# The Human Failure event: What is it and what should it be?

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**Abstract:** The human failure event (HFE) is typically the intersection point between the probabilistic risk assessment (PRA) of a complex engineering system (i.e., nuclear power plant (NPP)) and a separate human reliability analysis (HRA) methodology. In that lens, the HFE represents the total accounting of human error in the safety assessment of NPPs. The HFE is a pivotal aspect of any PRA. Identifying and quantifying the human error probability (HEP), which is the probability associated with an HFE, has typically been the focus of HRA methods in nuclear power. The HFE has typically been the intersection point between the parent PRA and its embedded HRA method. However, "HFE" has not been rigorously defined for either HRA or PRA, and so the entire field of risk analysis lacks a formal definition of what constitutes an HFE . HFE is, of course, a failure of some sort – but at what level of abstraction should the HFE be defined? Is the HFE simply the result of any failed task, or should it represent something larger in scope than a single task or even a set of tasks can define? In this paper, we discuss the need for rigorous definition as a subset of a much broader necessity in HRA for clarity around key terminology. We propose a framework for identifying and defining HFEs at a high level of abstraction. Recognizing that task failures are not the exceedingly rare phenomenon that the notion of a failure event might suggest, we propose that the idea of an HFE must be something more complicated than a single task failure.

## 1. INTRODUCTION

The concept of human failure is the genesis of HRA, which is fundamentally the study of human failure, with "reliability" being the successful (i.e., non-failed) performance of a mission [1]. The origin of HRA in nuclear power is typically ascribed to the Technique for Human Error Rate Prediction (THERP), which deals extensively with human error. The THERP method was borne from the WASH-1400 report, one of the first large-scale reactor safety studies in the United States [2]. The study recognized the variable, uncertain and consequential nature of human influence on nuclear power operations, and the associated need to understand human errors. Keeping with a relatively low-level view of operations, the THERP method defined human error as an "out-of-tolerance action" which is the "natural outgrowth of some unfavorable combination of people and the work situation" [1]. In the time since THERP crystalized HRA as a distinct field of study in nuclear power, scores of HRA methods have been developed and implemented to understand human actions and ultimately quantify the uncertainty surrounding human-involved errors via a probability. However, the intervening time has also seen a growth in scope of what is encompassed by HRA. Second-generation HRA methods introduced cognitive models and contextual thinking, and the third generation are working towards dynamic modeling of human reliability [3].

The rapid change in scope and applicability of HRA methods has resulted in a presently untenable situation for the field. Current popular HRA implementations (e.g., SPAR-H, ASEP, etc.) utilize the same technical foundations as THERP clad in a more operationalized construction. These methods are relatively simple to use and have changed little if anything from the theory established in THERP [4], [5]. HRA research is pursuing finer estimates of HEPs through simulation, advanced dependency assessments, and dynamic modeling capabilities. These are important areas of exploration but ignore fundamental gaps in the field which threaten the adequacy and accuracy of HRA methods. The lack of consensus around basic and critical concepts (i.e., HFE) has been noted previously with some attempts at resolving misconceptions around other concepts, specifically related to dependency [4]–[6]. In this paper, we discuss misconceptions and problems related specifically to the concept of HFE, which we propose has never had a consensus definition and continues to be mischaracterized in HRA.

Resolving the understanding of HFE is critical for risk analysts, who currently use HFE as the crux element representing the "human aspect" of critical process failures. The intersection of HRA and PRA therefore rests on a poorly defined element that may be cast at any level of abstraction, since there is no solid definition. This work is also critical for the complementary field of risk management, which identifies actionable/intervenable risk-significant elements and implements risk-handling activities to mitigate risk. The utility of the insights gained via risk analyses is determined by the ability to identify elements on which interventions can be made.

Section 2 of this paper compares the ideas of human error and HFE as defined and used in various HRA methodologies. Section 3 selectively reviews misconceptions of HFE in HRA. Section 4 proposes the requirements for a robust definition of the HFE. Section 5 provides a definition which will resolve the misconceptions and standardize its use in HRA. Section 6 discusses the impact of this work and Section 7 provides recommendations for future work related to fundamental aspects of HRA.

