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Human Reliability Analysis using a Human Factors Hazard Model

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ABSTRACT

Human Reliability Analysis (HRA) has found application within a diverse set of engineering domains, but the methods used to apply HRA are often complicated, time-consuming, costly to apply, specific to particular (i.e., nuclear) applications, and are not suitable for direct comparison amongst themselves.

This paper proposes a Human Factors Hazard Model (HFHM), which builds an HRA method from the tools of Fault Tree Analysis (FTA), Event Tree Analysis (ETA), and a novel model of considering serial Human Error Probability (HEP) more relevant to psychomotor-intensive industrial and commercial applications such as manufacturing, teleoperation, and vehicle operation. The HEP approach uses Performance Shaping Factors (PSFs) relevant to human behavior, as well as specific characteristics unique to a system architecture and its corresponding operational behavior. The HFHM tool is intended to establish a common analysis approach, to simplify and automate the modeling of the likelihood of a mishap due to a human-system interaction during a hazard event.

The HFHM is executed commercial software tools (MS Excel and SysML) such that trade and sensitivity studies can be conducted and iterated automatically. The results generated by the HFHM can be used to guide risk assessment, safety requirements generation and management, design options, and safety controls within the system design architecting process. Verification and evaluation of the HFHM through simulation and subject matter expert evaluation illustrate the value of the HFHM as a tool for HRA and system safety analysis in a set of key industrial applications.

INTRODUCTION

An engineered system is comprised of numerous human, electrical, mechanical, and software components and subsystems. These system building blocks are combined together into a larger, more complex system, that is used to perform a function per a specified design intent. Human beings (human actors), along with all other components in the design, can interact with the system to respond to off- design behavior to avoid a hazardous situation that may evolve into an accident [2]. These human- system interactions play a significant role in determining the reliability and safety of a system throughout its lifecycle [3]. The combined functionalities and associated interactions of all system elements, including human elements, must be modeled, analyzed, and documented as a matter of Systems Engineering (SE) best practice. System Safety analysis asserts that the reliability and hazard characteristics of the system design must be evaluated and analyzed, with all of the identified potential hazards eliminated or minimized, such that a failure will not result in a catastrophic outcome. To be considered complete, this engineering analysis must consider the interactions and risks posed by all human actors within the system context. A consistent and uniform approach to analyzing the human contribution to safety throughout the system lifecycle management process is preferred.

The contemporary inductive perspective of System Safety analysis tends to emphasize scrutiny of the non-human elements (electrical, mechanical, software) that are combined into the larger system architecture [6][20]. Typically, the probabilistic failure rates of these various elements are determined, and then accounted for in the larger system arrangement using established Hazard Analysis Techniques (HAT's). The prospective failure modes and safety related concerns of a system are evaluated based on the results of these HAT activities and documented for future abatement during subsequent design and testing activities [6]. In addition to the electrical, mechanical, and software elements that are commonly recognized as the core building blocks of a system design, human actors and their respective influence on system operations can be of equal or even greater importance, to the performance, reliability, and safety within the system lifecycle [3]. Accident rates attributable to human activity in system operations range from 10%, to as high as 80% depending on the industry and application [7][13]. Also, of note, the National Highway Traffic Safety Administration (NHTSA) reports that human error is the cause of up to 94% of all ground transportation accidents [21]. Although sometimes overlooked or minimized during system analysis and design, the various human interactions within the system context, and their possible impact on safety, should be properly scrutinized, with potential hazard probabilities being quantified explicitly [13].

There is no universal or general technique to evaluate the hazards associated with human-system interaction [7][11]. Several Human Reliability Analysis (HRA) approaches have been developed, but they are typically complicated and time consuming to implement and are not designed to be applied across engineering disciplines or applications [14]. Instead, HRA approaches generally have specific application within certain industries, environments, or operational activities [7]. For example, HRA techniques such as the Technique for Human Error Rate Prediction (THERP) and Success Likelihood Index Method – Multiattribute Utility Decomposition (SLIM-MAUD) have their origins and primary usage in the nuclear power industries, with an emphasis on procedural control room activities. A technique such as Maintenance Personnel Performance Simulation (MAPPS) focus primarily on human hazard analysis as it relates to maintenance activities, and Aeronautical Decision-Making (ADM) is an analysis technique specific to pilot-flight control interface analysis [14][15][16].

Based on this understanding of the state of the field, the proposed Human Factors Hazard Model (HFHM) seeks to provide a novel, commonly applied, and efficient approach to assessing system risk associated with human interactions.

HAZARD ANALYSIS TECHNIQUES AND THEIR APPLICATION IN SYSTEM SAFETY ANALYSIS

System safety analysis as an activity within Systems Engineering (SE) has its origins in the early 1960's, with the earliest contributor being the Department of Defense (DOD) under MIL-STD-38130 (Safety Engineering of Systems & Associated Subsystems) which was later superseded by the current MIL-STD- 882 (Standard Practice – System Safety) [6][17]. Following the development of these guidelines, other agencies were quick to adopt these system safety philosophies including the Nuclear Regulatory Commission (NRC), as well as the

National Aeronautics and Space Administration (NASA). These techniques have gained widespread acceptance and use across government and commercial industries.

It is common to perform detailed safety analysis using one or more of the various analysis techniques that have been developed [6].

Over 100 different HAT approaches are listed in The System Safety Analysis Handbook published by the International System Safety Society (ISSS) [6]. However, only 10-20 different HATs are regularly used by system safety experts [6]. Among the most common HAT approaches utilized in safety analysis include Fault Tree Analysis (FTA) and Event Tree Analysis (ETA). Both FTA and ETA have direct application in Probabilistic Risk Assessment (PRA) and are used extensively to evaluate the likelihood of failure related to system design. Correspondingly, these two HATs are utilized as a significant building block of the analytical basis for the proposed Human Factors Hazard Model (HFHM) described in this work.

As an overview, FTA is a technique used to compile the failure probability of individual events into larger logic networks, accounting for the interdependency and combined probability of failure [6][18][19]. All FTAs are composed of basic events that are combined using AND/OR logic gates into intermediate events. These intermediate events are then combined using the same logic gate structure to determine the probability of the top-level event. The FTA approach is very useful for evaluating the overall likelihood of a particular failure with a quantified probability. The individual FTA results can then be used in subsequent safety analysis activities to assess the hazard event severity and possible negative consequences of the failure.

Unlike an FTA, an ETA is used to evaluate a sequence of independent, but related events, and their cumulative probability of concluding in a desired or undesired outcome [6]. Hence, the primary purpose of an ETA is to determine the probability that a series of sequential pivotal events will culminate in success or failure relative to specific scenario. For the events identified and analyzed using ETA, the probabilities of all possible outcomes (success or failure) are evaluated and documented.

The FTA / ETA combination forms the computational basis of this proposed Human Factors Hazard Model (HFHM). The HFHM requires the development of Human Error Probabilities (HEP's) that can be combined to determine the joint likelihood of failure for a top-level hazard event using an FTA. The four FTA analyses (corresponding to the four pivotal events of a human response model) are then evaluated in an ETA to determine the top-level probability of success (and failure) for the specified human / system interaction.

Human Reliability Analysis and Human Error Probability

As a field of study, Human Reliability Analysis (HRA) is conducted with the intent of describing human interactions with related system elements and documenting the associated risks and potential failure modes [4]. HRA is also intended to help develop corrective actions and other possible countermeasures intended to reduce or eliminate the possibility of human caused failures. A recent literature review indicates that there are approximately 38 documented and commonly used HRA methodologies in the public domain [7]. Along with the method proposed in this work, there continues to be ongoing proposals for HRA predictive tools using various qualitative and quantitative approaches [26][27].

Among the most commonly utilized and cited HRA techniques are the Technique for Human Error-Rate Prediction (THERP) and Expert Estimation [7].

THERP was developed for application in safety analyses related primarily to nuclear power plant operations [8]. THERP includes well defined procedural steps to hazard analysis, as well as a comprehensive library of Human Error Probabilities (HEP) associated with common human-system interactions. These documented HEP values include considerations of design characteristics including training efficacy, instrumentation interpretation, control system actuation, as well as other common human factors considerations such as fatigue, distraction, and stress effects and their influence on HEP.

Expert Estimation (also known as Expert Judgement) is a general HRA approach with several different basic techniques used to assess HEP values associated with specific human-system interaction. Four basic approaches used for Expert Estimation have been documented, and they include: (1) paired comparison, (2) ranking / rating, (3) indirect numerical estimation, and (4) direct numerical estimation. Paired comparison and ranking / rating approaches produce equivocal results. Indirect numerical estimation will establish a HEP by relative comparison based on the probabilities of failure determined for other events. The direct numerical estimation technique produces a specific HEP based on an expert or group of expert's estimations of the likelihood of a specific error due to the relevant human factors as well as system characteristics [7][9].

