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# Developments and perspectives in human factor engineering: a critical analysis

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**Abstract.** Human dysfunctions must be given special attention, because the human operator represents the central element of safety. The human operator is targeted in a double position: both as a potential victim of an accident and as a source of insecurity or guarantor of safety. Consequently, the modeling of human behavior plays a role of primary importance in the analysis of related dysfunctions and in the integration of the results of this analysis in the global assessment of any work system. Although a large percentage of accidents are attributed to human error, the integration of human contribution into the safety of technical systems is often rudimentarily analyzed in industrial engineering. The focus is on reliability, availability, maintenance and especially security. Starting from the exact radiography of this factual reality, the present research materialized a critical analysis of the evolution of the available techniques for assessing human reliability, highlighting and emphasizing their strengths and limitations, from an evolutionary perspective. The results obtained provide Romanian experts with a realistic and scientifically based landscape, which would be the basis of concrete strategies and measures to minimize the dysfunctions associated with the human factor in industrial manufacturing activities, with the possibility of expanding the applicability of the results in other types of organizations affected by human fallibility.
**Keywords:** *Human Factor Engineering, Human Reliability Analysis, Performance Shaping Factors, Human Error Probability, Probabilistic Risk Assessment, cognition, safety culture*

## 1. Introduction

Human factors engineering (HFE) is the scientific and engineering discipline concerned with improving human performance and reducing human error in complex systems. HFE is a ***fusion of behavioral science*** and ***systems engineering*** and aims to integrate people into the workplace. The discipline had its beginnings in the aviation and aerospace industry. Figure 1 shows the IAOGP (International Association of Oil and Gas Producers) model of human factors [1].

It is important to note that although human error is the main object of study in Human Reliability Analysis (HRA), it must be analyzed taking into account possible causes and the specific context. Indeed, one of the undisputed assumptions in HRA approaches is related to the fact that the quality of human performance depends on the conditions in which tasks or activities are carried out [2]. These conditions, in turn, were named ***P****erformance* ***S****haping* ***F****actors* (PSF ) or ***P****erformance* ***I****nfluencing* ***F****actors* (PIF), and serve to either enhance or degrade human performance relative to the expected action. PSFs/PIFs can reflect organizational aspects (e.g. safety culture or climate, leadership, etc.); personal ones (e.g. work motivation) and others [3].

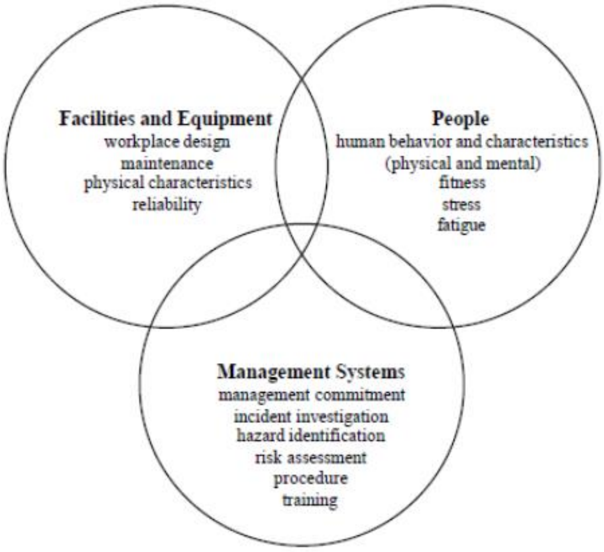


**Figure 1.** Human factors and their basic interactions

Human errors can generally be classified as ***errors of omission*** – when an operator fails to act, i.e. fails to perform a certain task, and ***errors of commission*** – when an operator fails to act, i.e. perform a task in a certain wrong manner, or at the wrong time. Human reliability is the probability that people will perform specific tasks with satisfactory performance. Tasks can be related to equipment repair, equipment or system operation, safety actions, analysis and other types of human actions that influence the overall performance of any complex socio-technical system [4].

## 2. Human reliability analysis in complex industrial systems

Evidence from specialized literature shows that human actions are a source of vulnerability for industrial systems, giving birth to HRA, Human Reliability Analysis, a discipline that aims to deepen the examination of the human factor at work [5].

The birth of HRA methods dates back to the year 1960, but most human factor evaluation techniques in terms of propensity to fail have been developed since the mid-1980s. Human reliability studies are a relatively recent field of research; its history can be traced back to 1952, when it was first approached for feasibility as a weapons system at Sandia National Laboratories, USA [6].

The first formal method for HRA was presented in November 1962 at the Sixth Annual Meeting of the Human Factors Society, followed by a monograph from Sandia Laboratories that included the development of the first human error quantification tool. This method, called ***T**echnique of **H**uman **E**rror **R**ate **P**rediction* (THERP), is still in use [7].

Throughout the 1980s, the number of HRA methods increased significantly. It is possible to see a strong correlation between the accident at Three-Mile Island on March 28, 1979 – which was the worst accident in the history of US commercial nuclear power plant operation – and the increase in the number of HRA methods [8].

