Investigating Quantitative Methods for Evaluating & Predicting Human Reliability & Applying NARA to Human-Robot Interactive Systems

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Abstract—**Human Reliability is a qualitative and quantitative measure defined relative to the operation of a system and indicates the degree of dependence on the human. Human reliability is very crucial factor in quantification and evaluation of a system because most of the systems depend on humans for their correct operation and obtainment of the goal. Human Reliability Analysis (HRA) is used to quantify or qualify the human reliability. It allows us to understand the required interactions of humans with their working environment to achieve the ultimate goal of the system. HRA accounts for the factors that lead humans to take unsafe and incorrect actions leading to disasters. Firstly, this paper gives an overview of some established and recent HRA methods that have been used frequently in human-involved systems [4], [5]. It compares all the three generations of HRA techniques developed after undertaking years of research in human reliability analysis and details about some popular HRA techniques employed historically in nuclear, aviation, and industrial fields. Secondly, the paper evaluates and benchmark a few HRA methods on the basis of a set of twenty attributes categorized into five groups.**

Finally, this paper aims to understand the role of human reliability in the human-robot interaction systems that have become widespread in recent years. In particular, many automation and manufacturing industries employ robots for carrying repeated and heavy-duty tasks while humans are monitoring these robots. In such scenarios where human and robots frequently interact, it becomes very important to understand and model human reliability in the context of the tasks and goals of the system. This paper also aims to extend a third generation HRA technique called as Nuclear Action Reliability Assessment (NARA) [9] - the only third generation HRA technique - to the Human-Robot Interactive (HRI) systems. This analysis will provide us a way to characterize the human factor in the context of HRI environments that have potential to replace most of the current human-based systems.

keywords: Human Reliability Analysis (HRA), Human Error Probability (HEP), Performance Shaping Factors (PSF), Nuclear Action Reliability Assessment (NARA), Human-Robot Interaction (HRI), Error Producing Conditions (EPCs)

I. MOTIVATION AND INTRODUCTION

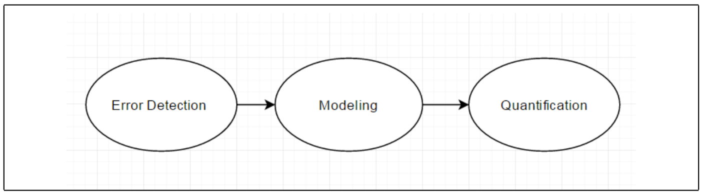


Fig. 1. Basic Phases of HRA

Over the past few decades, the errors and failures associated with technical causes has decreased substantially due to technological advancements in systems. However, humans still have a variety of roles in some crucial parts of those systems such as design, development, maintenance, control, supervision, etc [17]. This inevitable presence of humans in the systems constitutes for a major portion of the possible system failure reasons.

Human dependence can be observed in most of the systems ranging from automation industries to even the governments. Some of these systems are mostly operated by humans and their presence is one of the significant factors in determining the probability of achieving the goal of the system. In fact, there are some critical fields such as nuclear domain, aviation, transportation, industries, and the government where human errors can severely affect the entire system and its dependents. Hence analyzing human behavior and decision-making is essential to the success at achieving the system goals and avoiding disasters. Some of the most disastrous situations such as Chernobyl disaster, Fukushima nuclear meltdown, Bhopal chemical disaster, etc. occurred in human-critical systems as a result of human errors. Analysis and quantification of human errors is a potential solution to mitigating human errors and this would certainly help in avoiding such disasters in the future. Moreover, these concepts could be extended to any human-based system in order to create a safe and productive environment [1], [2], [3].

In recent years, we have seen a rise in the involvement of robots in human-based system. Robots are being introduced in places where continuous output and undeviated efforts are required. However, many of such systems also requires human to work alongside the robots in order to operate, monitor, supervise, and maintain these robots. Moreover, these robots are designed and developed by humans at the first place. These systems, also called as Human-Robot Interactive (HRI) systems, are becoming ubiquitous in industries. Therefore,

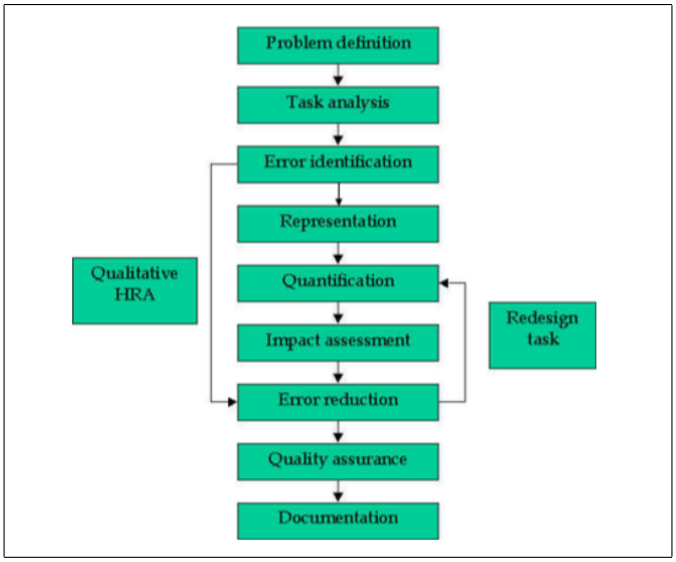


Fig. 2. HRA process in detail [1]

applying HRA techniques is essential for ensuring high reliability, safety, and productivity [5], [6], [7]. HRA techniques can not only be potentially applied to the human-centered aspects of HRI, but also to the human-robot interactions as a whole. A third generation technique called NARA, although developed for applications in a nuclear power plant, could be extended to HRI systems given its higher degree of flexibility.