Performance Shaping Factors and Human Error Probability Prediction

The likelihood that a human actor will fail to perform or incorrectly perform a required task, possibly resulting in a mishap, is referred to as Human Error Probability (HEP). The development of an analytical model used to predict HEP is primarily dependent on consideration of human factors and system characteristics. These two elements are referred to as Performance Shaping Factors (PSFs). PSFs are used to calculate HEP relevant to specific operational scenarios. For example, the complexity of a system design, the human actor's knowledge of system operation, the actor's distraction and stress levels, and the nature of the off-design behavior of the system, will all contribute to the probability that the actor will react correctly to the system behavior, and successfully avoid a mishap. A non- comprehensive list of elements that represent human factors and system factors in PSFs are presented in Table 1 [7][11][12]. Typically, the characteristics of PSFs are drawn from established and widely cited Human Reliability Analysis (HRA) and human factors engineering sources [8][10]. The proposed Human Factors Hazard Model (HFHM) uses PSFs and their associated literature in calculating HEP values used to calculate the overall failure probability.

These sets of PSFs are used to develop the conditional and combined probabilities of failure that can be used to determine the HEP values for use in the HFHM. These HEP values are bookkept in the model and are used to produce a prediction of failure related to a given hazard scenario. In general, HEP calculations can be used in their baseline state, or can be modified based on other PSF characteristics. For example, the baseline probability of failure (HEP) due to an actor's intellectual capacity can be modified by their stress level, fatigue level, impairment characteristics, or other relevant PSF values.

When a modified HEP is to be considered, factors attributable to specific PSFs are multiplied to change the baseline probability of failure for the characteristics of the scenario. This calculation is of the form:

$$P_f' = (P_f)\prod_{n=1}^{i} M_n \qquad (1)$$

Where:

P_f' = Modified Event Probability of Failure
P_f = Initial Event Probability of Failure
M_n = Probability Modifier, or PSF, n
i = Total Number of Probability Modifiers Applied

Table 1: Examples of the set of Human and System Factors Used to Determine PSFs for HFHM's Industrial and Commercial Application Set

HUMAN FACTORS	SYSTEM FACTORS
Training	System Complexity
Practice	Hazard Event Timing
Experience	Hazard Event Duration
Mental Acuity	Observability of System Behavior
Intellectual Capacity	Annunciation of System Behavior / Alarms
Gross and Fine Motor Skills	Instrumentation Availability to Monitor System Behavior
Sensory Acuity (Smell, Vision, Hearing, Touch)	Input Control Capabilities
Fatigue, Vigilance, and Impairment Level	Input Control Accessibility to Actor
Stress and Emotional Stability	System Behavior Feedback Characteristics
Reaction Time	Environmental Conditions (Temperature, Illumination, etc.)
Location and Orientation of Actor withing System Context	System Fail-Safes
Negligence and Malevolent Intent	System Safeguards

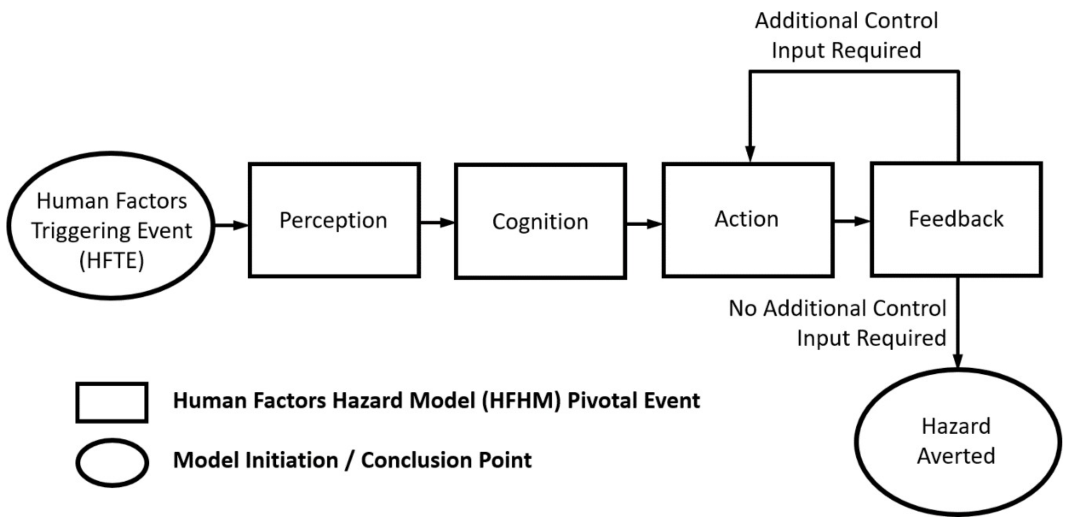

Figure 1: Hazard Event Human Response Model

When considering the chronology associated with the event from hazard initiation through a mishap or successful resolution, human reaction time is adjusted using a multiplier similar to the probability adjustments noted above. In this case, multipliers are not compounded, but applied individually, then summed to adjust the baseline human actor reaction time. If multipliers are used to modify the baseline reaction time, the calculation is of the form:

$$T_r' = T_r + \sum_{n=1}^{i} T_r(R_n - 1) \qquad (2)$$

Where:

T_r' = Modified Reaction Time

T_r = Baseline Reaction Time

R_n = Reaction Time Modifier or PSF, n

i = Total Number of Reaction Time Modifiers Applied

Using these modifications of the relevant baseline HEP values due to the unique PSFs of a given hazard scenario, the basic event probabilities are established for subsequent processing in individual Fault Tree Analyses (FTA's).

SUMMARY

Based on this understanding of the state of the field of HRA, we can identify the opportunities for development of a new model and process for human factors safety modeling. First, THERP (and its antecedents [8][7][15][28]) use a 1- or 2-stage model of human behavior that does not consider the multi-event feedback-inclusive nature of skilled human operation. The proposed HFHM embeds a computational architecture that implements a formal specification of the psychological theories of cognition, perception, and action [22][23][25][29], that are more complete for consideration of serial and psychomotor tasks. Second, many models of HRA are complicated to use and maintain. The classical methods are largely not computerized and are therefore inaccessible and costly for adaptation to minor commercial or industrial applications. HFHM provides both a MS Excel-based and SysML-based implementation of a relatively comprehensive HRA and extant PSF database, enabling modern document-based and model-based systems engineering application and scalability from small to large HRA problems [7][8][10].

THE HUMAN FACTORS HAZARD MODEL (HFHM)

The proposed Human Factors Hazard Model (HFHM) seeks to predict the likelihood of failure due to an actor's response to a Human Factors Triggering Event (HFTE), where the HFTE is defined as any interaction between a human being and the system which may result in a mishap [1]. The conceptual model of the steps involved in predicting the human response to an HFTE is a serial processing approach as illustrated in Figure 1. First, the event must be perceived and recognized as a hazard. Second, the actor will cognitively process the available observed information, and then establish a corrective action plan. Third, a planned remedial action by the actor is then communicated to the system via control inputs, and the subsequent system behavior response is then observed. Fourth, based on the system feedback behavior due to control input, the actor must decide whether to terminate control input because the hazard has been resolved, or continue to provide additional control corrections in an effort to eliminate the hazardous behavior completely. Each stage of the process detailed above in Figure 1 (Perception, Cognition, Action, and Feedback), indicates a point in the hazard sequence where a possible human failure could result in a mishap. This sequential approach to human information processing is a widely accepted model used to map a response in discrete, identifiable steps [22][23]. As an example, if the actor perceives the hazard event, but subsequently does not cognitively process it correctly, concluding that corrective action is necessary, the series of events will not progress to the action step, and thus, the HFTE will end in a mishap.

COMPONENTS OF THE HFHM

Under the proposed Human Factors Hazard Model (HFHM) technique, each of the individual pivotal events of Figure 1 are modeled using an embedded Fault Tree Analysis (FTA). The probability of success (or failure) for each of the four pivotal events are predicted via the FTA logic networks composed of basic events determined from the human factors and system characteristics (PSFs) unique to the problem being analyzed. The individual FTAs are each based on an evaluation of probability of failure associated with combinations of the various contributing events due to human interaction with the system. The set of failures considered and modeled in each FTA are derived from the set of HRA-derived failures [7][8][10] that the authors have considered relevant to a broad set of industrial and commercial applications. While this set is not comprehensive, it includes a broad set of human failure events that are relevant to HFHM's set of industrial and commercial applications, referencing the broad literature on HFA [8][9][10].

Each basic event probability of failure is evaluated using Boolean logic, through intermediate events, to subsequently arrive at a combined top-level probability of failure. The relevant symbols used in the HFHM Fault Tree Analysis logic networks are presented in Figure 2.