HRA deals with identifying, modeling and quantifying the probability of human error (HEP – *Human Error Probability*). The nominal probability of human error (HEP) is calculated based on operator activities, and to obtain a quantitative estimate of HEP, many HRA methods use performance shaping factors (PSFs), which characterize significant aspects of human error and provide a numerical basis for changing nominal levels of HEP values. PSF are environmental, personal, or activity-directed factors that have the potential to affect performance positively or negatively; therefore, identifying and quantifying the effects of a PSF are key steps in the HRA process. Another key step concerns the interpretation and simulation of human behavior, which is a dynamic process driven by cognitive and behavioral rules and influenced by physical and psychological factors [9].

Human behavior, although analyzed in numerous studies, remains difficult to fully represent in the description of all the nuances that characterize it. It is very clear how complex the effort has been in the literature to propose models of human behavior, favoring numerical values of the probability of error to predict and prevent unsafe behaviors.

For this reason, the study of human reliability can be seen as a specialized scientific subfield – a hybrid between *psychology, ergonomics, engineering, reliability analysis and system analysis*. Human reliability analysis plays an important role in the overall reliability analysis of a human-machine system. Industrial accidents like Bhopal, Three Mile Island, Chernobyl, Piper Alpha and Fukushima are examples of human failures and show how catastrophic the consequences can be [10].

HRA began as a purely quantitative discipline that closely followed the steps of probabilistic risk analyzes PRA (***P****robabilistic* ***R****isk Assessment*). The HRA community was aware of the simplifying assumptions made when treating people as technical components, but the empirical validity of HRA estimates only began to be questioned in the 1990s, as a direct consequence of the experience gained using early HRA techniques, which later expanded considerably. A new generation of methods, developed for deeper integration with risk analysis, aimed to better model the complexity of human performance [11].

Human reliability is directly related to staff competencies. A cornerstone of a new nuclear program, for example, is to have sufficient professionals with the necessary skills available in time [12].

Despite several differences between particular methods, HRA is often described as involving three distinct phases:

1. *Modelization of potential human errors* – by enlisting a variety of task analysis to break down a general sequence of events into smaller units suitable for analysis. There is no universally agreed standard for the best level of decomposition.
2. *Identification of potential contributors to human error* – through the selection of relevant performance shaping factors. As with task decomposition, there is no standard list of performance modeling factors and there is considerable variability among HRA methods, in this respect.
3. *Human errors quantification* – by calculating a human error probability (HEP). Each HRA method presents a different approach to quantification, including expert estimation, use of PSF multipliers, Bayesian approaches, and simulations. Quantification determines the probability that the particular action modeled in the previous steps will fail.

Some of the most relevant best practices are summarized in the following, as ***imperative general requirements***:

1. The HRA assessment should involve a complex multidisciplinary team and should include field observations, review/study/analysis of documents of the facility/system under review, and discussions with operators and technical and management staff of the facility/system;
2. The analysis should take into account the interdependencies between the probabilities of the materialization of human errors that may manifest themselves within an accident-causing sequence;
3. HRA should address both diagnostic and execution failures;
4. System-specific and activity-specific performance shaping factors (PSFs) should be included in detailed assessments;
5. All analyzes should define and consider recovery actions;
6. Analyzes should simultaneously address both errors of commission and errors of omission;
7. The application of human reliability analysis techniques must be sufficiently well/rigorously documented so that its results are traceable and reproducible.

The basic structure of the stages of applying an HFE method and using HRA data in order to minimize the materialization of human errors is schematized in figure 2.

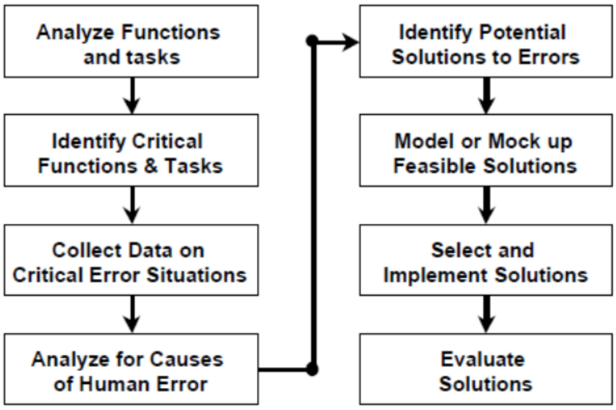


**Figure 2.** The basic structure of the steps of applying an HFE method and using the data to minimize the materialization of human errors

## 3. Evolution and progress in the study of human reliability

HRA techniques or approaches can be essentially categorized and framed, mainly following the criterion of temporality of appearance, into two classes: first generation and second generation. Currently, we are reaching the dynamic, third-generation HRA methods, understood as an evolution of the previous generations.

### *3.1. First generation HRA methods*

HRA methods of the first generation were strongly influenced by the point of view of the probabilistic risk assessment (PRA) and identified the human as a mechanical component, thus eluding all aspects of the dynamic interaction with the work environment, both as an environment physically as well as as a social environment.

In many of these methods—such as the *Technique for Human Error Rate Prediction* (THERP), the *Accident Sequence Evaluation Program* (ASEP), and the *Human Cognition Reliability* (HCR) - the underlying assumption is that, because they have natural deficiencies, people logically fail to perform correctly, all the time, the tasks assigned to them, as is the case with mechanical / electrical / technical components in general [13].