II. Basic Phases of HRA

HRA can be divided into three basic phases viz., error identification, error modeling, and quantification as shown in figure 1. Error identification involves identification of human errors and the scenarios where human errors could occur. Error modeling phase models the human error into a model that could be analyzed further for error quantification. In error quantification we use various analytical methods to quantify the human error in terms of a measure known as Human Error Probabilities (HEPs).

The detailed process of Human Reliability Analysis was described by Kirwan [2] in 1994 as shown in the flowchart in figure 2. According to Kirwan, HRA phases can be divided into following steps [1] : *Problem Definition, Task Analysis, Error Identification, Representation, Quantification, Impact Assessment, Error Reduction, Quality Assurance, and Documentation.* Each of the step could be performed using various methods, for example Quantification step could use one of the techniques such as HEART, SHEAN, THERP, etc. Before proceeding to the goal of this paper, we will first discuss each of the steps in brief.

*1) **Problem Definition**:* It is the first step in which the process consisting some form of human involvement is defined. Here we describe the general flow taken while solving the problem and the final goal that is needed to be achieved in order to mark the problem as solved.

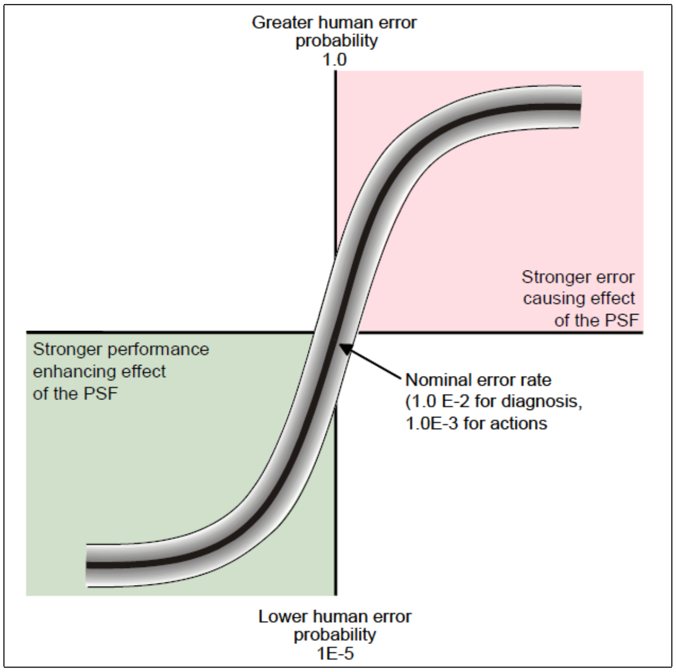


Fig. 3. Ideal HEP as a function of effect of PSF [6]

*2) **Task Analysis**:* It involves a range of techniques that understand the role of human in achieving the defined goal of the system. We express the job in terms of goals, operations, and plans. A book by Kirwan [3] details about a structured approach to analyze a task in a comprehensive manner.

*3) **Error Identification**:* It is a scheme that is used to identify specific human errors that could potentially occur during the task. It produces a list of errors that could potentially lead to goal failure.

*4) **Representation**:* It is the step wherein the errors are fit in a risk model that represents the operation of the system. An event tree could be used to model the features of the system.

*5) **Quantification**:* It measures the human error probabilities using a variety of available techniques as mentioned previously [2].

*6) **Impact Assessment**:* It is concerned with understanding the effects of the human errors on the outcome of the system process.

*7) **Error Reduction**:* It is an important procedure that is responsible for incorporating the historical information of the errors introduced in the system in order to avoid them in the future.

*8) **Quality Assurance**:* It is a qualitative assessment and maintenance procedure that ensures a high and consistent quality of the outcomes of the system.

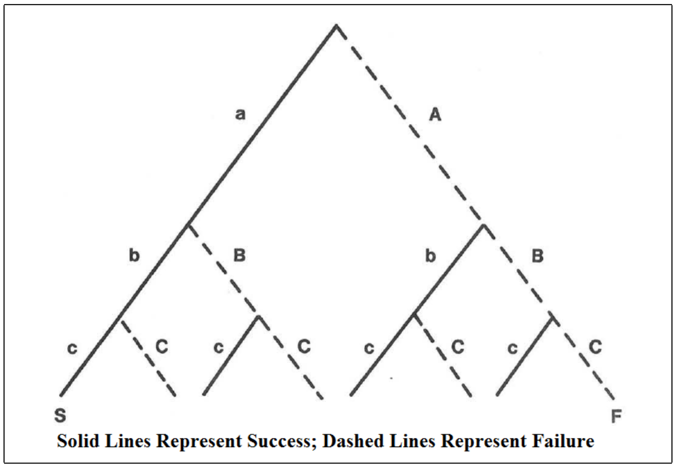


Fig. 4. Event Tree in THERP [12]

*9) **Documentation**:* It is the final step that involves reporting and cataloging all the information gathered during the earlier steps.

III. BASIC TERMINOLOGIES IN HRA

HRA is a systematic and a structured methodology to identify, model, and quantify the human errors and their probabilities. In this section, we review the basic terms in HRA.