## 2. HUMAN ERROR AND THE HUMAN FAILURE EVENT

The term "human failure event" (HFE) was not established with THERP, nor is it a recent addition to the HRA lexicon. Instead, the term appears to have originated (for HRA) some twenty years after THERP, in the course of developing a refined, multidisciplinary HRA framework [7]. In that context, "HFE" was proposed to bridge the cognitive, psychological concept of human error to the system safety implications that PRA characterizes. Therein, HFE connotes a system-relevant consequence of a human error and acts as the basic human event in PRA. As [7] makes clear, the terms "HFE" and "human error" are related but not interchangeable. Much like Major Crew Functions (MCFs) represent specific, system-oriented expressions of underlying macrocognitive functions, HFEs can be envisioned as the system-integrated expression of human errors [5], [8].

Human error, as defined in THERP, is simply an "out-of-tolerance action" and is fundamentally a psychological or cognitive aspect of human performance [1]. The "original" HRA methods for nuclear power, namely THERP and ASEP (Accident Sequence Evaluation Program) analyze human performance at the task level and strictly use the term "human error" to denote failed tasks [1], [9], [10]. As [7] points out, "human error" means all things to all people but has no direct connection to the systems with which PRA (and thus HRA) analysts are concerned. Plainly, "human error" lacks the underlying consistency that physical aspects of the systems have, reducing the effective modelability of "human error." Even as second-generation HRA methods increase the attention paid to cognitive processes, the notion of "human error" needs to be coupled to the system safety perspective to facilitate the ultimate goal of HRA, which is ensuring the safety and reliability of human involved engineered systems. Similarly, the consequence to an engineered system as the result of a human error is of little concern to behavioral scientists, who are interested principally in the cognitive error and why it occurred [7]. To rectify the disconnect between human error and the interests of risk analysis, ATHEANA (A Technique for Human Error Analysis), which was developed from [7], introduces the HFE as the system consequence of human error(s) and implicitly casts the HFE above human error in level of abstraction [11]. As an example, a "human error" might be a rule- or knowledge-based mistake of *creating an incorrect mental model*, but the associated human failure event would be the *incorrect diagnosis* based on that mental model [11], [12]. The examples provided in [11] relate human errors to "unsafe actions," i.e. failed tasks.

Since the implementation of ATHEANA, the term "HFE" has become somewhat ingrained in HRA; however, its use is far from consistent, particularly in terms of the level of abstraction at which it is defined and used in various HRA frameworks. The non-specification is partly a matter of engineered convenience; HRA methods have traditionally been beholden to their parent PRA method to define an appropriate level of abstraction for task analysis, the art of decomposing a scenario into distinct analytical elements. Unfortunately, this tight coupling with PRA means that HRA has failed to develop a consistent independent technical basis for many fundamental concepts [5]. As a result, HRA suffers from both inter- and intra-method inconsistencies when decoupled from any parent PRA methodology.

In most HRA methods, (e.g., ATHEANA, IDHEAS, and SPAR-H), the HFE has become the standard unit of analysis. However, these methods do not necessarily define or use HFE in a consistent manner. ATHEANA, ostensibly the origin of HFE in HRA, does not provide an explicit indication of an appropriate level of abstraction for conceptualizing or modeling the HFE. Instead, the examples in the method documentation imply that HFEs are to be defined as high-level objective failures, although the definition of HFE in a specific scenario is left to the analysts to determine "what the HFE is supposed to represent" [11]. SPAR-H (Standardized Plant Analysis Risk – HRA), the development of which was informed by ATHEANA, similarly allows analysts to define the HFE and does not provide a recommended level of abstraction. In the resolution of comments, it is explicitly stated that HFEs should "be decomposed to the level of tasks as appropriate," which indicates that, operationally, the HFE in SPAR-H may actually represent the failure of a single task [13]. Allowing analysts to define the HFE as appropriate for the situation provides the HRA methods with high flexibility to ensure that the level of analysis is appropriate to the parent PRA method. However, allowing analysts to define the HFE also means that there is high inconsistency between methods when applied to the same scenario. More concerningly, this also leads to inconsistency when different analysts use the same method. The inconsistencies were laid bare in a series of cross-sectional studies aimed at comparing and validating thirteen HRA methodologies, including THERP, ASEP, ATHEANA and SPAR-H. These studies required a set of pre-defined HFEs to facilitate basic comparisons between analyst teams and methods, and still saw significant inter- and intra-method inconsistencies in the quantification of HEPs [14].

Phoenix, a relatively new HRA method developed to address multiple issues in HRA, diverges slightly from previous methods regarding the definition of HFEs. Although analysts may iteratively develop "new" HFEs, Phoenix recommends using existing HFEs in the parent PRA method. Additionally, the HFE is considered at the level of "objective" (i.e., high-level) failures consistent with the parent PRA method [15]. While this reinforces the notion that HFE refers to a macro-level entity (as opposed to the micro-level human errors), inconsistency is inevitable without a robust, consistent definition of the HFE external to a parent PRA method.