Thus, human error probability (HEP) can be assigned based on operator task characteristics and then modified by performance modeling factors (PSF). In the first generation of HRA methods, the characteristics of a task, represented by the HEP, are considered major factors; context, which is represented by PSF, is considered a minor factor in estimating the probability of human failure. This generation focused towards the quantification component in terms of success/failure of the action, paying less attention to the depth of the causes and reasons of human behavior, which are aspects studied predominantly in the behavioral sciences [14]

THERP and approaches developed in parallel (such as HCR *Human Cognition Reliability*, developed by Hannaman, Spurgin and Lukic in 1985) describe the cognitive aspects of operator performance through the cognitive modeling of human behavior, based on the *Skills* - *Rules* - *Knowledge* model (SKR model), developed by Rasmussen (1984) [15].

We now only briefly specify (for reasons related to the continuity of the evolutionary exposition of the tools) the fact that this model is based on the classification of human behavior based on skills, rules and knowledge, depending on the cognitive level used (fig. 3). The attention and conscious level of thought an individual gives to the activities they perform decreases in this model, moving from level three to level one. This pattern of behavior fits very well with Reason's (1990) theory of human error, according to which there are several types of errors, depending on the results of actions implemented/materialized according to the intentions of the human operator.

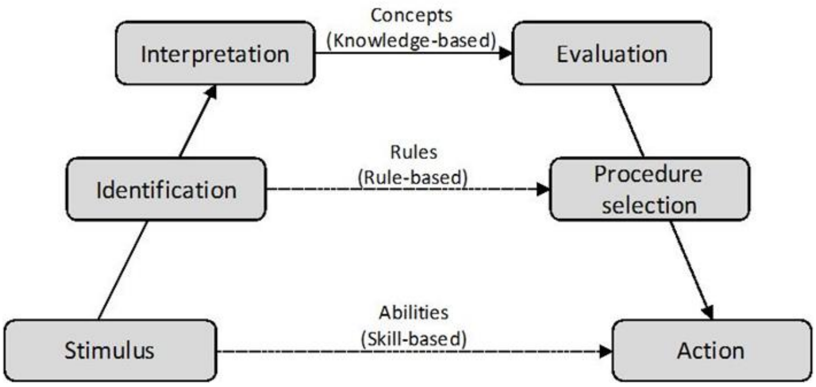


**Figure 3.** Rassmusen's SKR model (adapted from Rasmussen, 1984)

Reason emphasizes the distinction between: *misses*, understood as execution errors that occur at the skill level; *omissions*, i.e. execution errors generated by a memory malfunction; *mistakes*, which they consider as errors committed during the practical implementation of the action [16], [17].

Instead, in the THERP method, wrong actions are subdivided into *errors of omission* and *errors of commission*, which represent, respectively, the failure to perform the operations necessary to achieve the result and the execution of an operation that is not related to the respective request and which prevents the achievement of the result.

The *main characteristics of the first generation methods* can be summarized as follows:

a. Simplified binary representation of human operator actions (success/failure);
b. Special attention given to the phenomenology of human action;
c. The reduced emphasis placed on human cognitive actions (absence of a cognitive model);
d. Major emphasis on quantifying the probability component of the incorrectness of human actions;
e. Dichotomy between errors of omission and errors of commission;
f. Indirect treatment of context.

Among the first generation techniques are:

- APJ – ***A**bsolute **P**robability **J**udgement*;
- HEART - ***H**uman **E**rror Assessment and **R**eduction **T**echnique*,
- JHEDI - *Justified **H**uman Error **D**ata **I**nformation*;
- PHRA - ***P**robabilistic **H**uman **R**eliability **A**nalysis*;
- OATS - ***O**perator **A**ction Tree System*;
- SLIM - ***S**uccess **L**ikelihood **I**ndex **M**ethod*.

From these, the most frequently and efficiently used method is THERP, characterized, like other first-generation approaches, by a precise mathematical treatment of probabilities and error rates, as well as by the development of well-structured computer programs for interfacing with trees evaluation of human error by means of associated event and fault trees. The foundation of THERP lies in event tree modeling, where each branch represents a combination of human activities, influences on these activities, and outcomes of these activities. The basic analytical tool for human reliability analysis is represented by the related graphics and symbols, shown in fig. 4. First-generation HRA methods are shown to have a sufficient level of user experience, but are not able to provide sufficient prevention and adequately perform their tasks. The basic criticism of the adequacy of traditional methods is that these approaches tend to have a descriptive character of events and that only the formal aspects of external behaviors are observed and studied in terms of errors, without considering the reasons and mechanisms that cause them. These methods ignore the cognitive processes underlying human performance and in fact possess a cognitive model without adequate human and psychological realism.

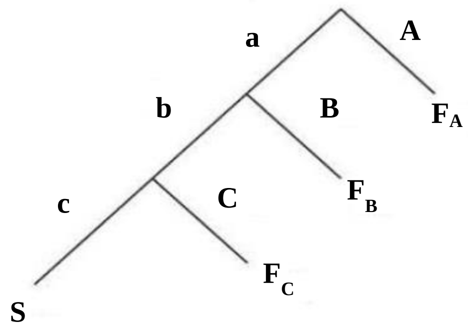


**Figure 4.** The principle scheme of building the HRA-THERP event tree
*(Each node in the tree is linked to an action, the sequence of which is displayed from top to bottom. From each node come two branches: The left branch, marked with a small letter, indicates success; the other, on the right and marked with a capital letter, indicates failure)*

They are frequently criticized for not taking into account the impact of factors such as the environment, organizational factors and other relevant factors shaping human performance. Despite the criticisms and disadvantages/limitations mentioned, they are regularly used in many industrial fields due to their ease of use and highly quantitative aspects.