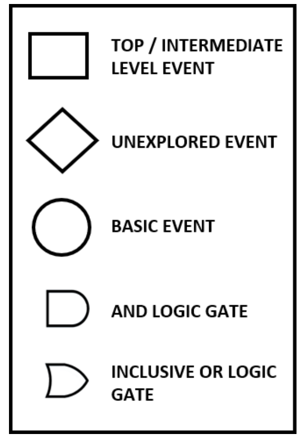

Figure 2: FTA Event Symbol Key

The assignment of AND/OR logic within the FTA model is dependent upon the interrelation of the events being considered. For example, if a visual hazard signal is generated both by observable system behavior as well as instrumentation communication to a control panel indicator, both events must fail for the actor to not receive information communicating the unfolding hazard event. Thus, an "AND" gate to model this scenario would be an appropriate approach to combined probability. Conversely, if no inherent redundancy exits within the relationship of events, an Inclusive "OR" would be appropriate, indicating that any individual or combination of failures would signal a failure at the next highest level within the FTA.

As noted, the HFHM utilizes four different FTAs to model human actor response to a Human Factors Triggering Event (HFTE). Each of these four FTAs represent the pivotal events (Perception, Cognition, Action, and Feedback) associated with human response to a hazard, as noted in Figure 1. All of the basic events introducing failure probabilities into their corresponding FTAs determine their respective values from the PSF information used to modify baseline HEP values using equations (1) and (2) as defined above.

The FTA corresponding to the **Perception** pivotal event is presented in Figure 3 and Table 2. The FTA corresponding to the **Cognition** pivotal event is presented in Figure 4 and Table 3. The FTA corresponding to the **Action** pivotal event is presented in Figure 5 and Table 4. The FTA corresponding to the **Feedback** pivotal event is presented in Figure 6 and Table 5.

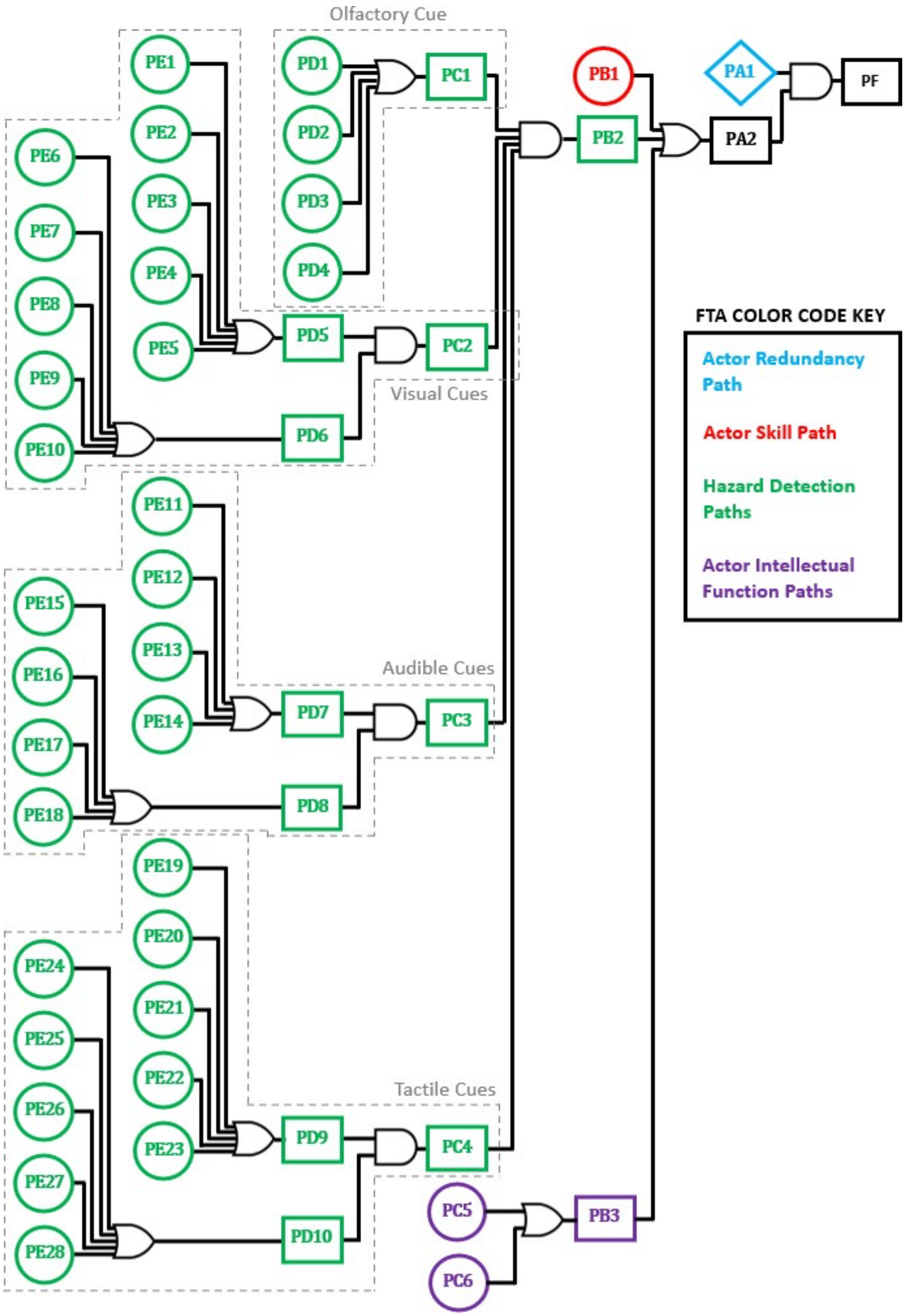

Figure 3: HFHM Perception FTA Used to Model the Probability of Fault for the Operator to be Unable to Perceive the Hazard

Table 2: HFHM Perception FTA Label, Descriptions, and Logic Gate Types

PERCEPTION PIVOTAL EVENT FTA NETWORK							
LABEL, EVENT DESCIPTION, AND EVENT LOGIC NETWORK GATE TYPE							
PF						Top Level Event	AND
	PA1					Redundant Actors	N/A
	PA2					Single Actor	OR
		PB1				Actor Skill	N/A
		PB2				Hazard Detection Cue	AND
			PC1			Olfactory Hazard Cue	OR
				PD1		Timing	N/A
				PD2		Location	
				PD3		Sensory	
				PD4		Olfactory Cue	
			PC2			Visual Hazard Cue	AND
				PD5		System Behavior Cue	OR
					PE1	Timing	N/A
					PE2	Location	
					PE3	Orientation	
					PE4	Sensory	
					PE5	Signal	
				PD6		Instrumentation Cue	OR
					PE6	Timing	N/A
					PE7	Location	
					PE8	Orientation	
					PE9	Sensory	
					PE10	Signal	
			PC3			Audible Hazard Cue	AND
				PD7		System Behavior Cue	OR
					PE11	Timing	N/A
					PE12	Location	
					PE13	Sensory	
					PE14	Signal	
				PD8		Alarm Cue	OR
					PE15	Timing	N/A
					PE16	Location	
					PE17	Sensory	
					PE18	Signal	
			PC4			Tactile Hazard Cue	AND
				PD9		System Behavior Cue	OR
					PE19	Timing	N/A
					PE20	Location	
					PE21	Orientation	
					PE22	Sensory	
					PE23	Signal	
				PD10		Control System Cue	OR
					PE24	Timing	N/A
					PE25	Location	
					PE26	Orientation	
					PE27	Sensory	
					PE28	Signal	
		PB3				Actor Intellectual Function	OR
			PC5			Actor Mental Acuity	N/A
			PC6			Actor Attention	