Another new HRA method, IDHEAS (Integrated Human Event Analysis System), similarly defers to a parent PRA method for a definition of the HFE. IDHEAS takes a somewhat paradoxical view of the HFE as both embodying a higher level of abstraction than the failure of a single task, while also being the result of a single failed "critical" task [16]. In this view, an HFE is decomposed into a network of critical tasks, the failure of any of which results in an HFE, and non-critical tasks which can interfere with the performance of critical tasks. The question should be raised as to the suitability of this decomposition scheme if the HFE is operationally cast as the failure of a single (critical) task. For instance, incorrectly reading an indication or developing an incorrect mental model (tasks) may be considered an HFE even if the resulting diagnosis is correct (objective). In such a case, are the task failures really HFEs, or simply failed tasks that *may* contribute to an HFE?

While the second generation of HRA methods sought greater inclusion of what was known of psychology and cognitive concepts, there were challenges integrating these concepts within the regimented nature of HRA. As discussed, there are important differences between the foundational characteristics of PRA and HRA. Specifically, non-human failures considered in a PRA model can be broken apart into observable aspects grounded in the laws of physics and principles of engineering. This contrasts profoundly with HRA's reliance on aspects of human error. At the time of THERP, the majority of psychological science was grounded in behaviorist principles which claimed that human cognition and psychology were observable by observing behavior, however this notion has been largely abandoned since the second half of the 20$^{th}$ century and the rise of cognitive psychology. Ultimately, in defining an HFE, it is important to capture the psychological realities of human error and what a human failure event means.

The context of human error in systems is the focus of HRA. However, when a human agent makes an error, the relevant system consequences are not necessarily impactful on the cognitive processes at play. Indeed, one of the largest challenges of HRA is that many of the cognitive processes which govern human error are unobservable entities with near infinite variability and potency. Further, human errors are fundamentally lacking in intentionality which can make capturing and categorizing the various types of human error. An HFE for the human agent is an unintentional action which then causes some higher order goal or task to fail, or produces an impact which manifests wholly outside of the human agent. Human errors certainly have mechanistic components. Attention, memory, and stress are examples of aspects that shape cognition and decision-making, however it bears mentioning that the understanding of these functions and processes is still at a very nascent stage.

## 3. USE OF THE HFE IN HRA

Beyond the inconsistent level of abstraction at which HFE is (or should be) defined, there is another, more fundamental, misconception of HFE as an objective or task that can be performed. This stands in contrast to the name "human failure event," which explicitly defines the HFE as a *failed state* rather than a distinct, performable action or decision. For instance, IDHEAS refers to the crew's performance and "success" of HFEs, when in reality crews perform tasks and objectives that, *when failed*, are recorded as HFEs [16]. A study on the cross-sectional validation and comparison of HRA methods similarly substitute the HFEs for objectives, referring to the "performance" and "failure" of HFEs [14]. This may seem to be a purely semantic concern, but ensuring a consistent definition and use of "HFE" requires addressing how the term is implemented in practice.

Characterizing the HFE as a distinct element in the task discretization of a scenario is inconsistent with both reality and previous usage of the term. The HFE is a failed state of an objective, similar to a system failing to perform an objective. If a pump fails to operate, we do not ascribe "objective" status to the failure. The objective was operation, which may either succeed or fail. The failure event is a part of, but distinct from, the objective itself as one possible outcome of performing the objective. The failure event has no "outcomes" – it is itself an outcome which either does or does not occur. The idea of successful HFE states is nonsensical.

Similarly, "HFE" should not be interchangeable with "HEP," which characterizes the probability of the failure event, but does not convey the same information contained within the HFE. The HFE denotes the failure process and includes the failed objectives which resulted in the HFE, while the HEP denotes only the probability of this occurrence. In classical risk analysis, "risk" is characterized (at minimum) by both frequency and consequence, but neither element can substitute for the other [17]. Frequency or consequence alone cannot adequately convey a risk; the HFE and HEP are similarly distinct and inseparable for HRA.