*A. **Human Error Probability (HEP)***

It is a measure to quantify the errors associated with each task constituting towards the goal of the system. Equation (1) gives the mathematical expression to calculate the HEP. This HEP could be calculated based on a range of sources of information such as historical records, collected data, simulated data, estimations, or field experience [1]. Typically, the range of probability of human error is from 1 (highly likely to fail) to 10^{-5} (least likely to fail) [18].

$$HEP = \frac{\text{Number of observed human errors}}{\text{Total number of possible human errors}} \tag{1}$$

This is a nominal value of HEP and it would get modified depending on several factors.

*B. **Performance Shaping Factors (PSF)***

It represents the modifications in nominal HEP that are driven by the human nature subjected by its ambient operating conditions. For instance, if the person working in a certain condition is fatigued then this might increase the nominal HEP by a factor of, say 100, resulting in a HEP of 100 time more than the nominal HEP.

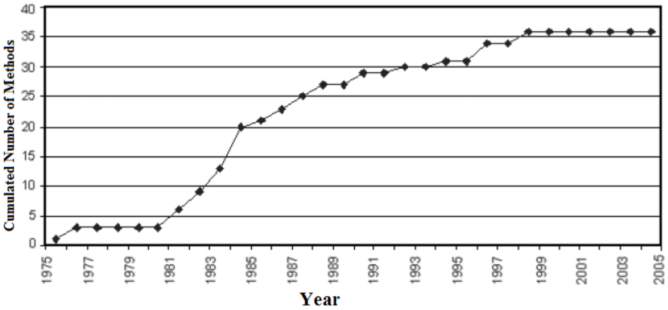


Fig. 5. Cumulated number of HRA methods per year [10]

In order to incorporate these modifications influenced by the operating conditions or scenarios, the concept of Performance Shaping Factors (PSF) was introduced. PSF are a range of task-based circumstances such as time constraints, psychological pressure, awareness, and so on. Each of the factors will have its own multipliers for the nominal HEP. As we can see in the figure 3, when the negative influence of PSF increases, a stronger error causing effect is observed and a higher value of HEP is seen. On the other hand, lower HEP is observed when PSF enhances the human performance. PSFs could be classified as *(a) External*, *(b) Stressor*, and *(c) Internal*.

*C. **Categorization of Human Errors***

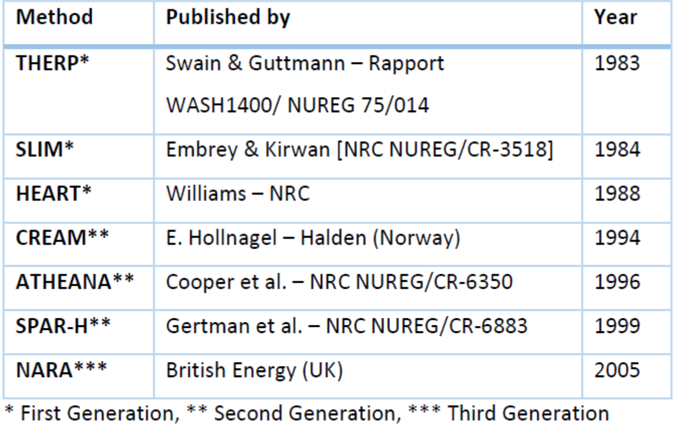
Human errors can be categorized into two classes: *(a) Errors of Omission* and *(b) Errors of Commission*. Errors of omission represent the errors caused due to omission of a task or a step in a task. Errors of commission represents the errors are caused when the human output is not as per the expected human output. These errors could be error in proper selection, error of sequence, error in timing, qualitative errors, etc.

IV. REVIEW OF POPULAR HRA TECHNIQUES AND GENERATIONS

The field of HRA started evolving since late 1970s and it was propelled by some of the most disastrous incidents that occurred due to human errors in the decade of 1980s. Figure 5 shows the rapid growth of number of HRA techniques since 1975.

*A. **First Generation HRA***

The first generation HRA methods a large significance was given to the characteristics of the task in order to calculate the total probability of human failure in the system. On contrary, the PSFs, which represented the ‘context,’ were given a small significance. These methods were strongly influenced by the concept of probabilistic safety assessment (PSA) [16]. PSA methods were based on the philosophy of *expert judgment*. THERP [8] (1983) adapted the PSA approach of task decomposition. The actions were either considered as errors of



Method	Published by	Year
THERP*	Swain & Guttmann – Rapport WASH1400/ NUREG 75/014	1983
SLIM*	Embrey & Kirwan [NRC NUREG/CR-3518]	1984
HEART*	Williams – NRC	1988
CREAM**	E. Hollnagel – Halden (Norway)	1994
ATHEANA**	Cooper et al. – NRC NUREG/CR-6350	1996
SPAR-H**	Gertman et al. – NRC NUREG/CR-6883	1999
NARA***	British Energy (UK)	2005

* First Generation, ** Second Generation, *** Third Generation

Fig. 6. Popular HRA Techniques [17]

omission or errors of commission. Omission was when human did not undertake the operation to achieve the goal, while commission was when human performed some unrelated task while proceeding towards the goal.

