Dependency Analysis Using the Integrated Human Event Analysis System Human Reliability Analysis Methodology

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Abstract: *Dependency in the context of human reliability analysis (HRA) refers to the impact of failure of a human action on the reliability of performing the subsequent human actions. Existing dependency models assess the level of dependency between two human failure events (HFEs) based on coupling factors or commonalities that exist for both HFEs, such as personnel or locations. The U.S. Nuclear Regulatory Commission (NRC) developed a new dependency model that is informed by behavioral and cognitive science and expands on existing dependency models by identifying the specific cognitive failure modes (CFMs), performance influencing factors (PIFs), and PIF attributes that are impacted by dependency. This new dependency model identifies and evaluates how failure of the first human action affects the context of subsequent human actions. The NRC presents the new dependency model in NUREG-2198, "The General Methodology of an Integrated Human Event Analysis System (IDHEAS-G)," issued May 2021 [1]. IDHEAS-G [1] is a new general HRA framework that can be used to develop application-specific HRA methods. The NRC used the IDHEAS-G [1] framework to develop a new method for assessing and quantifying individual human error probabilities (HEPs) for nuclear power plant probabilistic risk assessments that is documented in Research Information Letter 2020-02, "Integrated Human Event Analysis System for Event and Condition Assessment (IDHEAS-ECA)," issued February 2020 [2]. The NRC staff used the dependency model presented in IDHEAS-G [1] and the HRA quantification method presented in IDHEAS-ECA [2] to develop a new method for assessing dependency that is documented in Research Information Letter 2021-14, "Integrated Human Event Analysis System Dependency Analysis Guidance (IDHEAS-DEP)" [3]. This paper summarizes an NRC-endorsed approach for performing dependency analysis using IDHEAS-DEP [3].*

1. INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) staff developed a new process for identifying and estimating the impact of dependency on human error probabilities (HEPs). This new dependency method is based on the dependency model presented in the General Methodology of an Integrated Human Event Analysis System (IDHEAS-G) [1] and the HRA quantification method in IDHEAS for Event and Condition Assessment (IDHEAS-ECA) [2]. This new dependency method is documented in Research Information Letter 2021-14, "Integrated Human Event Analysis System Dependency Analysis Guidance (IDHEAS-DEP)" [3]. In comparison to existing dependency methods, IDHEAS-DEP [3] is better informed by cognitive and behavioral science. This paper provides a simplified overview of how to perform dependency analysis using IDHEAS-DEP [3]. IDHEAS-DEP [3] can be used to analyze the dependency between two human failure events (HFEs) that are in the same probabilistic risk assessment (PRA) event sequence. The method identifies and evaluates how failure of the first human action (HFE1) affects the context associated with the second human action (HFE2), which, in turn, affects the reliability of HFE2. In this document, dependency refers to the dependency between two HFEs.

1.1. Background

The IDHEAS-G dependency model evaluates dependency at the macrocognitive level and consists of three parts: (1) identifying whether a type of dependency exists such that occurrence of the preceding HFE (HFE1) changes the context of the subsequent HFE (HFE2), (2) determining how the identified type of dependency affects the context, e.g., critical tasks, cognitive failure modes (CFMs), performance influencing factors (PIFs) associated with HFE2, and (3) calculating the human error probability (HEP) of HFE2 based on changes to the context due to dependency. When dependency is present, occurrence of HFE1 typically impacts HFE2 by deteriorating certain PIFs associated with HFE2. Dependency can also cause additional PIFs or CFMs to be applicable to HFE2, or result in changes in time availability (i.e., the time required or time available to perform the human action) for HFE2. The impact of the change in context for HFE2 is modeled by applying additional CFMs, PIFs, or PIF attributes, increasing the PIF attribute levels, or changing the time available or time required parameters in IDHEAS-ECA [2].