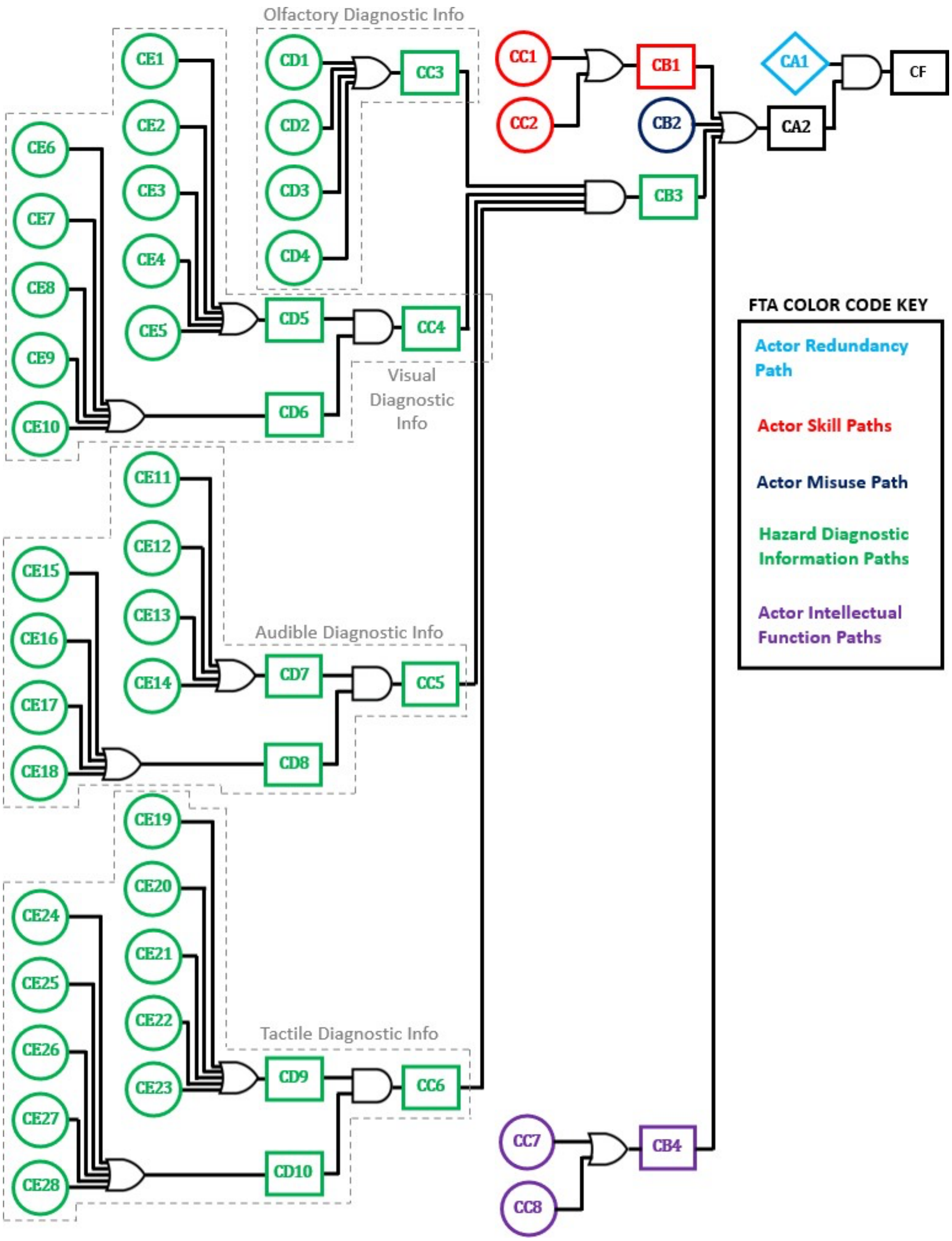

Figure 4: HFHM Cognition FTA Logic Network Used to Model the Probability of Fault for the Operator to be Unable to Cognitively Process the Hazard

Table 3: HFHM Cognition FTA Label, Descriptions, and Logic Gate Types

COGNITION PIVOTAL EVENT FTA NETWORK		
LABEL	**EVENT DESCIPTION**	**LOGIC NETWORK GATE TYPE**
CF	Top Level Event	AND
CA1	Redunant Actors	N/A
CA2	Single Actor	OR
CB1	Actor Skill	OR
CC1	Timing	N/A
CC2	Diagnostic Approach	
CB2	Misuse	N/A
CB3	Hazard Diagnostic Information	AND
CC3	Olfactory Diagnostic Information	OR
CD1	Timing	N/A
CD2	Location	
CD3	Sensory	
CD4	Signal	
CC4	Visual Diagnostic Information	AND
CD5	System Behavior Information	OR
CE1	Timing	N/A
CE2	Location	
CE3	Orientation	
CE4	Sensory	
CE5	Signal	
CD6	Instrumentation Information	OR
CE6	Timing	N/A
CE7	Location	
CE8	Orientation	
CE9	Sensory	
CE10	Signal	
CC5	Audible Diagnostic Information	AND
CD7	System Behavior Information	OR
CE11	Timing	N/A
CE12	Location	
CE13	Sensory	
CE14	Signal	
CD8	Alarm Information	OR
CE15	Timing	N/A
CE16	Location	
CE17	Sensory	
CE18	Signal	
CC6	Tactile Diagnostic Information	AND
CD9	System Behavior Information	OR
CE19	Timing	N/A
CE20	Location	
CE21	Orientation	
CE22	Sensory	
CE23	Signal	
CD10	Control System Information	OR
CE24	Timing	N/A
CE25	Location	
CE26	Orientation	
CE27	Sensory	
CE28	Signal	
CB4	Actor Intellectual Function	OR
CC7	Actor Mental Acuity	N/A
CC8	Actor Attention	

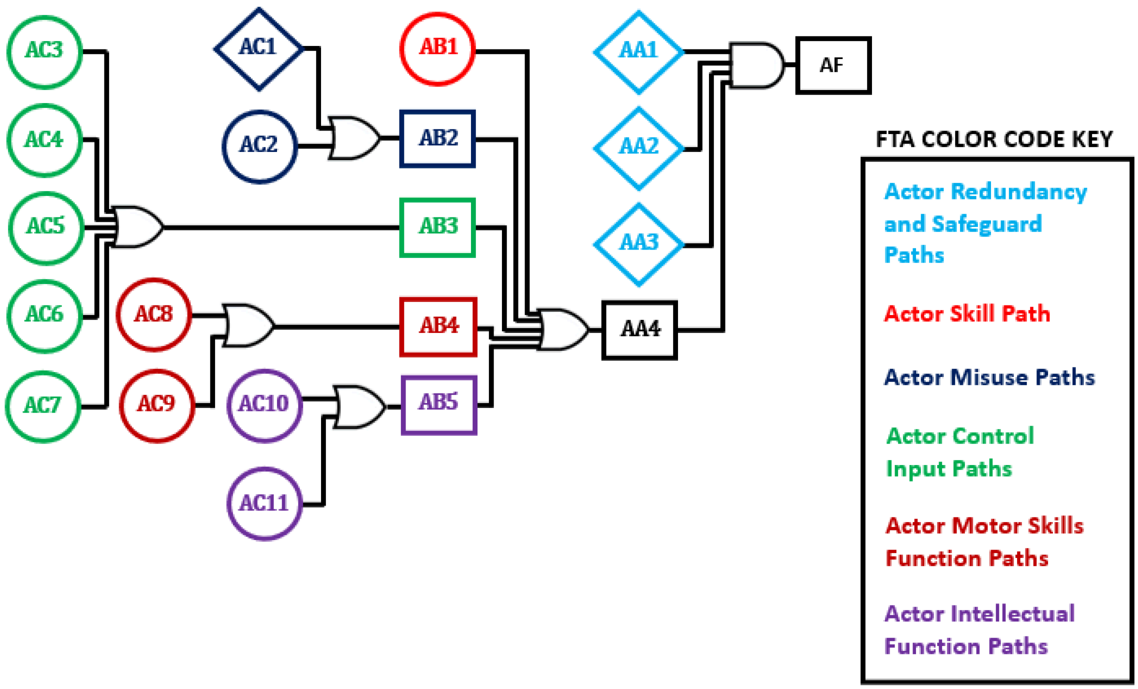

Figure 5: HFHM Action FTA Logic Network Used to Model the Probability of Fault for the Operator to be Unable to Correctly Apply Input Control to Correct the Hazard Behavior

Table 4: HFHM Action FTA Label, Descriptions, and Logic Gate Types

ACTION PIVOTAL EVENT FTA NETWORK					
LABEL, EVENT DESCIPTION, AND LOGIC NETWORK GATE TYPE					
AF	Top Level Event				AND
	AA1	Redundant Actors			
	AA2	Software Safeguards			N/A
	AA3	Hardware Safeguards			
	AA4	Single Actor			OR
		AB1	Actor Skill		N/A
		AB2	Misuse		OR
			AC1	Intentional Misuse	N/A
			AC2	Malevolence	
		AB3	System Control Input		OR
			AC3	Timing	
			AC4	Location	
			AC5	Orientation	N/A
			AC6	Sensory	
			AC7	Control Interface	
		AB4	Actor Motor Skills Function		OR
			AC8	Gross Motor Skills	N/A
			AC9	Fine Motor Skills	
		AB5	Actor Intellectual Function		OR
			AC10	Actor Mental Acuity	N/A
			AC11	Actor Attention	