*3.2. Second generation HRA methods*

In the early 1990s, the need to improve HRA approaches became a priority for a number of important research and development activities worldwide. These efforts generated significant progress, leading to the emergence/development of new techniques, identified as being part of the generic term "*second generation*". These HRA methods were quickly regarded as vague and uncertain, substantially because the methods were defined in terms of *what they should not be*—that is, they should be like the first generation of HRA methods. While first-generation HRA methods are largely behavioral approaches, second-generation HRA methods aspire to be *conceptual*.

The separation between generations of methods is evident in the abandonment of the quantitative approach to PRA/PSA in favor of greater attention to the qualitative assessment of human error. The focus was placed on the cognitive aspects of human behaviors, on the causes of errors rather than on their frequency, on the study of the interaction of factors that increase the probability of error and on the interdependence of performance shaping factors. HRA methods belonging to the second generation are based on a cognitive model more suitable for explaining human behavior. Clearly, any attempt to understand human performance must include the role of human cognition, defined as "*the act or process of cognition that includes both awareness and judgment*" by an operator [18].

From the perspective of the HRA practitioner, the immediate solution to consider human cognition in HRA methods was to introduce a new category of error: "*cognitive error*", defined as both the failure of an activity that is predominantly cognitive in nature and the inferred outcome as the cause of a failing activity. For example, in the ***CREAM method***, developed by Erik Hollnagel in 1993, the division between logical causes and consequences of human error was maintained. The causes of inappropriate behavior (genotypes) are the reasons that determine the appearance of certain behaviors, and the effects (phenotypes) are represented by the incorrect forms of the cognitive process and inappropriate actions [19].

Moreover, second-generation HRA methods aimed at the qualitative assessment of operator behavior and the search for patterns that describe the interaction with the production process. Cognitive models have been developed, which represent the logical-rational process of the operator and summarize the dependence on personal factors (such as stress, incompetence, etc) and on the current situation (normal driving system, abnormal conditions or even emergency conditions), such as and human-machine interface models, which reflect the production process control system. From this perspective, man must be seen in an integrated system, MTO - *Man* - *Technology* - *Organization*, or as a team of operators who collaborate to achieve the same objective, intervening in the technological process within a system of organization and management of the company and together represent the available resources [20].

From this perspective, the CREAM model of the human operator is more meaningful and less simplistic than that of first-generation approaches. The applied cognitive model is the ***contextual control model*** (COCOM), based on the hypothesis that human behavior is governed by two basic principles: *the cyclical nature of human cognition (fig. 5)* and *the dependence of cognitive processes on the context and work environment* [21].

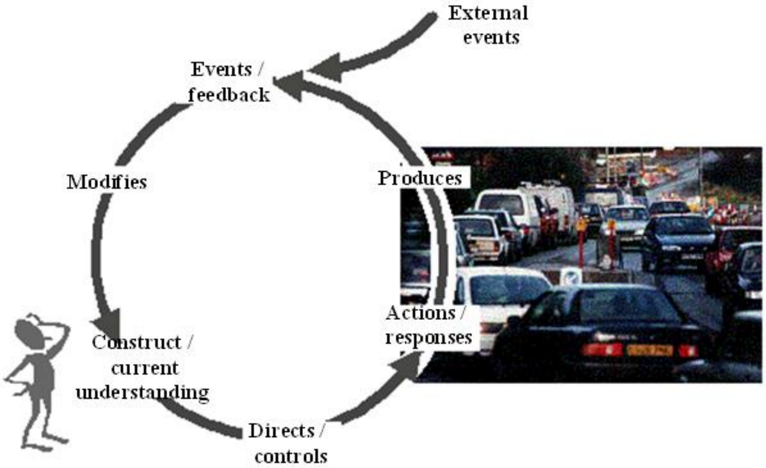


**Figure 5.** The basic cyclic model of human action (adapted from Hollnagel, 2016)

The model separately considers cognitive functions (perception, interpretation, planning and action) and their connecting mechanisms and the cognitive processes that govern evolution. Effective control requires that the user – and more generally the control system – be able to interpret events and find and choose effective action alternatives.

In the cyclic model of human action (fig. 6), the two arcs called "*event evaluation*" and "*action selection*" represent these activities. Associated with the former is the time required to evaluate events ($T_E$), while associated with the latter is the time required to select action alternatives ($T_S$). The time required to do both must be interpreted in relation to the time available ($T_A$) as well as the estimated – and required – time to perform an action ($T_P$). In most industrial fields, tasks are "force" paced—or process paced - rather than an operator's own pacing. The time available, $T_A$, is limited by the speed of the process and if ($T_E + T_S$) exceeds $T_A$, it imposes severe constraints on the ability of users/operators to evaluate events and select actions. Some processes, such as working on steel mills, e-commerce, or flying an airplane require fast or even near-instantaneous responses. Other processes, such as power generation, land transport or surgical interventions have less severe time requirements, but still require decisions and actions to be taken and implemented within a limited time.