The IDHEAS dependency model advances dependency analysis in that (1) the dependency evaluation explains what factors impact dependency because the evaluation is based on specific context changes and (2) calculation of the dependent HEPs is based on the same factors used for calculating individual HEPs. This process requires that one of the two HFEs being evaluated for dependency occurs before the other HFE. If the HFEs occur at the same time, the analyst must assume a time sequence in which one HFE occurs before the other. If more than two HFEs need to be evaluated for dependency, the analyst must break the HFEs into pairs based on the order in which they occur or their assumed time sequence.

1.2. Dependency Types

IDHEAS-G [1] identifies three types of dependency, as follows:

(1) Consequential dependency - Consequential dependency occurs when the outcome of an HFE directly affects the performance of subsequent HFEs. The outcome of HFE1 may affect various elements of HFE2, including HFE definition (e.g., HFE feasibility), critical tasks that must be performed, applicable CFMs, time availability, and applicable PIFs.

(2) Resource-sharing dependency - Resource-sharing dependency occurs when two HFEs share the same resources. Resource-sharing dependency can occur when HFE1 reduces the resources available for HFE2 or if the two HFEs are performed at the same time such that the combined demand for the resource exceeds what is available. Such dependency could change the feasibility of subsequent HFEs, the critical tasks to be performed, and the relevant CFMs and PIFs.

(3) Cognitive dependency - Cognitive dependency refers to the dependency in the cognitive flow of information for two consecutive HFEs. The cognitive flow includes detecting information, understanding the situation, making decisions, executing the actions, and coordinating the responses among different teams. The cognitive reason that HFE1 failed is also expected to impact HFE2.

1.3. Dependency Relationships

The dependency relationships describe how the occurrence of HFE1 affects HFE2. IDHEAS-DEP [3] defines the following five dependency relationships that can exist between HFEs:

(1) Functions or systems relationship (R1) - The functions or systems dependency relationship describes when HFE1 and HFE2 are performed using equipment that has the same functions, or equipment that is part of the same system. The same function means that both HFEs are performed with the same intended result, such as to restore core cooling, remove decay heat, or

restore power. The same system generally refers to an entire system, including all trains of equipment. However, if trains have different indications, controls, and equipment, some dependency impacts can be discounted.

(2) Time proximity relationship (R2) - The time proximity dependency relationship describes when HFE1 and HFE2 are performed close in time or the cues for HFE1 and HFE2 are received close in time. For performing actions, close in time means that the actions are performed close enough in time that there is a potential for HFE1 to impact the time availability for HFE2. For receiving cues, close in time means that the cues are received close enough in time that receipt of the second cue could be impacted. Actions for which the time available to perform the actions overlaps should be considered close in time.

(3) Personnel relationship (R3) - The personnel dependency relationship describes when the same personnel perform both HFE1 and HFE2. The same personnel can refer to a single person or a crew, depending on who is responsible for performing the action. For cognition actions, the entire crew or part of the crew may be responsible for decisionmaking because different people are detecting the information and choosing the correct procedure to enter. For execution actions, a single person is often responsible for the action but may direct other people to perform some of the steps in the procedure.

(4) Location relationship (R4) - The location dependency relationship describes when HFE1 and HFE2 are performed in the same location. This relationship can only exist when portions of the human action are performed in the same location. Same location refers to the same room or area when accessibility or habitability is a concern. The same location can be limited to the same physical location of the instrumentation and controls (such as a single panel) when distractions or interference are a concern. For example, the main control room should be considered as a single workplace when assessing habitability since noise, smoke, and temperature would impact all inhabitants; however, the MCR could be considered multiple locations when assessing the impact of performing actions at different panels if personnel would not distract or interfere with each other.