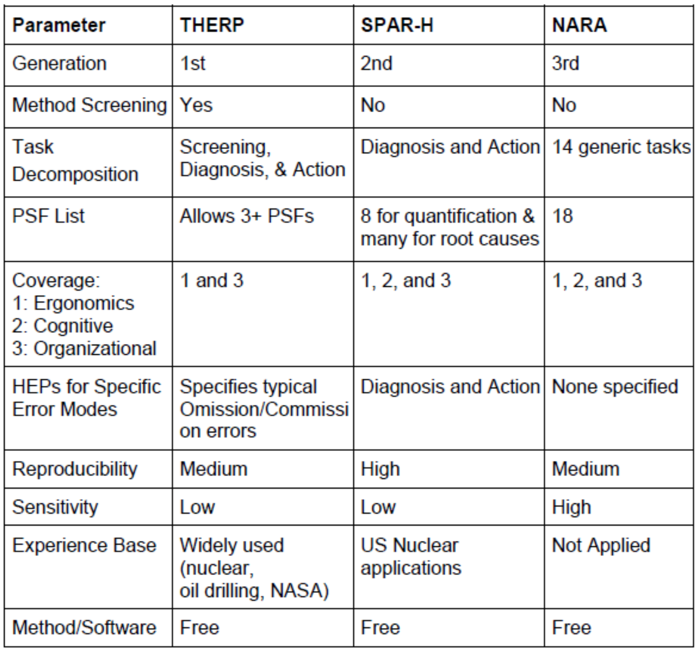
In the techniques like Absolute Probability Judgment (APJ) and Paired Comparisons, experts compared different human errors to decide the most likely error. SLIM (i.e., Success Likelihood Index Method, 1984) was somewhat different in that it considered in detail the important PSFs in absolute HEP calculation.

In 1985, the Human Error Assessment and Reduction Technique (HEART) was introduced [14]. It was flexible because it handled a smaller and generic task decomposition set. PSFs were modeled relatively and were also known as Error Producing Conditions (EPC). The first generation HRA modeled man as a ‘mechanical component’ of the system and thus there wan no dynamic interactions with the physical or social environment. These methods gave very low attention to the cognitive factors related to human actions. Human actions were represented in a binary format: either as a success or as a failure which is shown in figure 4 that depicts an event tree used in THERP. Success is one branch at each node while failure is the other branch. The goal will be obtained after following a connected path of success.

B. *Second Generation HRA*

The necessity to improve the behavioral techniques of the first generation gave rise to second generation of HRA techniques in the early 1990s. This was also propelled by the most worst human-error disasters mentioned earlier in the introduction. These method were focused on more cognitive aspects of human nature. This lead to increased importance of qualitative assessment of the human errors [16] and more attention was given to the ‘context’ in which humans work.

A Technique for Human Error Analysis (ATHEANA) in 1996 and the Cognitive Reliability Error Analysis Method (CREAM) in 1993 were the early techniques based on cognitive factors of human reliability. In these techniques, More importance was given to the causes of errors as compared to the frequency of occurrence. These techniques also emphasized on interdependency of various PSFs that modified the nominal HEPs. CREAM used a cognitive model called as Contextual Control Model (COCOM), that assumes the cyclical characteristic of cognition and dependence on the environment for the human cognition. Another method developed was the Standardized Plant Analysis Risk - Human reliability analysis (SPAR-H) for the nuclear power plants in the United States [12], [17].



Parameter	THERP	SPAR-H	NARA
Generation	1st	2nd	3rd
Method Screening	Yes	No	No
Task Decomposition	Screening, Diagnosis, & Action	Diagnosis and Action	14 generic tasks
PSF List	Allows 3+ PSFs	8 for quantification & many for root causes	18
Coverage: 1: Ergonomics 2: Cognitive 3: Organizational	1 and 3	1, 2, and 3	1, 2, and 3
HEPs for Specific Error Modes	Specifies typical Omission/Commission errors	Diagnosis and Action	None specified
Reproducibility	Medium	High	Medium
Sensitivity	Low	Low	High
Experience Base	Widely used (nuclear, oil drilling, NASA)	US Nuclear applications	Not Applied
Method/Software	Free	Free	Free

Fig. 7. Comparison of THERP, SPAR-H, and NARA [5]

The second generation techniques incorporated the interactions of humans with their operating environment. However, the second generation techniques lack sufficient experimental base supported by a database before they are completely validated [16].

C. *Third Generation HRA*

The only third generation method available today is the **Nuclear Action Reliability Assessment (NARA)** [9] which was developed in 2004 by Kirwan et al. in order to overcome the problems in first two generations of HRA techniques. This is a modified version of HERAT technique using the error data compiled in a dataset known as CORE-DATA. This method uses a small set of tasks and PSFs along with the ‘anchors’ in order to allow modification of task probabilities (HEPs). Just like the second generation techniques, this third generation technique is not validated completely and it does not have sufficient experimental base. We will discuss in details about the procedures and terms related to NARA in the further sections of this paper.

Although the newer generation are focusing on the independence from the expert judgment in PSF formulation, according to Kirwan [18] "formal expert judgment is still in use today as a HRA method for many applications."

Figure 6 gives details about the inventors and the generation of some of the HRA techniques mentioned earlier. Figure 7 gives a general comparison of three HRA techniques each one of which is taken from one of the three generations.

V. EVALUATION OF HRA METHODS

In this section we will evaluate some of the widely used HRA techniques such as THERP, ATHEANA, NARA, SPAR-H, and CREAM. Since each of the HRA method was developed along the guidelines for a specific application, a moderate amount of research and literature [7], [19], and [20] can be found that compares and collocates these different methods. A report that summarizes such work of benchmarking the HRA methods was published by Sandia National Laboratories in 2008 [21]. This report briefly elaborates about the HRA benchmarking efforts carried out by European Agencies, Kirwan, Zimolong, and Maguire. It also provides some general guidelines to evaluate and validate the HRA methods.