It would clearly be better if enough time were available, i.e. if ($T_E + T_S$) were less than $T_A$, because the human operator would have more time to refine their current understanding, to plan before act, so be in control of the situation. This can be achieved if the time constraints can be relaxed, for example by slowing down the process. A more common/frequent approach is to reduce either $T_E$ or $T_S$ by improving system and interface design, although this has usually been done piecemeal. This corresponds to the basic finding and reality that humans, unlike machines, can be more or less thorough in what they do, depending on, among other things, the time available. This reveals a unique way of conceptually expressing the time-control dependence, as well as a simple way of implementing it from a computational point of view.

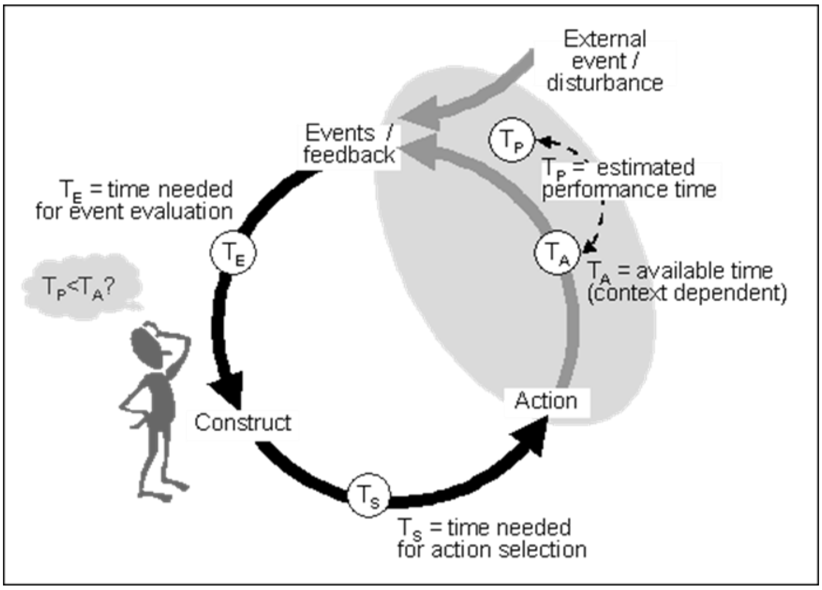


**Figure 6.** Time and control in the cyclic COCOM model of human cognition (adapted from Hollnagel, 2016)

The ***Standardized Method for Human Risk and Reliability Analysis*** (SPAR-H) is built on an explicit model of information processing associated with human performance, derived from the *behavioral science* literature [22].

An information processing model is a representation of perception and perceptual elements, memory, sensory storage, working memory, search strategy, long-term memory, and decision-making. The components of the behavioral model specific to the SPAR-H method are presented in figure 7.

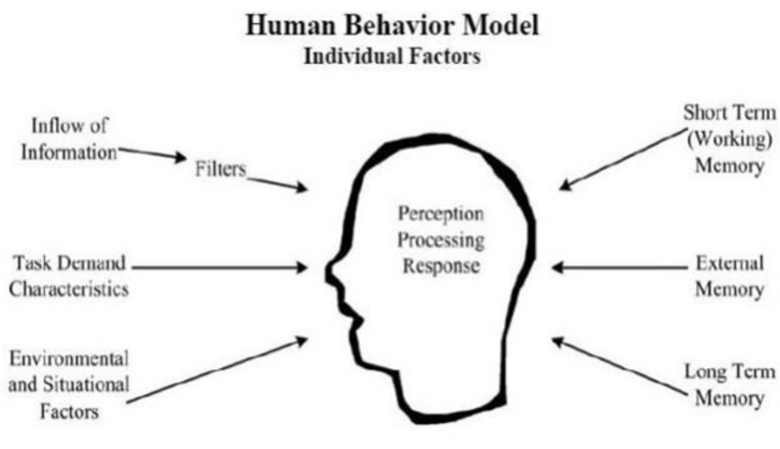


**Figure 7.** The human performance model for the foundation of SPAR – H (adapted from Gertman et al., 2005)

Another difference between the first and second generations of methods refers to the way of choosing and using the performance shaping factors (PSF). None of the first-generation HRA approaches attempt to explain how PSFs exert their effect on performance; In addition, performance-shaping factors – such as managerial methods and attitudes, organizational factors, cultural differences and irrational behavior – are not adequately addressed in these methods. The first generation PSFs were mainly obtained by focusing on the environmental impact on the operators, while the second generation PSFs were obtained by focusing on the cognitive impact on the operators. Among the methods of the second generation can be mentioned:

- ATHEANA - A Technique for Human Error Analysis,
- Cognitive Environmental Simulation (CES),
- Connectionism Assessment of Human Reliability (CAHR);
- Methode d'Evaluation de la Réalisation des Missions Opérateur pour la Sûreté (MERMOS).

*3.3. Current generation of methods (third generation)*

In recent years, the limitations and shortcomings of second-generation HRA methods have led to further developments related to the improvement of pre-existing methods. The only method now defined as *third generation* is NARA – *Nuclear Action Reliability Assessment*, and it is actually an advanced version of the HEART method for the nuclear domain. The shortcomings of the second generation methods, highlighted above, were the HRA experts' starting point for new research and improvement of existing methods [23].