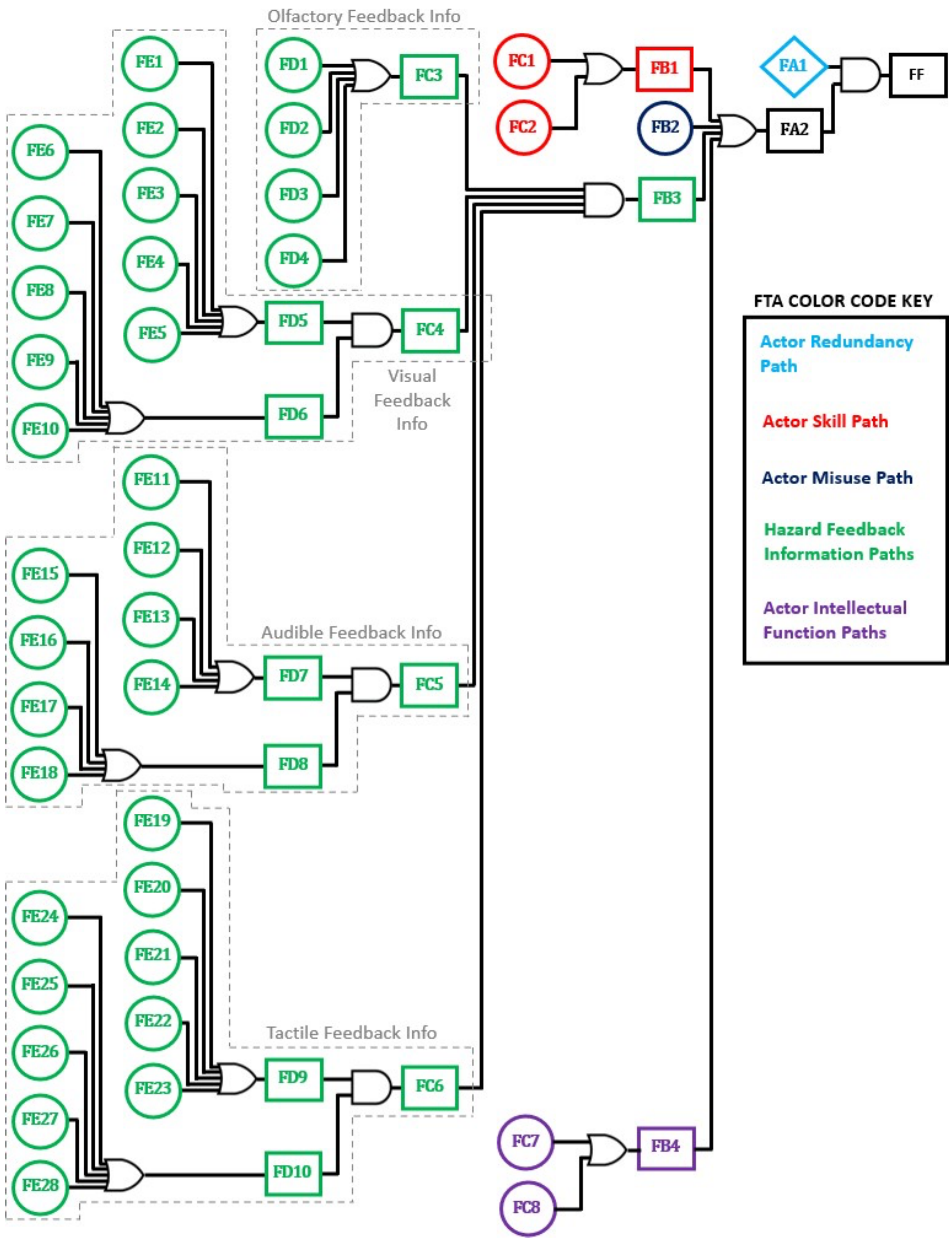

Figure 6: HFHM Feedback FTA Logic Network Used to Model the Probability of Fault for the Operator to be Unable to Receive and React Correctly to System Feedback Generated by Prior Input Control Action

Table 5: HFHM Feedback FTA Label, Descriptions, and Logic Gate Types

FEEDBACK PIVOTAL EVENT FTA NETWORK							
LABEL, EVENT DESCIPTION, AND LOGIC NETWORK GATE TYPE							
FF						Top Level Event	AND
	FA1					Redunant Actors	N/A
	FA2					Single Actor	OR
		FB1				Actor Skill	OR
			FC1			Timing	N/A
			FC2			Feedback Interpretation	
		FB2				Misuse	N/A
		FB3				Hazard Feedback Information	AND
			FC3			Olfactory Feedback Information	OR
				FD1		Timing	N/A
				FD2		Location	
				FD3		Sensory	
				FD4		Signal	
			FC4			Visual Feedback Information	AND
				FD5		System Behavior Information	OR
					FE1	Timing	N/A
					FE2	Location	
					FE3	Orientation	
					FE4	Sensory	
					FE5	Signal	
				FD6		Instrumentation Information	OR
					FE6	Timing	N/A
					FE7	Location	
					FE8	Orientation	
					FE9	Sensory	
					FE10	Signal	
			FC5			Audible Feedback Information	AND
				FD7		System Behavior Information	OR
					FE11	Timing	N/A
					FE12	Location	
					FE13	Sensory	
					FE14	Signal	
				FD8		Alarm Information	OR
					FE15	Timing	N/A
					FE16	Location	
					FE17	Sensory	
					FE18	Signal	
			FC6			Tactile Feedback Information	AND
				FD9		System Behavior Information	OR
					FE19	Timing	N/A
					FE20	Location	
					FE21	Orientation	
					FE22	Sensory	
					FE23	Signal	
				FD10		Control System Information	OR
					FE24	Timing	N/A
					FE25	Location	
					FE26	Orientation	
					FE27	Sensory	
					FE28	Signal	
		FB4				Actor Intellectual Function	OR
			FC7			Actor Mental Acuity	N/A
			FC8			Actor Attention	

The four FTA logic networks are designed to calculate the associated probability of failure for the top- level event based on the modified HEP values and all intermediate probabilities calculated in the logic network. The corresponding probability of success for each top-level FTA is:

$$S = 1 - F \quad (3)$$

Where:

S = Event Probability of being Successful

F = Event Probability of being Unsuccessful (Failure)

Using the values for probability of success, as calculated using equation (3). The Event Tree Analysis (ETA) then calculates the probability of success and failure for each sequential event. The logical basis of the ETA assumes that each pivotal event must occur in order, without failure, for an ultimate successful outcome. In the case of the HFHM, all four events must successfully occur sequentially for the HFTE to be resolved. If any individual pivotal event experiences a failure, then all subsequent events are null, and the HFTE has resulted in a mishap. Per this logic network, each individual pivotal event is considered to be mutually exclusive in that any individual failure precludes success for all subsequent events. The logic network and associated mathematical basis of the ETA is presented in Figure 7. Where PF, CF, AF, and FF are failure probability inputs from each respective FTAs.

In summary, the HFHM model allows for users to model human error in considering overall system performance. The characteristics of the system design and human actor are used to determine Performance Shaping Factors (PSFs) and the related modified HEPs. The modified HEP values are then used as the basic event probabilities that are utilized at the entry levels of the four FTA networks. In cases where the human factors and system characteristics are considered to be standard and universally applicable, the baseline HEP values can be derived from existing literature [8][10]. When certain PSF values are more specialized and standard values are not universally established or published, the HEP values can be based on an Expert Estimation / Expert Judgement approach [9]. For unique cases, where empirical data for specific operational scenarios have been derived, the HEP values can be directly specified in the HFHM. Once the individual HEPs are determined, and the respective pivotal event FTAs are calculated, ETA is then used to determine the cumulative probabilities of the individual pivotal events and calculate the overall