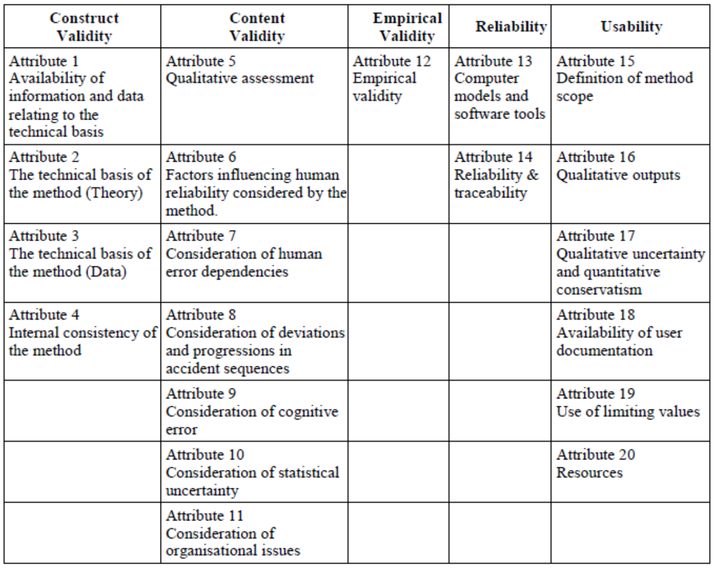
However, in order to evaluate the HRA methods, we use the report [11] published recently in 2015 by the **Nuclear Energy Agency (NEA).**

NEA is a specialized agency of senior scientists and engineers within the Organization for Economic Co-operation and Development (OECD). NEA has an international committee established in 1973 responsible for nuclear safety and research called as Committee on Safety of Nuclear Installations (CSNI). The report mentioned earlier is a collective research work of groups from different countries under NEA and it presents the research that identifies and evaluates the desired characteristics of the HRA methods.

Although the committee states that the results of this study are not for recommending, ranking, or scoring the HRA methods, we can assess the results and come up with some scores that would rate these methods relative to each other. The outcomes of the report that lists the strengths and limitations of some widely used methods are used in this paper to benchmark and score these methods. However, users of these methods are advised to identify the desirable attributes specific to their applications and select the best possible method.

A. *Evaluation Metrics and Procedures*

NEA report was developed after carrying out two phases. In first phase the researchers arrived with a set of 20 attributes that are essential to an HRA method based that is formulated on calculations of HEPs. In second phase NEA selected a set of HRA expert teams that evaluated the HRA methods in context of the 20 attributes shortlisted in the first phase.



Construct Validity	Content Validity	Empirical Validity	Reliability	Usability
Attribute 1 Availability of information and data relating to the technical basis	Attribute 5 Qualitative assessment	Attribute 12 Empirical validity	Attribute 13 Computer models and software tools	Attribute 15 Definition of method scope
Attribute 2 The technical basis of the method (Theory)	Attribute 6 Factors influencing human reliability considered by the method.		Attribute 14 Reliability & traceability	Attribute 16 Qualitative outputs
Attribute 3 The technical basis of the method (Data)	Attribute 7 Consideration of human error dependencies			Attribute 17 Qualitative uncertainty and quantitative conservatism
Attribute 4 Internal consistency of the method	Attribute 8 Consideration of deviations and progressions in accident sequences			Attribute 18 Availability of user documentation
	Attribute 9 Consideration of cognitive error			Attribute 19 Use of limiting values
	Attribute 10 Consideration of statistical uncertainty			Attribute 20 Resources
	Attribute 11 Consideration of organisational issues			

Fig. 8. Five categories of twenty attributes from the NEA report [11]

According to the report [11], NEA classified the 20 attributes into 5 groups of attributes as described below. Table in the figure 8 taken from the report gives the classification of these 20 attributes into 5 categories mentioned earlier.

1) **Group 1: Construct Validity**
   "It is the measure of internal validity of the method. It evaluates if the method is measuring and assessing what it claims to. It verifies if the method is in accordance with the underlying model or data on which it was formulated." This category has 4 attributes (attribute 1 to attribute 4).
2) **Group 2: Content Validity**
   "It is another measure of internal validity. It verifies if the method is evaluating the essential factors of human reliability." This category has 7 attributes (attribute 5 to attribute 11).
3) **Group 3: Empirical Validity**
   "This group of attributes verifies whether the outputs of the method are consistent and correlate with the available sources of data on human reliability." This category contains only one attribute (attribute 12).
4) **Group 4: Reliability**
   "It measures the degree to which the outputs of the HRA method, either qualitative or quantitative, are consistent and coherent with the available knowledge of the human reliability." This category has 2 attributes (attribute 13 to attribute 14).
5) **Group 5: Usability**
   "It is a measure of degree to which the HRA method

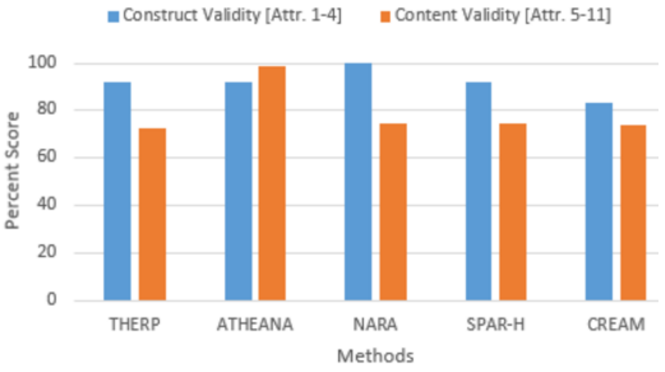


Fig. 9. Construct Validity and Content Validity Scores [11]

gives a guidance for applying it to a specific scenario. It also depend on the usability of the output of HRA method and the resource requirements for the method in order to implement it." This category has 6 attributes (attribute 15 to attribute 20).