On the surface, the misuse of HFE appears to be a semantic issue. The HFE retains its status as an analytical element of HRA and PRA even in this confusion. Identifying, characterizing, and quantifying HFEs (via the HEP) is still a focus of HRA. However, characterizing the HFE as the process rather than an outcome is another symptom of the root cause that the HFE is a poorly defined construct in HRA. Further, the recency with which this issue has arisen indicates that the confusion surrounding this term is growing rather than shrinking. HRA is some sixty years into its development as a distinct field, yet fundamental concepts are continuously being misused.

The use of the HFE as the objective rather than a failed state becomes more problematic when viewing HFEs as the culmination of a failure process, which we propose in Section 4 to be the correct level of abstraction for the HFE [8]. The failure process is composed of at least one failed objective and the HFE is one outcome of the process but is not equivalent to the process itself.

## 4. METHODOLOGY: HFE DEFINITION REQUIREMENTS

As Sections 2 and 3 indicate, the HFE has no universal definition as an HRA concept or analytical element. There are discrepancies in methods between its definition (explicit or implicit) at a high level of abstraction and its use as the outcome of a single task-level element. Further, there is the false notion of the HFE as an objective rather than the *failed state* of an objective. Previous work aimed at reviving HRA for an integrated human-machine team framework discusses the HFE as the culmination of a failure process [8] involving one or more failed function-level elements. This formulation, we believe, is more consistent with the original interpretation of HFE as the failed outcome of a high level of abstraction (e.g., objectives), as developed in ATHEANA.

The use of hierarchical terms in describing the placement of the HFE is intentional, as the definition of the HFE partly determines the remainder of the task analysis process. A generic hierarchical structure for task analysis is used here to distinguish various elements of a scenario. Objectives, the overall goal(s) of the crew in a given scenario, are the highest level of abstraction, which are met through the completion of a set of functions [5]. Functions in turn are composed of a set of tasks, which are typically the lowest level of abstraction considered in many HRA methods, but can be broken into subtasks as required. Events are those occurrences (internal or external in origin) that induce a significant change in the scenario, for instance transitioning a crew from “normal operations" into “emergency operations," as shown in Figure 1. Considering the example proposed in Section 2, the creation of a mental model could be a function composed of multiple information-gathering tasks; this function feeds an *objective*, e.g., diagnosing the scenario. In this hierarchy, the HFE would be cast as the occurrence of at least one *failed* objective.

Consistent with the ATHEANA intentions, the general trend of definitions in subsequent HRA methods and the process-oriented view of human performance, we propose that HFE be defined as an outcome corresponding to a performable objective level entity. Since task decomposition in HRA remains a somewhat open question, defining the HFE at a given level of abstraction may seem a functionally meaningless proposition. However, taking the view that an “objective” is the highest level of abstraction in HRA models (with “task” being the lowest), defining the HFE at the level of the “objective” places HFE at the high level of abstraction typically required by PRA applications [5].

Further, the HFE should be robustly defined as the outcome of the failure process rather than an element of the process or the process itself. Specifically, redefining the HFE as the failed state of an objective-level entity entails curtailing references to “successful” states of the HFE or “performance” of HFEs. Instead of discussing the HFE as a tangible element of the failure process it should be viewed as one possible outcome of the process which, if failed, is realized as the failure process. The objective whose failure generates an HFE should be composed of at least one functional-level element (e.g., MCF).

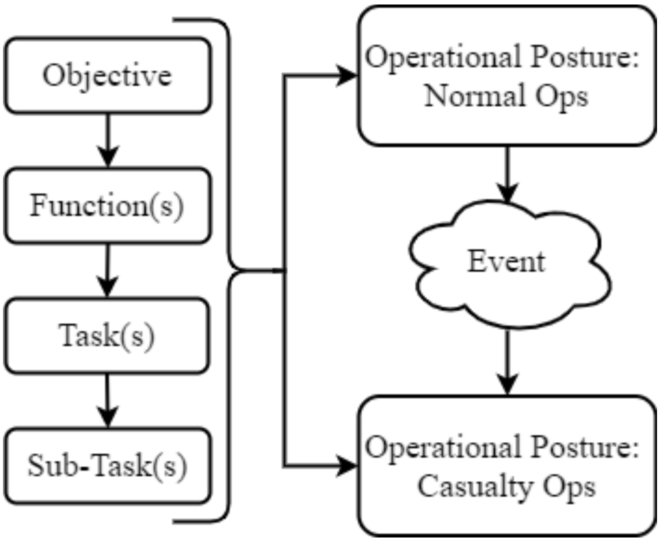
## 5. RESULT: HFE DEFINITION FOR HRA

Informed by the requirements set out above for what the HFE should convey to HRA, and the previous misconceptions that should be avoided, we propose the following definition for the HFE:

*The HFE is the failed state of some overarching objective, defined by the analysts in accordance with the scenario and analysis requirements. The HFE is not a distinct element, but the culmination of the failure process, which is composed of at least one failed function-level element (e.g., MCF). The HFE is therefore the failed state of one (or more) objective-level elements and the likelihood of its occurrence is quantified probabilistically by the HEP. The HFE is initiated by an erroneous, unintentional action by a human agent which, when not recovered, leads to a higher order impact.*

The HFE remains an unsettled construct in HRA, but with the recognition that it represents the failed state of a process, rather than a tangible, performable element of the process (e.g., an objective/function), discussion and quantification of the HFE should become more straightforward. Defining the HFE as the failed state of an objective is congruent with recent endeavors at HRA data collection, such as the U.S. Nuclear Regulatory Commission’s (NRC) SACADA and Korea Atomic Energy Research Institute’s (KAERI) HuREX databases [18], [19]. These programs pursue a lower

**Figure 1: Generic Hierarchy of Task Analysis Language. Figure from [5].**



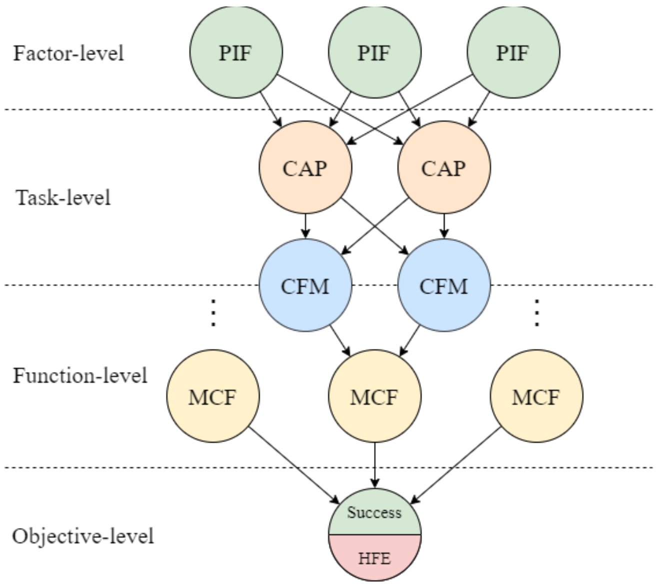

level of abstraction to more comprehensively characterize human performance and serve the needs of both HRA and nuclear operator training [18], [19]. These efforts record human performance at the "Major Crew Function" (MCF), Task, or Subtask level, which are developed by decomposing objectives. As a result, these efforts are capturing the failure process, and can help HRA analysts to define HFEs for particular scenarios. The iterative process of defining HFEs and capturing HRA data predicated on the specific HFE will both improve the collection and use of HRA data, as well as the definition of the HFEs and what should (and should not) be considered an HFE.

Given the definition of HFE proposed above, the HFE is not a distinct element, but the failed state of an objective-level element. Understanding the HFE necessitates understanding the causal factors which weigh on the corresponding objective, which requires decomposing it into combinations of elements at lower levels of abstraction. These elements include the MCFs, "Crew Failure Modes" (CFMs), "Crew Activity Primitives" (CAPs) and "Performance Influencing Factors" (PIFs) [8]. The decomposition process can be done with a graphical model, such as a Bayesian Network (BN), which can also identify the causal relationships between these elements and quantify the probabilistic effects at each element. but is represented as the failed state of the element at the highest level of abstraction, which is the "objective" that is formed from at least one MCF. Figure 1 depicts this hierarchy for a single objective-level element. The failed state of this element is the HFE. Bayesian Networks (BNs) are graphical models that depict and quantify the relationships between elements. BNs can therefore express the hierarchy and dependencies between HRA quantitative elements, namely performance influencing factors (PIFs), crew activity primitives (CAPs), MCFs and crew failure modes (CFMs) [8], as shown in Figure 2. BNs can visualize and quantify the failure process at multiple levels of abstraction depending on how the CAPs and MCFs, which represent tasks and objectives, are defined. In a PRA application, this new definition of HFE means that the basic event models an objective that can be successful or failed; the HFE is the *failure branch* that represents the failed objective.

