps, then tried to stop a main feedwater pump and booster pump. Accordingly, the operator's action caused a loss of main feedwater. This action is related to human factors degradation, especially for procedures and HSIs. It is a post-initiator. An action CFM and recovery action can be credited. The relevant PIFs, i.e., task complexity, procedures and guidance, and training and experience, can be evaluated using the following options. Although indicators for the pumps were not showing the correct information, operators still had a chance to recognize the errors via other parameter values. Procedures that operators used did not provide alternative ways to check the status of the pumps. Operators may be familiar with the scenario but might not expect that indicators show the wrong information. [11].

- C3: Detection demands for high attention
- PG3: Procedure lacks details
- TE5: Operator is inexperienced

As a result of HEP evaluation, assuming a nominal HEP (all HSI work successfully) of 1.00E-04, the HEP under degraded PSF conditions was estimated to be 4.30E-03. Accordingly, the delta HEP was calculated as 4.20E-04.

III.C. OPIS No. 190510HB1

During the control rod extraction process, operators failed to correctly evaluate the impact of the control rod extraction on reactivity. This human error occurred due to a combination of many problems in safety culture, operator experience, violation, etc. This action is related to human factors degradation, especially for procedures. To highlight the impact of procedure errors, this report did not consider all the problems from the event when calculating an HEP. The relevant PIF, i.e., procedures and guidance, can be evaluated using the following option. [11].

- PG3: Procedure lacks details

As a result of HEP evaluation, assuming a nominal HEP (all HSI work successfully) of 1.00E-04, the HEP under degraded PSF conditions was estimated to be 3.20E-04. Accordingly, the delta HEP was calculated as 2.20E-04.

IV. CONCLUSIONS

This study reviewed and evaluated various HRA methodologies for application in the regulatory PSA model, with a focus on supporting the SDP. Among the methods, IDHEAS-ECA was selected for its comprehensive treatment of cognitive and contextual factors. However, limitations remain, particularly the absence of finalized methods for dependency and recovery analysis. To address this, alternative methodologies were compared. While evaluation results were broadly consistent, the

NUREG-1921 method for dependency showed notable strengths, especially in practical applicability and technical basis. A case study using OPIS event data illustrated the impact of degraded PSFs on human error probability, highlighting the need for realistic modeling. Overall, while IDHEAS-ECA serves as a strong foundation, incorporating systematic dependency and recovery analysis methods will be essential for improving the robustness and completeness of HRA in regulatory PSA applications.

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