B. *Ratings for the attributes*

The report evaluates in phase two a number of HRA methods viz., THERP, ASEP, THERP-EBT, ATHEANA, NERMOS, NARA, SPAR-H, CBDT, HCR/ORE, CREAM, FLIM, and HuRECA. In phase two, the teams of experts rated these methods for each of the 20 attributes and provided a justification for the ratings. They used a thee-level scale to rate these methods: *(a) High*, *(b) Intermediate*, and *(c) Low*. In order to benchmark the methods in terms of scores represented by numbers, we assigned a percent value to these three ratings as explained below.

- **High** (percent value 100%) represents that the method was able to meet significantly the requirements expected by the guideline of that attribute provided in the table 8.
- **Intermediate** (percent value 66.66%) rating suggests that the method met a certain requirements but not all the expected requirements cited in the attribute description.
- **Low** (percent value 33.33%) rating against an attribute indicate that either the method could not satisfy the expected requirements or the method was not satisfying the requirements evidently.

C. *Results of evaluation*

We used these ratings given by the experts in HRA field to these 20 attributes and calculated average of each of 5 categories described above. In this manner we evaluated five widely used methods (THERP, ATHEANA, NARA, SPAR-H, and CREAM) for five categories and evaluated the results.

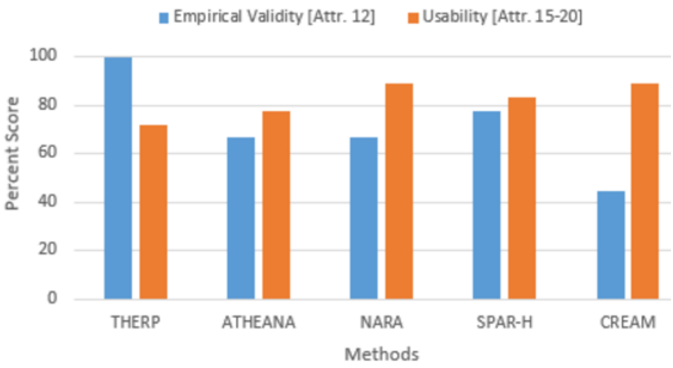


Fig. 10. Empirical Validity and Usability Scores [11]

Figure 9 shows the percent scores of Construct Validity (Group 1) and Content Validity (Group 2) plotted for each of the five methods. We observe that NARA outperforms other method in the category Construct Validation owing to the fact that NARA was developed using a practical database (CORE-DATA) from the nuclear fields. Contrary to this, ATHEANA scores the highest in Content Validity category.

Figure 10 shows the percent scores of Empirical Validity (Group 3) and Usability (Group 5) plotted for each of the five methods. THERP scores the highest in Empirical Validity category with NARA being the second best method. In terms of the usability of the method, NARA and CREAM clearly are the most usable methods because these methods were relatively new and were developed while considering the usability factor for their general applications.

Figure 11 shows the percent scores of Reliability (Group 5). The reliability measures for all the methods except ATHEANA ranges from 50% to 60%.

In order to collocate the methods in a general but not a strict sense, we averaged the scores of all the five groups. Figure 12 shows the mean percent scores for all the five methods. From these results are able to rank the methods relative to each other. We observe that ATHEANA clearly outscores other methods in most of the attributes, and therefore it has the highest percent score of about **86%**. NARA, being a third generation method, also scores comparable to ATHEANA with a percent score of about **83%**. Thus, we are able to rank the methods using the mean percent score for all 20 attributes.

VI. APPLYING NARA TO HRI SYSTEMS

A. *A brief about NARA*

NARA method (2004, Kirwan) for HRA was originally developed for the assessment of human reliability in nuclear power plants. This method was developed with a supporting database called as Computerized Operator Reliability and

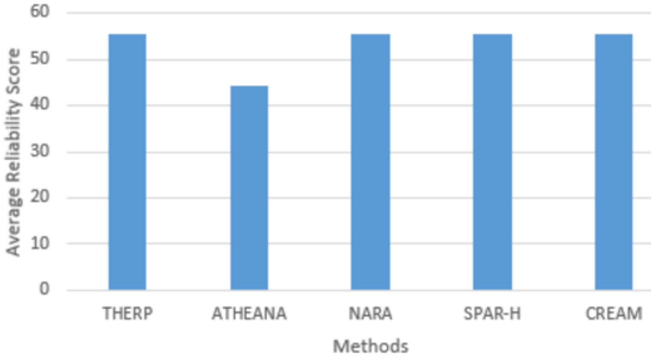


Fig. 11. Average Reliability Score [11]