Some of the more recent studies focused on the ***lack of empirical data for the development and validation of an HRA model*** and aimed to define the HRA database that could provide the methodological tools needed to use more types of information in future HRAs and reduces the uncertainties associated with the information used to make human reliability assessments. There are currently several databases for HRA analysts that contain human error data, with bibliographic sources cited, to improve the validity and reproducibility of HRA results. Examples of such databases are HERA (*Human Event Repository and Analysis - NUREG/CR-6903*), SACADA and HFIS (*Human Factors Information System*).

From another perspective, PSFs are an ***integral part of error modeling and characterization*** and play an important role in the human reliability assessment process; for this reason, in recent years, HRA experts have focused their efforts on PSF. Despite continuous advances in research and applicability, one of the main weaknesses of current HRA methods is their limited ability to model the mutual influence between PSFs, seen both as a dependence between the individual states of the PSFs and from the perspective between the influences ( impact) of PSFs on human performance (fig. 8).

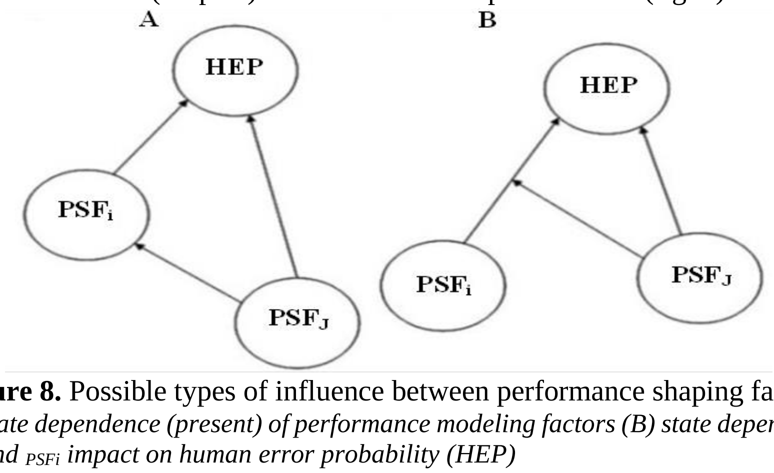


**Figure 8.** Possible types of influence between performance shaping factors
*(A) state dependence (present) of performance modeling factors (B) state dependence $PSF_j$ and $_{PSFi}$ impact on human error probability (HEP)*

Some HRA methods—such as CREAM, SPAR-H, and IDAC—attempt to provide guidance on how to deal with dependencies at the level of factor ratings, but do not consider that a PSF category may depend on itself and that the presence a certain PSF could modulate the impact of another PSF on the HEP; therefore, they do not adequately take into account the relationships and dependencies between PSFs. In contrast, the study by De Ambroggi and Trucco (2011) deals with the development of a framework for modeling the mutual influences existing between PSFs and the development of a related method to evaluate the importance of each PSF in influencing the performance of an operator, in a specific context, taking into account these interactions (fig. 9) [24]

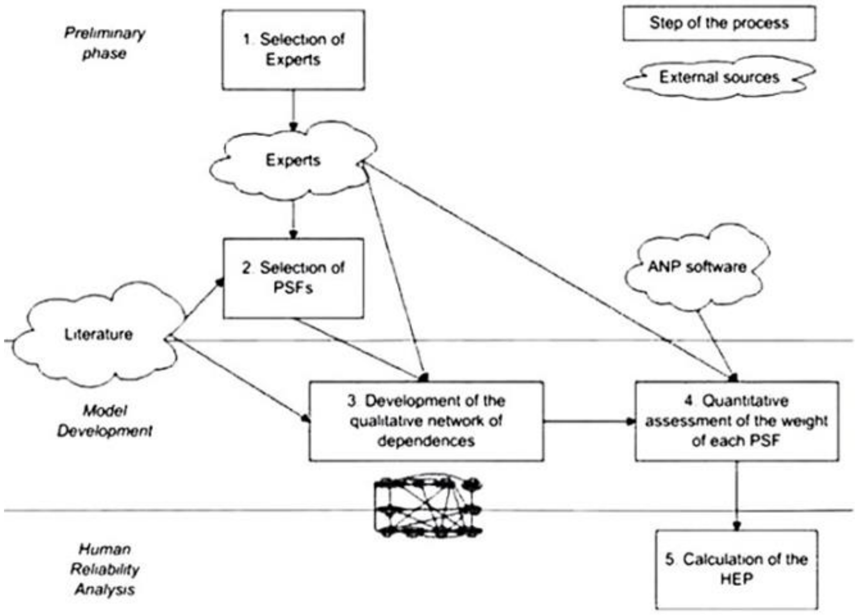


**Figure 9.** The structure of the modeling procedure and evaluation of the mutual influence between the performance modeling factors
(adapted from De Ambroggi şi Trucco, 2011)

Another limitation of current HRA methods is the ***heavy reliance on expert opinion*** to assign values to PSFs; in fact, during this attribution process, subjectivity plays an important role, causing difficulties in ensuring the consistency of the process. To overcome this problem and obtain a more accurate estimate, Park and Lee (2008) suggest a new and simple method: **AHP–SLIM**. This method combines the AHP (*Analytical Hierarchical Process*) decision tool – a multi-criteria decision method for complex problems where qualitative and quantitative aspects are considered to provide objective and realistic results – with the *Success Probability Index Method* (SLIM), a simple method and flexible of the expert for HEP estimation [25], [26].