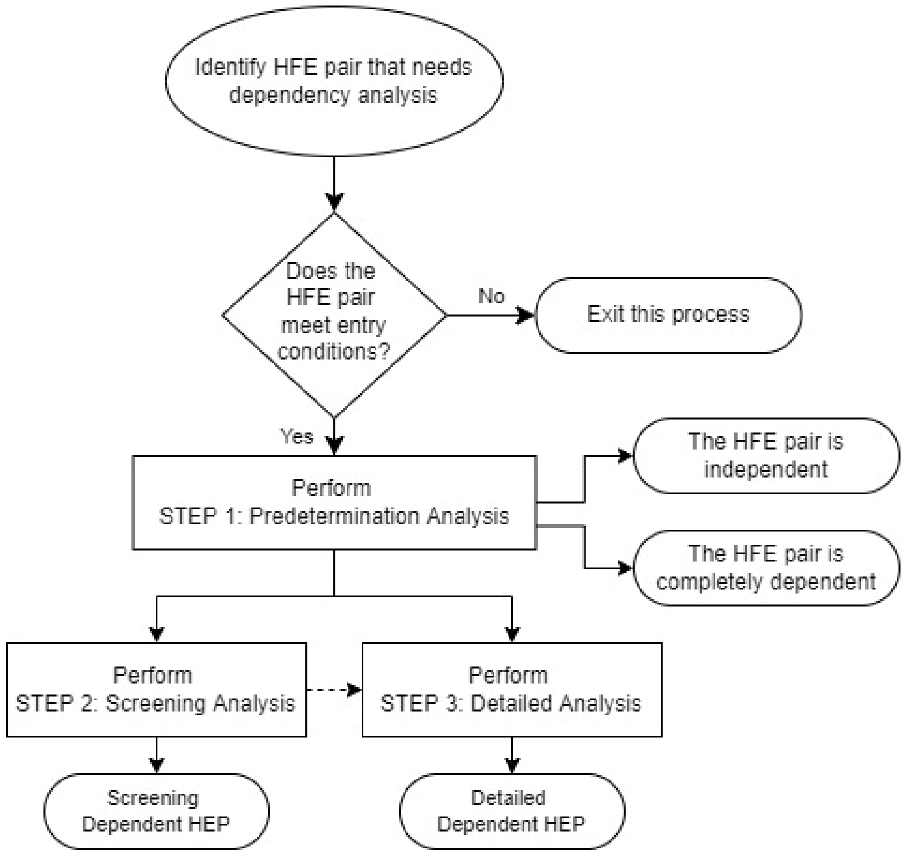
(5) Procedure relationship (R5) - The procedure dependency relationship describes when HFE1 and HFE2 are both performed using the same procedure. The same procedure can refer to a single procedure or a single part of a multisection or multisheet procedure, like an emergency operating procedure (EOP). If a procedure section has different entry conditions from other parts of the procedure (like independent sections of an operating procedure) or is executed by itself (like a leg of an EOP flowchart), it can generally be considered a different procedure.

2. DEPENDENCY ANALYSIS PROCESS

2.1. Overview

The dependency analysis process, as discussed in this paper, begins after the HFE pairs that require dependency analysis have been identified. Section 2.2 of this paper refers to this as “entry conditions.” If the entry conditions are met, the analyst proceeds to Step 1, Predetermination Analysis, which will determine whether the HFEs are completely dependent, independent, or require further evaluation. Further evaluation is performed using Step 2, Screening Analysis, or Step 3, Detailed Analysis. Figure 1 below shows an overview of the dependency analysis process.

Figure 1: Overview of the Dependency Analysis Process



The Predetermination Analysis (Step 1) identifies whether any dependency relationships are applicable to the two HFEs.

The Screening Analysis (Step 2) identifies the applicable dependency factors associated with each applicable relationship and assigns a value for each factor. During the Screening Analysis, the analyst only needs to evaluate the potential dependency factors for the relationships that were identified as applicable in the Predetermination Analysis. Each potential dependency factor represents a unique dependency consideration that can impact HFE2. Every dependency factor has a set of discounting factors that can be used to determine whether the potential dependency factor is applicable. The impact of each applicable (undiscounted) dependency factor on the probability of HFE2 is classified into three levels—Low, Medium, and High. Each level has a corresponding screening HEP (P_d). The adjusted probability of HFE2 is the probabilistic sum of the individual HEP of HFE2 (P_2) and the undiscounted dependency impacts (P_d). The outcome of Step 2 is the screening dependent HEP for HFE2.