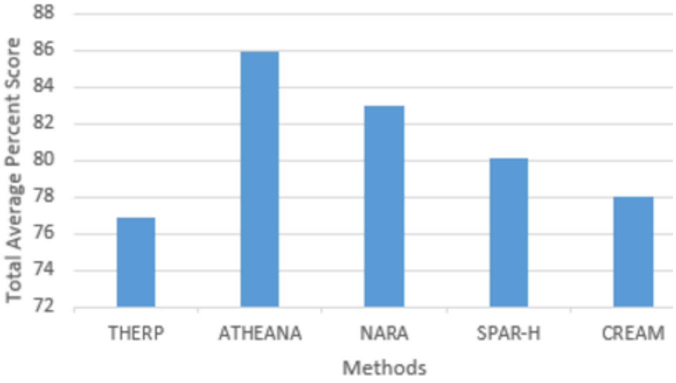


Fig. 12. Average score calculated for all 20 attributes [11]

Error Database (CORE-DATA) of human performance. Validation of NARA on CORE-DATA makes it one of the few methods that were based on the empirical database collected from the nuclear fields [5]. NARA uses similar approach as its parent method HEART to calculate the HEPs. However, NARA was devised using a field dataset and it uses generic tasks that are grouped together into four sets: A, B, C, and D. NARA is capable of analyzing long duration scenarios which are commonly seen in nuclear and even HRI fields. It also incorporates task dependency in the mentioned 14 generic tasks.

The Performance Shaping Factors (PSFs) are called as **Error Producing Conditions (EPCs)** in case of NARA. NARA has a set of 18 EPCs (and more under development as of 2005) that could modify the basic HEP by a factor depending on the degree of effect of the EPCs. Table shown in figure 13 gives some of the EPCs that are listed in the NARA method.

One of the appealing features of NARA is that it can be learned and practiced by an HRA analyst with a necessary experience of approximately an year in the field. Moreover, it is available for free of cost for public use and thus can be adopted by any HRI-based organization. Although, the database on which the method was developed is private and can be purchased if needed for testing purpose.

B. *NARA in HRI*

Owing to the generic nature of the task that model NARA method, it is possible to extend the principles used in NARA to any field other than the nuclear fields where it was originally applied. We can use the given 14 generic tasks that are illustrated in details in the literature [5], [9] and remodel them in order to fit in accordance with the tasks performed in a HRI system. In fact, all of the 14 tasks viz., A1 through A6, B1 through B5, C1 and C2, and D1 can be considered unalterably in case of HRI system. However, instead of reviewing the parameters of nuclear plant (such as set point in B4, stuck open boiler in A4, etc.), we should review the parameters that apply to a HRI plant or factory. These factors could be, for example, calibrate the encoders for motors in robot joints, calibrate the proximity sensors used by the robot controller, and so on.

In NARA, the final HEP after considering the effects of each of the Error Producing Conditions is given by following formula. The same formula will be used in case of HRI system.

$$Final\ HEP = $$

$$Basic\ HEP \times \prod_{i=1}^{n}[(Effect_{EPC(i)} - 1) \times State_{EPC(i)} + 1]$$

where, n is the number of EPCs considered for the task, and $0 \leq State_{EPC(i)} \leq 1$. This value of state is assigned by assessing the nature and degree of severity of the EPC affecting human actions. It assumes a value of 0 for best and positive effect and 1 for worst and negative effect on the human actions.

In following section we will analyses a few typical examples in HRI fields wherein presence of human operating along with the robots might give rise to an erroneous situation leading to the failure of the task in hand.

C. *Examples of NARA applied to HRI system*

1) *Example 1:*

- **Scenario:** Consider a student intern working in Wolf Robotics under some time pressure (EPC 3). Since it is an intern, we should expect operator inexperience (EPC 8). Suppose the student is working with a little illness (EPC 17).
- **Task:** The student is supposed to perform a *generic task* “Start or reconfigure a system from the Local Control Room following procedures, with feedback” (A3 in NARA generic task table; HEP = 0.003)
- **HEP Calculation:** The ‘Effects’ of EPC 3, 8, and 17 are respectively 11, 8, and 2. Also assume that the state multipliers for each of these EPCs to be 0.9 (close to

worst), 0.75 (bad), and 0.25 (close to best). Using the formula above to calculate the final HEP as follows:

Final HEP = 0.003 * [(11-1)*0.9 + 1]*[(8-1)*0.75 + 1]*[(2-1)*0.25 + 1] = **0.234375**.

- **Conclusion:** Therefore, under the given circumstances there is a probability of 0.2343 that the student intern will cause some error.

2) *Example 2:*

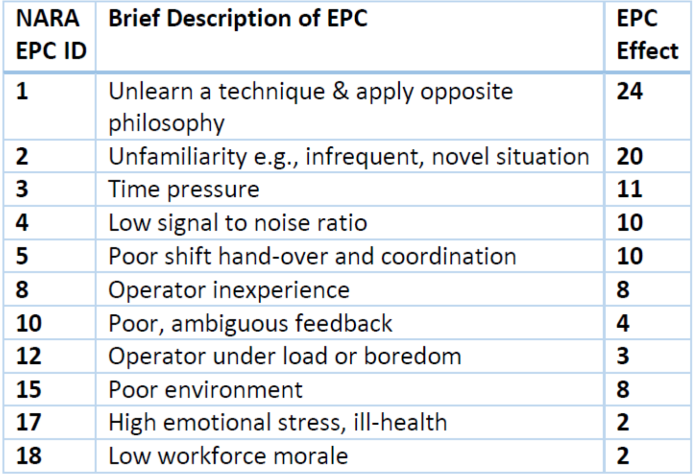
- **Scenario:** Consider an employee monitoring a Welding Robot in a low-light poor operating environment (EPC 15). Suppose that the operator is at the end of his shift and user boredom (EPC 12) and he is required to finish the job in hand in moderately under-constraint time period (EPC 3).
- **Task:** The employee is supposed to perform a *generic task* "Carry out simple single manual action with feedback. Skill-based and therefore not necessarily with procedure" (A1 in NARA generic task table; HEP = 0.005)
- **HEP Calculation:** The 'Effects' of EPC 15, 12, and 3 are respectively 8, 3, and 11. Also assume that the state multipliers for each of these EPCs to be 0.5 (moderate), 1 (worst), and 0.5 (moderate). We get the final HEP as follows:

  Final HEP = 0.005 * [(8-1)*0.5 + 1]*[(3-1)*1 + 1]*[(11-1)*0.5 + 1] = **0.405**.
- **Conclusion:** Therefore, there is approximately 40% chance that the experienced employee might cause an error in while monitoring the welding robot under the given circumstances.

3) *Example 3:*

- **Scenario:** Suppose that an inexperienced factory worker has just walked in for his shift of controlling a Palletizer Robot. Since the worker is not well experienced we can expect that he has not faced some rare breakdown phenomenon in the robot (EPC 2). Suppose that he has not been properly warned about this situation by his co-worker who just finished his shift (EPC 5). Also, the guideline procedures are not informative enough to explain the situation to the worker (EPC 11).
- **Task:** The worker should respond to the alarm set off by the rare phenomenon. This is described by the *generic task* "Judgment needed for appropriate procedure to be followed, based on interpretation of alarms/indications, situation covered by training at appropriate intervals." (A5 in NARA generic task table; HEP = 0.01)
- **HEP Calculation:** The 'Effects' of EPC 2, 5, and 11 are respectively 20, 10, and 3. Also assume that the state multipliers for each of these EPCs to be 0.7 (almost worst), 0.2 (close to best), and 0.6 (moderate). We get the final HEP as follows:

  Final HEP = 0.01 * [(20-1)*0.7 + 1]*[(10-1)*0.2 + 1]*[(3-1)*0.6 + 1] = **0.8808**.



NARA EPC ID	Brief Description of EPC	EPC Effect
1	Unlearn a technique & apply opposite philosophy	24
2	Unfamiliarity e.g., infrequent, novel situation	20
3	Time pressure	11
4	Low signal to noise ratio	10
5	Poor shift hand-over and coordination	10
8	Operator inexperience	8
10	Poor, ambiguous feedback	4
12	Operator under load or boredom	3
15	Poor environment	8
17	High emotional stress, ill-health	2
18	Low workforce morale	2

Fig. 13. Example Error Producing Conditions (EPCs) in NARA [5]

- **Conclusion:** In given scenario, there is about 88% chance that the inexperienced worker will fail to handle the alarm in a proper manner.

4) *Example 4:*

- **Scenario:** Let us assume that a regular worker operating in a control room that controls a set of robots in the immediate environment. He is receiving an overload of information from the different feedback consoles connected to different robots. The information is arriving simultaneously and it is non-redundant in the sense that the worker must register all the information and respond appropriately (EPC 9). Given the overload of information and the lone operator, the operator tend to follow a shorter and dangerous procedure to respond to the information (EPC 14).
- **Task:** The worker should register the simultaneous information analyze it for further use. This is described by the *generic task* "Carry out analysis." (B5 in NARA generic task table; HEP = 0.03)
- **HEP Calculation:** The 'Effects' of EPC 9 and 14 are respectively 6 and 2. Let the state multipliers for each of these EPCs to be 0.9 (almost worst) and 1 (worst). We get the final HEP as follows:

  Final HEP = 0.03 * [(6-1)*0.9 + 1]*[(2-1)*1 + 1] = **0.33**.
- **Conclusion:** We can conclude that, the worker will cause some error while carrying out the analysis of the received

information with a probability of about 33%.

In this way, analyzing the various scenarios that occur frequently or rarely in an HRI system would help in predicting the outcomes of a task in terms of the probabilities of success and failure. These examinations calculating human error probabilities a priori help in assigning and adjusting the human resources so as to achieve the maximum throughput in terms of time and human hours. Moreover, it helps in avoiding disastrous situations that would otherwise need extended amounts of time and resources to recover to a normal state.

VII. Conclusion

A thorough overview of the most widely used HRA techniques provides us a guidance to choose a specific technique provided that we know the characteristics of the human-involved system to be analyzed. For the application fields other than the ones (e.g., nuclear, aviation, transportation) over which the mentioned HRA techniques are developed, we must choose an HRA technique that provides a higher flexibility. The generic nature allows us to modify the technique in order to make it compatible for our applications. Therefore, choosing a technique such as SPAR-H, NARA gives us a higher generality and flexibility for generic tasks and the PSFs i.e., EPCs.

Evaluation of a few methods using the metrics defined by NEA shows that ATHEANA and NARA score the most in all five categories listed in the NEA report.

Illustrations of modifying NARA method for HRI application show that NARA is a generic method capable of adopting to a variety of non-nuclear applications. NARA's solid foundation based on empirical CORE-DATA makes it a validated and reliable method to use. It is possible to remodel the method by altering the generic tasks and EPCs that represent some specific applications as we showed for a particular case of HRI system. Therefore, we can conclude that NARA has a potential to get generalized for a human-robot interaction system.

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