The real development concerns today, however, are related to the so-called ***reliability dynamics methods***. Cacciabue (2013) emphasized the importance of simulation and dynamic modeling of human performance for the field of HRA. Specifically, simulation and modeling address the dynamic nature of human performance in a way not found in most previous HRA methods. A cognitive simulation consists of reproducing a model of cognition using a numerical application or computational software [27].

As illustrated in fig. 10, simulation and modeling can be used in three ways to capture and generate data that is meaningful to HRA:

- simulation exercises produce logs (databases) that can be analyzed by experts and used to substantiate and rigorously document the process of estimating the probability of human error;
- simulation can be used to produce PSF estimates, which can be quantified to produce/generate human error probabilities;
- a final approach is to establish specific performance criteria by which virtual human operators in the simulation are able to succeed or fail at certain tasks. Through enough iterations of the task, which systematically explore the range of human performance, it is possible to arrive at a value for the frequency of failure (or success). This value can be used as a reasonable approximation of the HEP.

Concurrent with the advent of simulation and modeling, several authors (e.g. Jae and Park, 1994; Sträter 2004) postulated the need for dynamic HRA and began to develop new HRA methods or modify existing HRA methods to account for dynamic progression of human behavior that led to human failure events [28].

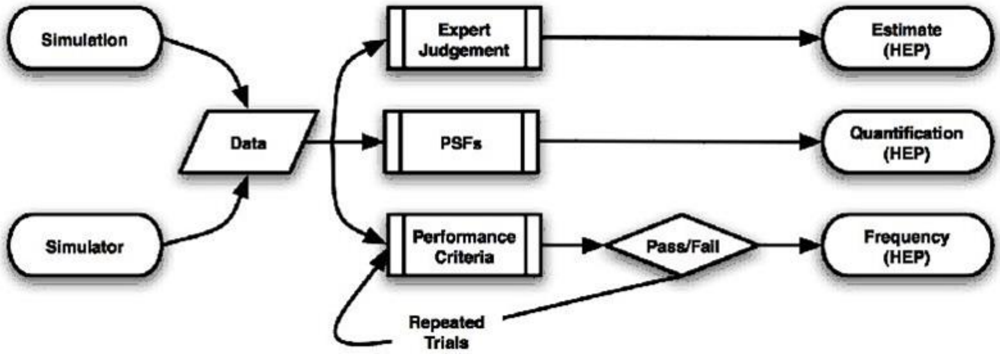


**Figure 10.** Uses of simulation and modeling in human reliability analysis

There is still no modeling and simulation tool that fully or perfectly combines all the basics of HRA simulation. There is, however, significant ongoing research, such as the PROCOS simulator, developed by Trucco and Leva in 2015 [29], [30] or the IDAC system, which combines a realistic plant simulator with a cognitive simulation system capable of model the PSF [31].

In addition to systems such as MIDAS (*Man-machine Integration Design and Analysis System*), where error modeling has already been included, further efforts are being made to instill the SPAR-H specific PSF into the simulation system [32].

PROCOS is a probabilistic cognitive simulator for HRA studies, developed to support human reliability analysis in complex operational contexts. The goal is to integrate the quantification capabilities of HRA methods with a cognitive assessment of the operator (fig. 11).