## 6. IMPLICATIONS OF THIS WORK

This work provides a single definition for the human failure event (HFE), which was not robustly defined before being widely incorporated as an analytical element in HRA. Defining the HFE at the objective level (Figure 2) is congruent with the original, implicit definition of HFE as the bridge from human errors to system-level consequences. As the failed state of a high-level objective, which itself is composed of at least one function, and at least one task, the HFE represents an event of significant consequence to the system, rather than a single low-level error which may be inconsequential or even recovered. The HFE maintains the level of abstraction typically required in a PRA, and allows HRA analysts to develop complex, causal models of the elements underlying the HFE-generating objective.

**Figure 2: Hierarchy of HRA Variables with the HFE as Failed Outcome of Objective.**




The objective-function-task hierarchy (Figure 2) supported by this definition of HFE is consistent with how procedures are designed and implemented, and how HRA scenarios are currently decomposed. Further, current HRA methods need not be scrapped or even significantly altered to accommodate the new definition of HFE. All that is required to implement this definition immediately is to recognize that the HFE represents the failed state of an objective, rather than the objective itself. This definition should therefore assist analysts in defining the HFEs of a scenario. The objectives which correspond to the HFEs are easily discernible in the procedures, SACADA/HuREX frameworks, and/or operator experience.

Defining the HFE as the failed state of an objective does not substantially change how HRA is integrated into a parent PRA method but does alter the meaning of the HRA elements included in the PRA. As mentioned in Section 5, the basic event represents an objective, while the failure branch or failed state of the basic event represents the occurrence of an HFE in the performance of that objective. This replaces the view of the HFE as "true or false" and allows for the recognition that objectives may have multiple distinct failures, corresponding to multiple possible HFEs. HFEs, as the failure of an objective, consist of multiple lower-level tasks and associated failure modes, meaning that multiple distinct HFEs could describe the same failed objective. Accordingly, it may be easier to identify the required objectives rather than defining all of the possible HFEs. Further, using the objective as a PRA basic event conforms to the "success/failure" convention better than using a "true/false" HFE basic event.

The definition of HFE offered here can further the integration of HRA and Resilience Engineering, an evolving paradigm of safety analysis which focuses on what can go right rather than what may go wrong, the purview of traditional risk analyses. Resilience focuses on the ability of a system to cope with complexity and adjust its functioning prior to, during or following operational disturbances [20], [21]. This paradigm offers an entrancing proposition to the HRA community, which is often mired by the limitations imposed by static models of pre-determined notions of human-machine team performance. Defining the HFE at the objective-level supports the systems-oriented focus of HRA. By recognizing the function- and task-level human errors that *produce* an HFE, this definition works to create a common understanding of the two terms (human error and HFE) in a manner that supports both systems-HRA and cognitive HRA.

## 7. CONCLUSIONS AND FUTURE WORK

The definition and use of HFE varies around HRA methods and is subject to multiple misconceptions. The definition provided in Section 5 is not a panacea for the issues surrounding the HFE, but it does represent a significant step in the standardization and reinforcement of the technical basis of HRA. The definition provided here casts the HFE at the high level of abstraction typically required by PRA methods and distinguishes it as the failed state of a high-level objective, formed by at least one major function (the failure process), rather than being an objective itself. Further, the HFE is linked to its quantification (HEP) but delineated as a separate construct.

The problems discussed here regarding the definition of HFE and its use in HRA are symptoms of larger issues regarding the technical basis of HRA as a discipline. A large number of concepts, and the associated mathematics, have been recycled from the HRA origins despite concerns over their applicability and veracity. As a result, HRA literature is overwhelmed by inconsistencies surrounding fundamental elements of HRA, multiple redundant definitions for same/similar concepts, analysis methods that outpace the technical basis of their analysanda, and partially-updated HRA methods which retain largely the same issues as previous iterations. Correcting the theoretical foundations of an established field is a Herculean undertaking, but technical correctness is a necessary investment if HRA is to truly characterize human reliability. Beyond definitional clarity, the critical aspects HRA that are still in flux are namely task analysis/decomposition, and the conception and implementation of dependency. To that end, this work provides a clear and implementable definition of the HFE that supports the performance of HRA and PRA.

Future work dedicated to revising the technical foundations of HRA is required to address the systemic issues noted here and in previous literature [5], [22]. Our work here addresses one aspect of this work; future work should undertake a systematic review of additional core concepts of HRA to ensure that their definition and implementation are consistent, coherent and scientifically based. The foundations of HRA need to be settled and agreed upon before substantive progress toward dynamic and/or quantitative HRA can be achieved.

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