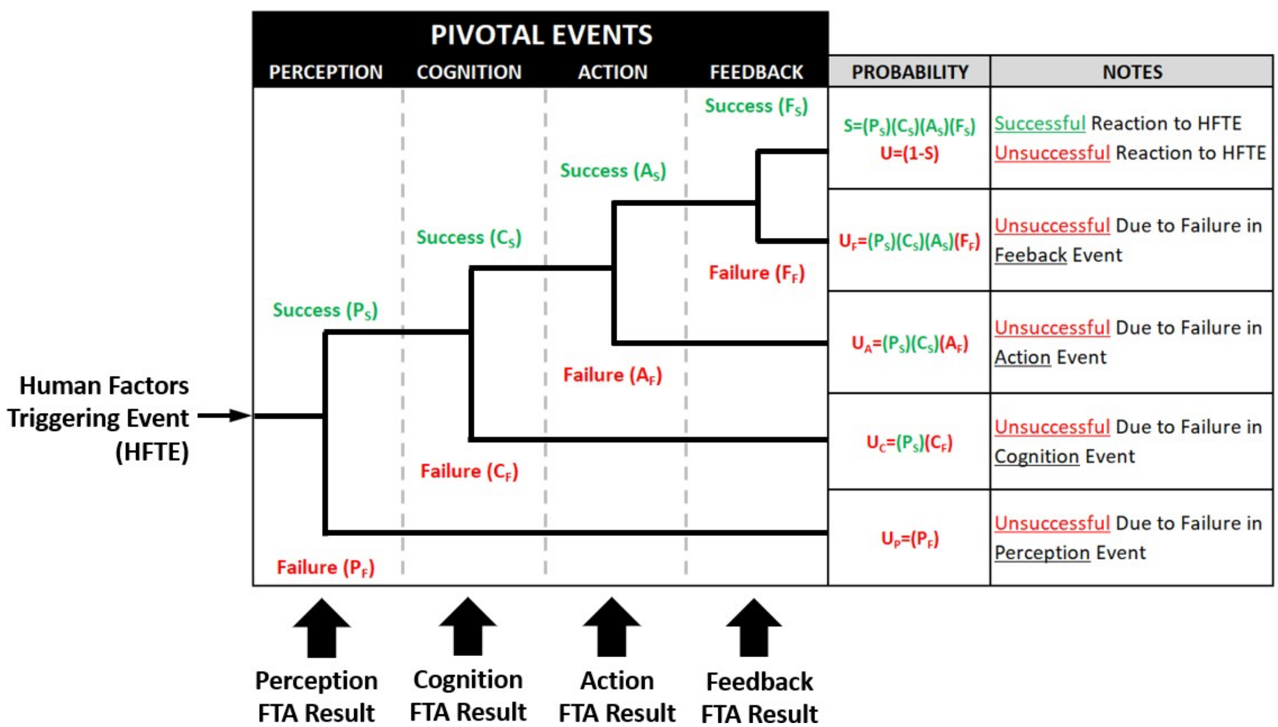

Figure 7: HFTE Sequential Processing Model ETA

probability of human error for the HFTE under consideration.

THE HUMAN FACTORS HAZARD MODEL (HFHM) AUTOMATED SOFTWARE INTERFACE

A large number of calculations are required to establish the Performance Shaping Factors (PSFs) and associated Human Error Probability (HEP) values that feed into the individual Fault Tree Analysis (FTA) models. Additionally, the associated quantity of calculations required to establish all intermediate and top-level probabilities in the FTA and ETA networks are also voluminous. Several thousand individual calculations are required to complete any single design iteration of the HFHM. Performing these calculations manually would require a large amount of time and would likely be prone to errors. The HFHM must therefore rely on a computational platform to efficiently produce results. Microsoft Excel, the spreadsheet software that is included as part of the standard MS Office software suite, was selected to be used as the analytical foundation of the HFHM model. MS Excel is commonly available, and many users are familiar with the software. The structure and functional flow of the HFHM within the spreadsheet software is presented in Figure 8.

As illustrated in Figure 8, Step (1) involves the primary user interface where information specific to the human factors being analyzed as well as characteristics of the system design are entered into the program. The information specified at this step is typically derived from three possible sources. These include:

- Source material (literature derived values from established HRA methods or documented human behavior databases).
- Expert Estimation values based on standardized value of HEP.
- User defined values as determined by the specific hazard scenario circumstances, experimentally derived data, or custom determined human error probabilities.

For programs that pull HEP data from published sources, Step (2) executes the algorithms that utilize the human factor (HF) and system factor (SF) data to define the relevant PSF's used to modify the various HEP's that are then passed to the FTAs of the four pivotal events. As previously discussed, the PSF modifying factors used to adjust baseline HEP values are defined in equations (1) and (2) above. If Expert Estimation or user specified probabilities are specified in Step (1), then the HEP data flows directly into Step (3) without modification. Step (3) includes all four FTAs used to predict the likelihood of failure due to the corresponding pivotal events, namely: Perception, Cognition, Action, and Feedback. The probabilities calculated in the FTAs of Step (3), are

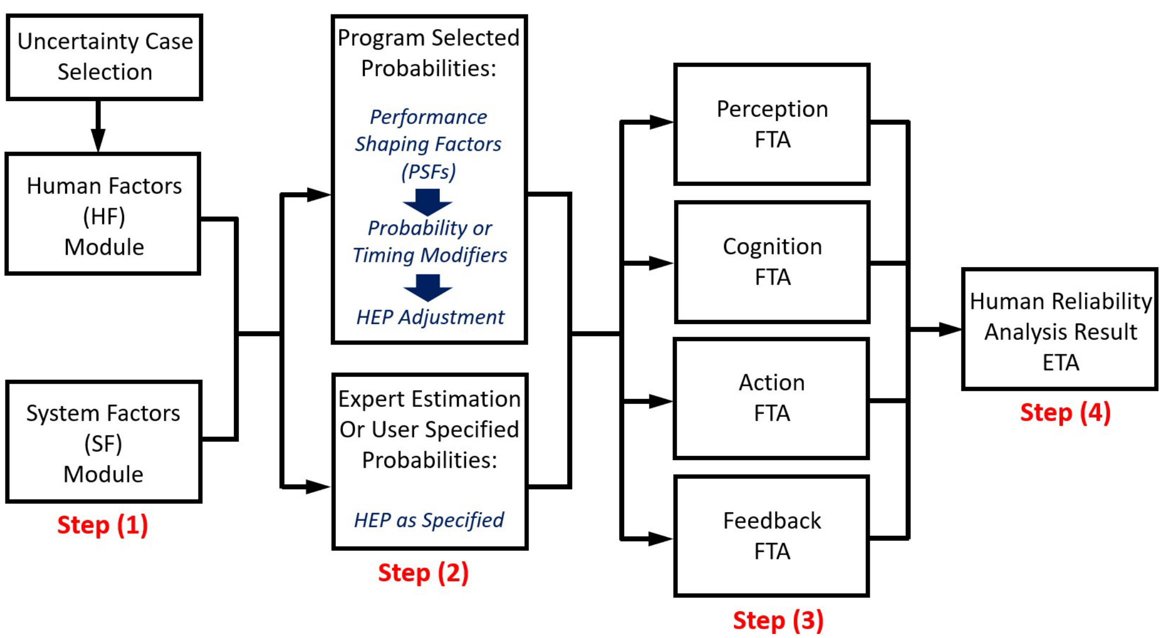

Figure 8: HFHM Software Functional Diagram

then passed to the Event Tree Analysis (ETA) in Step (4) to calculate the overall probability of success (and failure) attributable to the human actor's response the hazard event.

As with all probabilistic analyses, statistical uncertainty is present in all HEP determinations. Uncertainty within the Human Factors Hazard Model (HFHM) can be represented to model a maximum possible (worst case), minimum possible (best case), and most likely (nominal) probability of failure for Human Error Probability (HEP) calculations. Any of these three cases can be specified by the HFHM user in their initial analysis specification. As illustrated in Figure 8, based on user selection of best case, worst case, or most likely case, the entire series of HEP will be calculated and the probabilities will be reported accordingly in the HFHM. As recommended in the Technique for Human Error-Rate Prediction (THERP) [8], uncertainty in the HEP calculations is accomplished by using an Error Factor (EF), that is applied to the nominal (most likely) HEP value. The maximum possible probability of failure is calculated using:

$$P_{max} = P_{nom}(EF) \qquad (4)$$

Where:

P_{max} = Maximum Event Probability
P_{nom} = Nominal Event Probability
EF = Contributing Event Probability of Failure

Using an identical Error Factor, the minimum possible probability of failure is calculated using:

$$P_{min} = \frac{P_{nom}}{(EF)} \qquad (5)$$

Where:

P_{min} = Minimum Event Probability
P_{nom} = Nominal Event Probability
EF = Contributing Event Probability of Failure

The Error Factors used to establish uncertainty in the model are specified by the user in one of three ways: first, when published HEP data is utilized by the program the associated Error Factor is also selected from that source data. If a probability is selected from the standard Expert Estimation values, a corresponding standard Error Factor is automatically selected for the HEP value used. For user specified HEP entries, the analyst is also required to provide an associated Error Factor to use in the uncertainty calculation. The HFHM analyst selects which extreme case is desired to be calculated (best, or worst) at Step (1), and equations (4) and (5) are used to establish HEP values throughout the model, otherwise the original HEP value is utilized in the model for the most likely case.

VERIFICATION AND EVALUATION OF THE HUMAN FACTORS HAZARD MODEL (HFHM)

Verification is an important aspect of ensuring that a given simulation of a model is accurate and applicable for its intended uses. In this section, we document the verification of HFHM through its quantitative comparison to a baseline conceptual model of HEP developed using the Technique for Human Error-Rate Prediction (THERP). As one of the additional important aspects of HFHM is its usability, this research also executed a survey of systems engineers who would be expected to execute HFHM in industrial, and commercial settings. These can be analyzed numerically and narratively for evidence of the usability of the HFHM tool. Finally, HFHM is evaluated through demonstration in an industrial manufacturing test case.