The Detailed Analysis (Step 3) identifies additional critical tasks, CFMs, PIFs, PIF attributes, and time availability issues caused by the applicable dependency factors, and then recalculates the probability of HFE2 accounting for the impact of the dependency factors. The Detailed Analysis may be performed with or without performing a Screening Analysis. The outcome of Step 3 is the detailed dependent HEP for HFE2.

2.2. Entry Conditions

The dependency analysis process includes identifying minimal cutsets associated with an initiating event, determining which pairs of HFEs in each cutset require dependency analysis, and evaluating dependency for each HFE pair. IDHEAS-DEP [3] is intended to be used to evaluate dependency between HFEs in an HFE pair after the minimal cutsets have been developed and the HFE pairs requiring analysis in the minimum cutsets have been identified. The entry conditions for applying IDHEAS-DEP [3] are as follows:

(1) HFE1 and HFE2 are in the same PRA event sequence or minimal cutset, AND there are no relevant human action success events between HFE1 and HFE2 in the sequence, OR

(2) The initiating event is caused by human actions and is analyzed as the first HFE, such that the subsequent HFEs need to be assessed for dependency. These are also called at-initiators and are common in shutdown operations.

Dependency analyses will be conducted on HFE pairs that meet one of the two conditions above.

2.3. Predetermination Analysis

The Predetermination Analysis provides a quick assessment of whether a potential for dependency exists for the HFE pair being evaluated. Table 1 below is used to perform the Predetermination Analysis. The first column identifies the dependency relationship being considered. Each row assesses a single potential dependency relationship. The second (middle) column lists the guidelines used to assess whether the dependency relationship is applicable to the HFE pair being evaluated. The third (last) column documents the YES or NO answer to the assessment guideline questions in the second column. If YES is checked in the last column, the dependency relationship is applicable to the HFE pair being evaluated. The outcome of the Predetermination Analysis is that the HFE pair is either completely dependent, independent, or requires further evaluation to determine the dependency impact.

Table 1: Predetermination Analysis

Dependency Relationship	Assessment Guidelines	
Complete Dependency	(1) HFE1 and HFE2 use the same procedure, ***AND*** (2) HFE1 is likely to occur because of issues associated with the common procedure (such as having an ambiguous or incorrect procedure), ***AND*** (3) There is no opportunity to recover from the issue with the procedure between HFE1 and HFE2. Note: Opportunity for recovery may exist if there is adequate time to recover, ***AND*** steps are in the procedure to recover, ***AND*** additional personnel outside the crew, such as a shift technical advisor, are available to identify the need to recover.	□ YES □ NO
R1 — Functions or Systems	(1) HFE1 and HFE2 have the same functions or systems, ***OR*** (2) HFE1 and HFE2 have coupled systems or processes that are connected due to automatic responses or resources needed.	□ YES □ NO
R2 — Time Proximity	(1) HFE1 and HFE2 are performed close in time, ***OR*** (2) The cues for HFE1 and HFE2 are presented close in time.	□ YES □ NO
R3 — Personnel	(1) HFE1 and HFE2 are performed by the same personnel.	□ YES □ NO
R4 — Location	(1) HFE1 and HFE2 are performed at the same location, ***OR*** (2) The workplaces for HFE1 and HFE2 are affected by the same condition (such as low visibility, high temperature, low temperature, or high radiation).	□ YES □ NO
R5 — Procedure	(1) HFE1 and HFE2 use the same procedure.	□ YES □ NO

The Predetermination Analysis is performed as follows:

(1) Assess complete dependency first. If all the assessment guideline statements in the first row of Table 1 are met, then the HFE pair is completely dependent, the adjusted probability of HFE2 is set to 1.0, and the dependency analysis is complete. Otherwise, continue assessing each potential dependency relationship between HFEs.