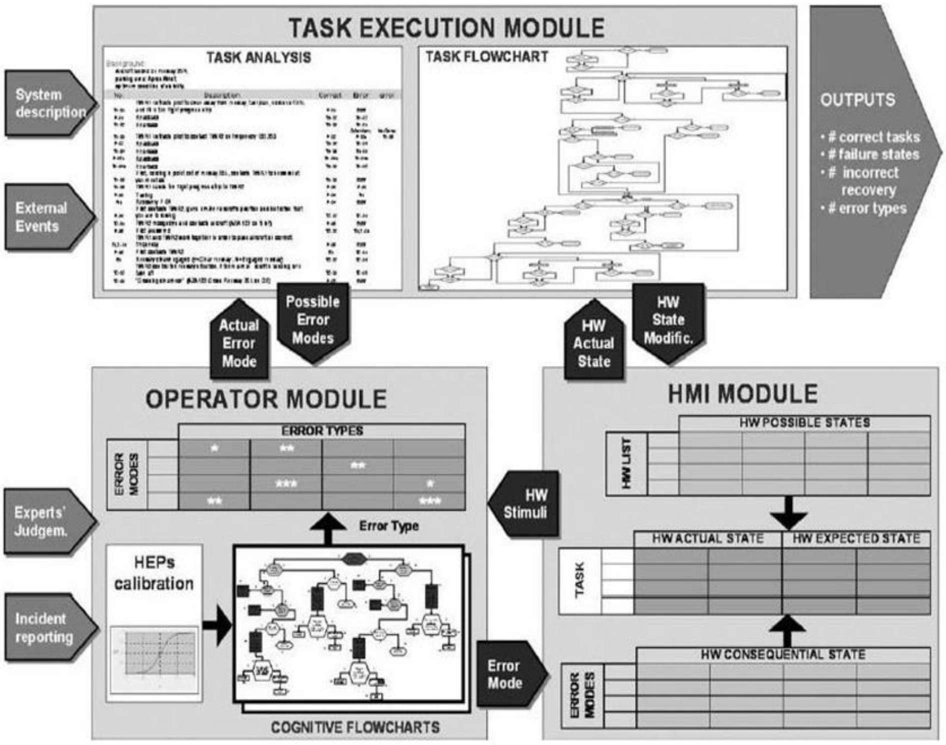


**Figure 11.** Architecture of the PROCOS simulator

The IDAC model is a model of operator behavior developed based on many relevant findings from cognitive psychology, behavioral science, neuroscience, human factors, field observations, and various first- and second-generation HRA approaches. At a high level of abstraction, IDAC is composed of models of information processing (I), problem solving and decision making (D), and action execution (A) by a team of human operators (C). Due to the variety, volume and level of detail of the input information, as well as the complexity of applying its internal rules, the IDAC model can currently only be implemented through a computer simulation (fig. 12).

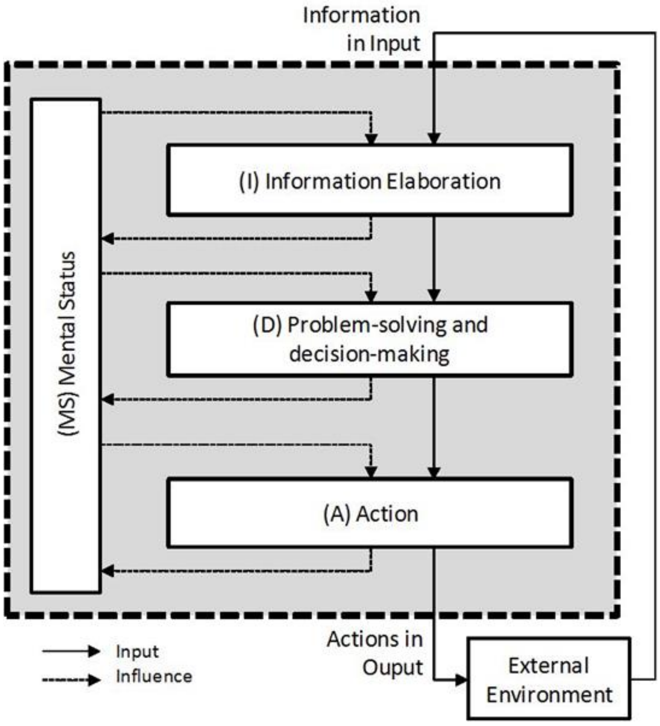


**Figure 12.** The IDAC model of human operator cognitive flow
(adapted from Chang and Mosleh, 2007)

IDAC covers the various phases of dynamic operator response, including situation assessment, diagnosis and recovery actions in dealing with an abnormal situation.

## 4. Conclusion and recommendation

Although human reliability analysis has evolved a lot as a discipline over the past four decades, many HRA methods still have shortcomings, including the lack of traceability and reproducibility of the analysis. The current efforts of the HRA community to address these deficiencies benefit from an impetus that combines the following aspects:

i. *Increasing the level of understanding of human behavior.* The second generation of HRA tools advanced human error analysis by including aspects of human cognitive response within the developed methods. Since then, there is a growing understanding that HRA should benefit from the fields of cognitive and behavioral sciences. Bringing these sciences into the equation greatly improves HRA's ability to correctly model how operators interact with the system, how failures can occur, and why they occur..

ii. *Data collection initiatives required for human reliability analysis*. Recent efforts in collecting data for use in the HRA include the development of the SACADA database. The *Scenario Authoring, Characterization, and Debriefing Application* (SACADA) database was developed by the U.S. NR (Nuclear Regulatory Commission) to meet the need for data in the HRA. In addition to expert reasoning and cognitive science, HRA methods can now use extensive empirical data to model and quantify human actions.

iii. *Development of more robust quantification methods*. Some HRA methods use simple approaches to quantification, such as a multiplicative method, adjusting a reference number to account for contextual factors. While these may be useful in some applications, HRA can benefit from much more robust quantification frameworks. Methods such as *Bayesian Belief Networks* (BBN) are increasingly used in HRA. The widespread adoption of robust quantification methods is implicit and closely related to the next point.

iv. *Wider access to improved computing power*. Increasingly easy access to powerful software and hardware allows HRA to be performed using more complex models without necessarily increasing analysis time.

v. *The high level of experience gained in the use of HRA*. The nuclear industry has developed and used a variety of HRA methods for a long time. Industry now has extensive experience with the advantages and limitations of applying these methods. Moreover, the specific tools and techniques have extended their applicability in various types of activities and systems – socio-technical complex such as offshore drilling, oil and gas extraction and processing, in the construction industry and in manufacturing processes.

The aforementioned aspects are a major common thread in arguing the state of the art of HRA in the nuclear industry and can be leveraged by the oil and gas industry when implementing/developing/adapting established methods. It is more than possible that the oil and gas, mining, chemical, manufacturing and other industries will not share exactly the same requirements as the nuclear industry (for example, in terms of how and where data collection can be achieved) in this moment, but almost all the elements mentioned above should be considered with utmost seriousness and responsibility in defining a road map/technical evolutionary structures leading to a credible HRA method for various other industries.

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