VERIFICATION OF HFHM BY COMPARISON TO THERP

Quantitative verification of the HFHM analysis is supported through the direct comparison of HFHM results against results derived using THERP. A validation case was established incorporating elements typical of a Human Factors Triggering Event (HFTE). The HFTE included an assumed hypothetical hazard event, communication of system behavior to a human actor via visual and audible signals, cognitive processing by the actor to establish a corrective action response, control system input, and feedback resulting from control system input. A typical HRA event tree was established for the probability analysis per THERP methodology [5][8]. The validation case event tree is presented in Figure 9.

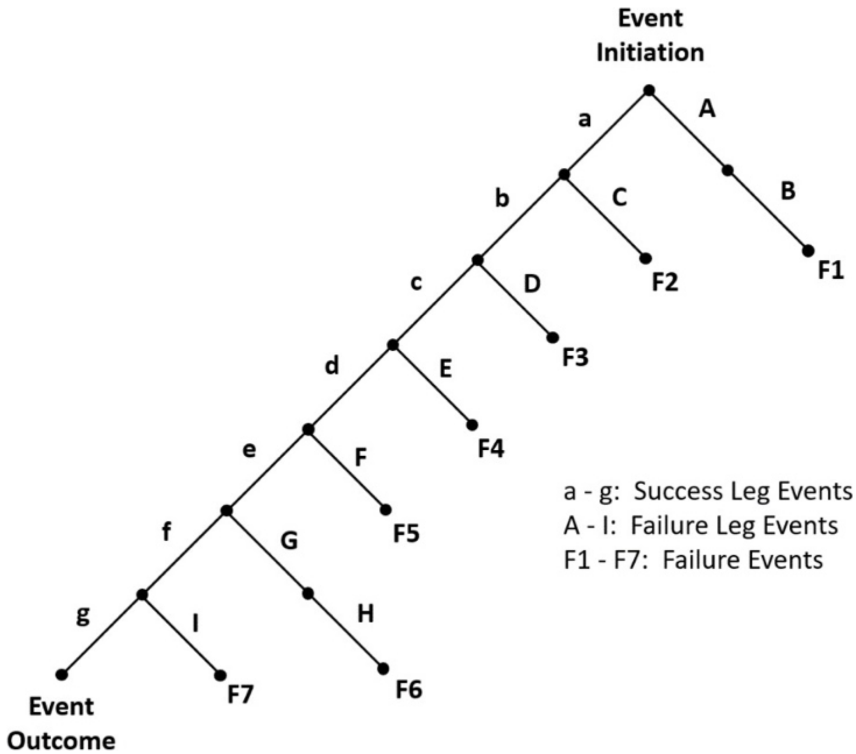

Figure 9: THERP Verification Model Event Tree

For the event specified in Figure 9, several opportunities for a failure related to human interaction with the system are detailed. The possible failure legs are labeled in the HRA event tree as event A-I. Each failure leg represents an opportunity for the human actor interacting with the system to correctly or incorrectly respond to system behavior. For each failure leg, the actor is required to either successfully receive a signal from the system, process that signal, provide appropriate input action to the system, or interpret system feedback relevant to the control input rendered. The various human-system interactions that correspond to these possible failure legs are presented in Table 6.

Several permutations of the baseline case were then established by modifying various human and system factors, thus altering the Performance Shaping Factors (PSFs). These factors include various actor stress levels, training and practice parameters related to the human actor, and instrumentation and control interface organization and ergonomics. Each new human and system factor noted establish revised PSFs that are then used to modify Human Error Probability (HEP) for the various permutations of the baseline

Table 6: THERP Verification Model Failure Leg Event Descriptions

PROBABILITY TREE - FAILURE LEG	DESCRIPTION
A	Recognize Alarm
B	Recognize Indicator Lamp
C	Read Pressure Gage (Analog Meter)
D	Diagnose Hazard
E	Actuate Control (Push Button)
F	Actuate Control (Rotary Dial)
G	Recognize Alarm Shut-Off
H	Recognize Indicator Shut-Off
I	Cease Control Input

Table 7: Human and System Factors Used to Establish PSFs

PERFORMANCE SHAPING FACTOR (PSF)	DESCRIPTION
1	System Training w/ Hazard Practice
2	System Training w/o Hazard Practice
3	Instrumentation & Controls are Organized or Stereotyped
4	Instrumentation & Controls are not Organized or Stereotyped
5	Optimum Stress
6	Extremely High Stress

analysis. As the human and system factors are adjusted in both analyses (THERP and HFHM), the resulting top-level probabilities of success and failure will adjust accordingly. A list of the various human and system factors used to establish the PSFs that are present in the comparative study are presented in Table 7.

As a result of the variations applied to the baseline case, a total of eight operational scenarios are evaluated using THERP and compared with corresponding HFHM analyses. The analysis results for each permutation of the baseline model, utilizing the baseline and updated values are presented in Table 8.

Good agreement between the failure probabilities as calculated by THERP and the HFHM are demonstrated in this verification study. The average variability between the THERP and HFHM probability of success results, over the eight different trial cases, is 4.8%. The ranges of variability between the THERP and HFHM solutions are between a minimum of 0.1% and a maximum 11.5% depending on the exact combinations of PSF employed in the analysis.

These results provide quantitative evidence of the applicability of HFHM to THERP's application domain, and a quantitative estimate of the verification error of HFHM relative to baseline tools in the field.

SUBJECT MATTER EXPERT EVALUATION OF THE HFHM

Evaluation of the Human Factors Hazard Model (HFHM) was accomplished via testing, assessment, and feedback provided by a total of six engineering Subject Matter Experts (SME) with professional positions. The assessment team consisted of personnel representing Systems Engineers and Systems Engineering managers of a large, publicly traded defense and aerospace corporation, production and plant design managers of a mid-sized, privately owned aerospace products corporation, and a former facilities operations manager of a large public university and current faculty member of the Construction Management department at a public 4-year university. A sample size of six evaluators is considered adequate to achieve meaningful feedback in eliciting qualitative input from highly qualified SMEs [24].

Table 8: THERP and HFHM Analysis Results Comparison for All Design Study Cases

	PROBABILITY OF SUCCESS							
	PERFORMANCE SHAPING FACTOR (PSF) COMBINATIONS							
PROBABILITY TREE - SUCCESS LEG	1-3-5	1-3-6	1-4-5	1-4-6	2-3-5	2-3-6	2-4-5	2-4-6
a	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
b	0.997	0.997	0.970	0.970	0.997	0.997	0.970	0.970
c	0.999	0.990	0.999	0.990	0.990	0.900	0.990	0.900
d	1.000	1.000	0.995	0.995	1.000	0.995	0.995	0.995
e	0.999	0.999	0.990	0.990	0.999	0.999	0.990	0.990
f	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
g	0.999	0.990	0.999	0.990	0.990	0.900	0.990	0.900
THERP Probability of Success=	0.994	0.976	0.954	0.936	0.976	0.803	0.936	0.774
HFHM Probability of Success=	0.986	0.908	0.973	0.895	0.950	0.878	0.938	0.863
Agreement Between THERP & HFHM=	0.7%	7.5%	2.0%	4.6%	2.7%	9.4%	0.1%	11.5%
							Average Agreement Between Approaches=	4.8%

None of the Systems Engineering SMEs are experts in HRA, and therefore are making comparisons and evaluations relative to their needs to design and build human-machine systems in the aerospace, construction, and manufacturing applications. The methods and results of their evaluations are summarized below.

The HFHM software was presented and demonstrated to the SMEs. The SMEs were then requested to test the software's functionality in their applications of interest, using their self-designed case studies representing the application of the model to their specific industries and job responsibilities. Following their evaluation of the HFHM, the participants responded to a survey to identify their opinions on the function and fit for purpose of the HFHM model and software. Each respondent answered an online survey utilizing standard 5-point Likert scale responses. All of the questions were worded such that the most desirable answers were in the "Strongly Agree" and "Somewhat Agree" categories. To quantify the survey responses for analytical comparison, a point system was established corresponding to each possible user response. Integer values were assigned to each response ranging from zero (least desirable response) to four (most desirable response), with two indicating a neutral opinion. A composite score for each survey question was then

Table 9: SME Survey Responses on a Likert Scale with Zero (0) Corresponding to Strongly Disagree, Two (2) Indicating Neutral, and Four (4) Corresponding to Strongly Agree