(2) Assess R1, R2, R3, R4, and R5 individually by answering YES or NO to the assessment guideline statements in the middle column of Table 1. Each dependency relationship is evaluated in isolation. For example, when the analyst evaluates "function or systems," it is irrelevant to the analyst whether the function can be performed by the same or different personnel, at the same or different locations.

(3) If all the answers to the assessment guideline statements are NO, then HFE2 is independent of HFE1. The adjusted probability of HFE2 is equal to its individual HEP and the dependency analysis is complete. Otherwise, continue to the next step.

(4) If one or more answers to the assessment guideline statements are YES, then there is a potential for dependence between HFE1 and HFE2. The analyst may choose to perform Step 2, Screening Analysis, or Step 3, Detailed Analysis.

2.4. Screening Analysis

The Screening Analysis process is based on the idea that dependency relationships between HFEs can result in one or more dependency factors, and each dependency factor potentially impacts some PIFs associated with HFE2. The impact of each dependency factor on HFE2 is based on how occurrence of HFE1 changes the context for HFE2. If occurrence of HFE1 would not result in any changes to the context associated with HFE2 for the dependency factor being assessed, the dependency factor may be discounted. The discounted dependency factor is not considered for further analysis in the Screening Analysis process. If all the dependency factors for all the dependency relationships are discounted in the Screening Analysis, there is no impact on the HEP of HFE2 due to dependency using this process.

Each undiscounted dependency factor potentially results in new PIFs, new PIF attributes, or worsening of the PIF attributes that were originally assessed in the individual HEP of HFE2. Some PIF attributes impact HEPs more significantly than others. The Screening Analysis process focuses on evaluating the more significant PIF attributes. The Screening Analysis process groups the impact of the most likely affected PIF attributes for each dependency factor into "Low," "Medium," and "High" categories according to their impacts on the HEP and assigns a corresponding dependency impact value, P_d. The dependency impact values are based on IDHEAS-ECA [2].

The Screening Analysis is performed using Tables 2.1 through 2.5 in IDHEAS-DEP [3]. There is one table for each of the five dependency relationships. The first column of each table lists the potential dependency factors associated with each dependency relationship. The dependency factors are denoted by capital letters. Each row in the first column is for a single dependency type (cognitive, consequential, or resource-sharing) and dependency relationship (R1-R5) combination. The second (middle) column provides example justifications for discounting each dependency factor listed in the first column. The example justifications are labeled with letters corresponding to those used for the associated dependency factor in the first column. The third (last) column presents the impact of the dependency factors and example justifications for selecting a "Low," "Medium," or "High" dependency impact. Table 2 below shows a partial reproduction of Table 2.1 from IDHEAS-DEP [3] for the Cognitive Dependency Type and Functions or Systems Dependency Relationship combination (Combination R1.1).

Table 2: Screening Analysis Guidance for the Cognitive Dependency Type and Functions or Systems Dependency Relationship Combination