SURVEY QUESTION	COMPOSITE LIKERT SCORE (OUT OF 4.0)	COMMENTS
The Human Factors Hazard Model (HFHM) has an intuitive interface, it is well organized, and can be used efficiently with minimal training and practice.	3.3	Survey participants indicated general satisfaction with the software user interface and its overall usability.
The Human Factors Hazard Model (HFHM) can be utilized in a timely manner, and is able to generate a result in a timeframe useful to a safety analyst or engineer.	3.3	Survey participants generally found the HFHM approach can be utilized in an expedient manner, resulting in timely results.
The Human Factors Hazard Model (HFHM) is an effective tool for use in analysis related to human error probability within a system design, and would be useful in driving a standardized, uniform, and comparable approach to safety analysis.	3.8	Survey participants indicated a high level of confidence that the HFHM approach would be effective in standardizing human hazard response by making results comparable and uniform.
The Human Factors Hazard Model (HFHM) has a high degree of flexibility and can be used to analyze systems ranging from those that are very simple through those that are very complex.	3.7	Survey participants indicated a high level of confidence that the HFHM approach is sufficiently flexible that analyses ranging from simple systems to very complex systems can be evaluated.
The Human Factors Hazard Model (HFHM) will facilitate an efficient approach to design and trade studies as it relates to system safety analysis, and particularly, human factors within a system design.	3.3	Survey participants indicated a general level of confidence that the HFHM approach allows for an efficient approach to design and trade studies as they relate to human factors in system safety.
The Human Factors Hazard Model (HFHM) is useful in identifying potential safety oversights, as they relate to human factors, and can be used to help guide design activities to reduce risk associated with human actors being present in a system design.	3.7	Survey participants indicated a high level of confidence that the HFHM approach will act as a guide to system design activities related to risks associated with human factors.
The Human Factors Hazard Model (HFHM) has a high level of utility, and would improve my organization's ability to predict the hazards associated with human activity within a system, and reduce overall safety risk.	3.3	Survey participants indicate a general consensus that the HFHM approach is an improvement over their current approach to Human Reliability Analysis (HRA).

calculated. The survey questions, composite scores, and response commentary are presented in Table 9.

As noted in the table, the survey participants were posed with these seven questions eliciting their impressions and assessment of the HFHM and its functionality. The first question in the survey is regarding the software interface and general usability of the model. This question was intended to exclusively solicit user satisfaction (or dissatisfaction) with regards to the user friendliness of the program. This question was used to establish if follow-up inquiries were likely required to guide design of an improved user interface for future software versions. The other survey questions were intended to support the validation of the HFHM's ability to standardize, simplify, be flexible, timely to use, and provide an overall improvement, both in functionally, as well as in overall accuracy, to the current Human Reliability Analysis (HRA) techniques being employed by the user. Feedback from the SME team provides evidence that HFHM has utility in application to system safety analysis, particularly with regards to human factors and risk assessment in the industrial and commercial engineering applications favored by these SMEs.

EVALUATION OF HFHM BY APPLICATION TO A MANUFACTURING ENVIRONMENT HAZARD SCENARIO

Additional evaluation of the HFHM was conducted via a design study of a manufacturing system experiencing a malfunction that depends upon human intervention to recover successfully. For this hypothetical case, a workpiece is assumed to be manufactured using a semi-manual machine tool (lathe). In this type of machining operation, the work piece is turned on a rotational centerline, and material is removed using a shaped cutting insert. During the material removal, a fluid is discharged onto the insert and work piece to remove machining debris as well as lubricate and cool the workpiece and tooling. If the part envisioned in this study is machined too aggressively, or done so without adequate cooling, it risks the generation of an alpha case defect due to surface heating, thus damaging the part beyond salvaging. In this scenario it would be scrapped at a high cost to the company, thus constituting the hazard event.

The design study being used to assist in the HFHM evaluation considers the operator's (human actor's) reaction to an unexpected low coolant flow. The Human Factors Triggering Event (HFTE) is defined as during a normal machining operation, the system experiences a drop in coolant flow, which potentially endangers the component being manufactured. The low coolant flow can be the result of three different possible root causes. The low flow rate root causes include: 1) an obstruction in the flow path restricting the coolant flow, 2) insufficient pump flow (pressure and / or pumping capacity), or 3) a low fluid level in the supply reservoir, thus starving the system of coolant. The manufacturing system design being analyzed includes the machining mechanism, coolant tank and pumping hardware, the control panel / user interface, and a human actor. The human actor via the control panel provides input control to the machining center and coolant management system. The control panel also provides instrumentation feedback to the actor regarding system performance and operational parameters.

A baseline case is established with Performance Shaping Factors (PSFs) based on the human factors as well as system characteristics. Two subsequent updates to the design were then analyzed within the HFHM. The two updates reflected what would be considered improvements to the system safety, which should in turn reduce the hazard probability associated with human intervention in system operations. The HFHM results, including a breakdown of probability for all four pivotal events, were established for the baseline case and the two update analyses. These analysis results are presented in Table 10.

As noted in the table, the baseline analysis indicates a probability of success that the actor will react correctly to the Human Factors Triggering Event (HFTE) of approximately 25.2%. With improvements made to the control panel, as well as improved observability of the system operations, and lowered distraction and stress levels, the probability of success is increased to approximately 96.2%. With the final improvement specified in the second update being hazard simulation and practice related specifically to the undesired system behavior, a final probability of success is determined to be approximately 97.9%.

Table 10: Evaluation of HFHM by Application to a Manufacturing Environment Hazard Scenario Summary

HFHM DEFINITION AND PSF INPUTS			HFHM OUTPUTS				
DESIGN CASE & DESCRIPTION	**PERFORMANCE SHAPING FACTORS**		**PROBABILITIES OF SUCCESS**				
Baseline Case			**PERCEPTION**	**COGNITION**	**ACTION**	**FEEDBACK**	**OVERALL**
Machining operation coolant flow failure with a required human operator intervention to avoid a mishap.	Moderately young actor (30 yrs)	→	0.433	0.814	0.853	0.839	**0.252**
	No Impairment						
	No appreciable fatigue						
	Normal actor visual acuity						
	Typical actor reaction time						
	Actor trained and experienced with system operations						
	Actor has no practice with specific HFTE behavior						
	Event occurs early in shift (1st hour of 8 total hours)						
	Instrumentation not organized or stereotyped						
	Instrumentation not annunciated for hazard alert						
	No audible alarm for hazard alert						
	Input controls not organized or stereotyped						
	No direct observation of machining operation by actor						
	Moderately high stress						
	Moderate distraction level						
	No adverse environmental conditions to inhibit actor response to HFTE						
	System operations are considred to be simple to understand						
Update 1			**PERCEPTION**	**COGNITION**	**ACTION**	**FEEDBACK**	**OVERALL**
All characteristics carried over from the Baseline Case with the noted revsions.	Instrumentation organized and stereotyped	→	0.988	0.997	0.980	0.997	**0.962**
	Annuciated indicators added for HFTE behavior						
	Audible alarm added for HFTE behavior						
	Input controls organized and stereotyped						
	Viewport added for direct actor observation of machining process						
	System organized for simultaneous viewing of process, instrumentation, and input control						
	Optimal stress level						
	Low distraction level						
Update 2			**PERCEPTION**	**COGNITION**	**ACTION**	**FEEDBACK**	**OVERALL**
All characteristics carried over from the Baseline Case with the noted revsions.	Consistent practice of HFTE response by actor	→	0.997	0.996	0.989	0.997	**0.979**

These results support a hypothesis that as design improvements are implemented, the HFHM will predict an overall positive trend in hazard reduction related to human-system interaction[1]. HFHM was able to be used to perform this analysis in ~1hr of engineer time, and sensitivity analysis and design revision was performed automatically in minutes of additional effort. This can be contrasted to the time to develop a THERP or similar quantitative probabilistic HRA, which would be measured in 10s of hours.

CONCLUSIONS

The proposed Human Factors Hazard Model (HFHM) is intended to provide a simplified, standardized, broadly applicable, and repeatable approach to assessing human error probabilities and their relationship to mishaps. The model is based on established error probabilities and human performance characteristics that have been experimentally derived over the past several decades but embeds these into a multi-staged and feedback-enabled model of human psychomotor response that is more applicable to common industrial, commercial, and manufacturing conditions. The model makes allowances for Expert Estimation or case specific empirical data to be combined or substituted for Human Error Probability (HEP) data embedded in the base functionality. An Excel and SysML implementation allow for design and sensitivity studies to be quickly and efficiently performed.

Based on evaluation by industry experts, design studies, and quantitative verification relative to existing Human Reliability Analysis (HRA) methods, the HFHM generates results comparable to other established methods in conventional applications, has utility for system engineering activities, and is easy to apply to manufacturing, industrial and commercial applications. HFHM can help guide system design activities to minimize or eliminate those hazards before they are much more hazardous, difficult, or costly to manage.

AUTHORSHIP CONTRIBUTIONS

Dustin Birch: Conceptualization, Methodology, Investigation, Software, Formal Analysis, Writing – Original Draft Preparation. Thomas Bradley: Project Administration, Supervision, Visualization, Writing – Review and Editing. Erika Miller: Supervision, Visualization, Writing – Review and Editing.

COMPETING INTERESTS

All authors declare they have no potential competing interests.

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