Potential Dependency Factors	Basis for Discounting the Potential Dependency Factor	Dependency Impact
R1.1 Same functions or systems leads to cognitive dependency A. Occurrence of HFE1 leads to the scenario or parts of the scenario being different from what was typically trained on; thus, the scenario associated with HFE2 becomes less familiar. (Note: Occurrence of HFE1 alters the scenario for HFE2; thus, HFE1 causes some level of unfamiliarity with HFE2.) B. Occurrence of HFE1 leads to an incorrect or biased mental model of the situation associated with HFE2.	□ A—HFE2 was trained on in the scenarios in which HFE1 occurs (e.g., Feed & Bleed is the last action after others fail), so there is no unfamiliarity due to HFE1. □ B—HFE2 is well trained on in various scenarios such that personnel are unlikely to develop a wrong mental model due to occurrence of HFE1. □ A/B—There is no cognitive link (similar thought process) between the two HFEs; thus, occurrence of HFE1 has no impact on scenario familiarity or the mental model associated with HFE2. □ B—There are opportunities between the HFEs to break the incorrect mental model, such as multiple crews or diverse cues.	This cognitive dependency affects the PIF for scenario familiarity, which addresses the mental model. Scenario familiarity is applicable when something is wrong with the mental model and no diverse methods are available to correct the wrong mental model. Low: P_d = 5E-2 □ Parts of the scenario become unfamiliar (e.g., different from what was trained on), ***OR*** □ HFE1 creates a biased mental model or preference for wrong strategies. Medium: P_d = 1E-1 □ Parts of the scenario become unfamiliar (e.g., different from what was trained on), ***AND*** □ HFE1 creates a biased mental model or preference for wrong strategies. High: P_d = 3E-1 □ HFE1 creates a mismatched or wrong mental model for HFE2 due to close cognitive links between HFE1 and HFE2 (i.e., thought process).

The Screening Analysis is performed as follows:

(1) For every dependency relationship assessed as YES in Table 1 as part of the Predetermination Analysis, assess all the potential dependency factors in the first column of the associated Table 2.1 through 2.5 of IDHEAS-DEP [3] for that dependency relationship. Each potential dependency factor is assessed individually.

(2) For each dependency factor being assessed, review the description of a single potential dependency factor in the first column and the corresponding description of the ways that factor can be discounted in the second column. Determine whether it is appropriate to discount the dependency factor. The dependency factor can be discounted if any of the discounting factors associated with that dependency factor apply. The analyst may use additional justifications to discount the dependency factors. If the analyst does not have sufficient information to discount a dependency factor, the potential dependency factor remains undiscounted.

(3) For every undiscounted dependency factor, use the example justifications in the last column to determine the dependency impact—Low, Medium, or High. The analyst can use additional justification to support their selection. The dependency impact values, and example justifications presented in the third column are adapted from the IDHEAS-ECA [2] PIF attributes that are affected by the applicable dependency factors. If the analyst does not have sufficient information to select the most likely dependency impact, the analyst should select "High" as the default dependency impact.

(4) Repeat steps 2 and 3 for each dependency factor that needs to be assessed.

(5) Calculate the dependent HEP of HFE2 by taking the probabilistic sum of the individual HEP of HFE2 (P_2) and each of the undiscounted dependency impact values (P_d), as follows:

$$\text{Dependent HEP of HFE2} = 1 - (1 - P_2)\prod_{i=1}^{m}(1 - P_{d_i}) = 1 - (1 - P_2)(1 - P_{d_1}) \dots (1 - P_{d_m}) \quad (1)$$

NOTE: When the dependency impact values are small, the screening dependent HEP can be approximated by summing the dependency impact values and the individual HEP of HFE2. This approximation should not be used when any "High" dependency impact values are applicable.

Table 3 summarizes the results that can be obtained using Tables 2.1 through 2.5 from IDHEAS-DEP [3] by showing the dependency impact that each dependency type and dependency relationship combination can have on HFE2.

Table 3: Summary of the Potential Dependency Factors and Dependency Impacts

HFE Relationship	Potential Dependency Factors	Dependency Impact			
		No Impact	Low	Medium	High
R1 — Functions or systems	**R1.1** Same functions or systems leads to cognitive dependency	0.0	5E-2	1E-1	3E-1
	R1.2 Same functions or systems leads to consequential dependency	0.0	1E-2	5E-2	2E-1
	R1.3 Same functions or systems leads to resource-sharing dependency	0.0	2E-3	1E-2	5E-2
R2 — Time proximity	**R2.1** Close time proximity in performing HFE1 and HFE2 leads to consequential dependency	Varies depending on the ratio of time available to time required (T_a/T_r) for performing HFE2			
		> 4 0.0	≥ 3 and ≤ 4 1E-3	≥ 2 and < 3 1E-2	≥ 1 and < 2 1E-1
	R2.2 Close time proximity in receiving the cues for HFE1 and HFE2 leads to consequential dependency	0.0	5E-3	5E-2	1E-1
R3 — Personnel	**R3.1** Same personnel leads to cognitive dependency	0.0	5E-2	1E-1	3E-1
	R3.2 Same personnel leads to consequential dependency	0.0	2E-3	1E-2	3E-2
	R3.3 Same personnel leads to resource-sharing dependency	0.0	2E-3	1E-2	5E-2
R4 — Location	**R4.1** Same location leads to consequential dependency	0.0	2E-3	5E-3	2E-2
	R4.2 Same location and time leads to consequential dependency	0.0	2E-3	5E-3	7E-3
R5 — Procedure	**R5.1** Same procedure leads to cognitive dependency	0.0	5E-3	5E-2	3.5E-1

2.5. Detailed Analysis

The Detailed Analysis uses IDHEAS-ECA to calculate the dependent HEP of HFE2 based on how occurrence of HFE1 changes the context associated with HFE2. The Detailed Analysis may be performed after the applicable dependency relationships are determined in the Predetermination Analysis (Step 1), or it may be performed after the screening dependent HEP is determined in the Screening Analysis (Step 2). If the Detailed Analysis is performed after performing the Screening Analysis, the undiscounted dependency factors identified in the Screening Analysis can be used to inform the Detailed Analysis. The Detailed Analysis is performed using Tables 4.1 through 4.5 of IDHEAS-DEP [3]. There is one table for each of the five dependency relationships. The first two columns of Tables 4.1 through 4.5 in IDHEAS-DEP [3] are the same potential dependency factors and discounting factors from the Screening Analysis. The last column is specific to the Detailed Analysis and lists the CFMs, PIFs, and PIF attributes that can potentially be impacted by the dependency factors.

If a Screening Analysis was performed, the Detailed Analysis is performed as follows:

(1) For every undiscounted dependency factor, use the last column of the respective Table 4.1 through 4.5 from IDHEAS-DEP [3] to determine which CFMs, PIFs, and PIF attributes are most likely impacted by dependency. Dependency could impact other CFMs, PIFs, and PIF attributes.

(2) Using the IDHEAS-ECA software, identify any new or changed CFMs, PIFs, and PIF attributes associated with HFE2 that could be impacted by occurrence of HFE1. If HFE2 has multiple critical tasks, review the CFMs for each critical task. If multiple CFMs are potentially impacted, review the PIFs and PIF attributes impacted for each CFM.

(3) If the time proximity dependency relationship (R2) is assessed as YES in Table 1 as part of the Predetermination Analysis, evaluate the impact of occurrence of HFE1 on the time available and time required to perform HFE2. If there is an impact, reestimate the probability distributions for the time available and time required for HFE2.

(4) Enter any changes in CFMs, PIFs, PIF attributes, and time availability using the IDHEAS-ECA software and recalculate the HEP of HFE2. The outcome of the recalculation is the detailed dependent HEP of HFE2.

3. CONCLUSION

This paper summarizes the guidance in IDHEAS-DEP [3] for applying the IDHEAS dependency model to assess the dependency between two HFEs. This dependency analysis process includes three main steps: Predetermination Analysis, Screening Analysis, and Detailed Analysis. This process provides the flexibility to accommodate different HRA methods and resource availability. The outcome of the Screening Analysis is a screening dependent HEP based on a quick assessment of potentially applicable dependency factors. The outcome of the Detailed Analysis is a detailed dependent HEP that identifies the specific CFMs, PIFs, and PIF attributes impacted by occurrence of the preceding HFE. Both the Screening Analysis and Detailed Analysis provide the dependent HEP of an HFE and identify the dependency relationships between the HFEs, dependency factors, and PIFs impacted by occurrence of the preceding HFE.

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