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Principal Issues in Human Reliability Analysis

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***Abstract*— The purpose of this article is to review the criticisms made to human reliability models. As a result of this review the observations and critiques are grouped into three main issues: (1) model's theoretical basis (including taxonomy and concept's specificity), (2) definition and use of performance shaping factors (PSF) and (3) HRA quantification. The cross-cutting aspects in the three issues suggest the use of a human abilities taxonomy based on cognitive theories and a mathematical tool that allows the quantification of vague parameters.**

***Index Terms*— Human reliability models, human factor, human error**

I. Introduction

THe great majority of authors in human reliability agree that there are no "good enough" methodologies or models to guide human reliability analysis (HRA). "Good" is placed in quotes because it is precisely the purpose of this paper to examine the expectations placed on being a "good" human reliability model or, from another angle, what are the criticisms that involves the phrase "not good enough". Each author shows up some weak aspect of human reliability, and then tries to solve it by some innovation on an existing model or creating a new model.

The first HRA methods date from 1960, but most of the techniques for assessing human factor, in terms of propensity to fail, have been developed since the mid-80. By March 4, 2013 there were 807 methods for safety analysis [1], 174 or them (22%) are human performance analysis techniques and 390 (48%) cover in some way human factors (the factors considered are hardware, software, procedures, organization and human, technical spanning). 73% of the techniques were developed after 1980.

In this paper we review the principal critiques to current HRA models and methods. The review process demonstrated that HRA criticism may be classified in three main issues: (1) model's theoretical basis (including taxonomy and concept's specificity), (2) definition and use of performance shaping factors (PSF) and (3) HRA quantification.

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II. A Review of First and Second HRA Critiques

HRA techniques or approaches can be basically divided into two categories: first and second generation.

The main features of the first generation models are [2]: (1) binary representation of human actions (failure/success), (2) attention on human actions' phenomenology (human error taxonomy), (3) low attention in cognitive actions (lack of a cognitive model), (4) emphasis on quantifying errors, (5) dichotomy of errors (omission and commission), (6) indirect treatment of context. The most common criticism of first generation models is the absence of environmental, organizational and other relevant factors, inadequate treatment of commission errors and inadequate expert judgment methods. In many first generation methods, commission errors are not explicitly identified. The inclusion of commission errors is, in essence, to understand why people make mistakes and under what circumstances [3]. Currently, systems have guards or barriers that automatically compensate the omitted act and make the human error of omission irrelevant [4].

Traditional theories often fail to consider latent errors [5]. Errors that occur outside the immediate control of the plant (administration, design, maintenance) are not instantly visible, but affect many decisions and can manifest suddenly at plant operations´ level [6].

No first generation model explains how PSF exert their effect on performance. Further, in first generation models, human reliability is described in terms of hardware reliability, this assumption is no longer applicable especially in high cognitive demand tasks and in advanced man-machine interfaces [2]. Most theories are based on implicit functions that relate PSF with error probabilities, however, fail to consider the variability, uncertainty and incomplete knowledge that characterizes many domains [7].

First generation models don't have a well-defined classification system, an explicit model and an adequate representation of system´s dynamic interactions [8]. Traditional techniques are often complex and require much time and information to make a correct and complete analysis.

The major disadvantages of probabilistic methods HRA are [9]: (1) lack of reliable information, (2) insufficient criterion to support PSF's selection, (3) are practically restricted to behavior based in rules and skills, and they have a limited ability to assess cognitive behavior, (4) human errors are considered as a phenomenon without attention on their causes. For dynamic and complex actions, des-compositional models (as THERP) fail to capture the underlying causes of human error [10].

Models should account the system ability to recover from human error based on plant feedback [3]. This concept is captured, for example, in the model developed by Subotic et al [11]: they use Recovery Influencing Factors (RIFs) to calculate the Recovery Context Indicator (RCI).

Modern or second generation models are characterized by [6]: (1) consideration of cognitive and organizational factors, (2) refer to cognitive model and/or group / organization model, (3) need to be carried out by a team of experts including experienced operators, design and control engineers, cognitive or work psychologists. Second generation models are focus in error causes rather than error frequency, with emphasis on qualitative aspects, interaction and factors' interdependences [12].

Second generation models introduce a new type of error: "cognitive error" [12]. Technological advances drastically reduce the possibilities of human error at the level of physical activity, but increase the impact of the consequences of reasoning or cognitive errors (usually very rooted to socio technological context). This type of errors, may violate the system protections and become very difficult to be controlled and contained [6].

The deficiencies of second generation models are [12]: (1) lack of experimental data for model´s validation and development, (2) deficiencies in human behavior model (better inclusion of cognitive aspects), (3) large variability in implementation, (4) high reliance on expert judgment.

Second generation models don't consider adequately the interrelationships and dependencies of performance factors. Despite the advances of the second generation HRA techniques, the problem of subjectivity and uncertainty of input information remains [8].

III. Main issues in human reliability

Principal issues in HRA are: (1) model's theoretical basis (including taxonomy and concept's specificity), (2) definition and use of performance shaping factors (PSF) and (3) HRA quantification.

A. *HRA model's theoretical basis*

One of the most discussed aspects of human reliability methods is their theoretical basis, i.e. what are the theoretical foundations that support the method. Kirwan [13] states that models based on theories are required in HRA rather than expert judgment or taxonomies based on incidents. Many early models emerge from risk analysts´ experience, and consider human reliability as an emergent property of systems. The assumptions of first generation HRA model aren't theoretically supported [13].

A full understanding of errors and their causes will result in more effective prevention and mitigation strategies [14]. A theoretical and empirical development will place HRA in a more scientific training, since many techniques are more an art to help evaluator [13].

Many models describe human error from the behavioral point of view; there is an absence of cognitive depth [15]. First and many second generation HRA models are dominated by an engineering fashion, i.e. human reliability is taken as analogous to mechanical reliability of components, this favors the decomposition of human tasks in simple acts and validate the use of PSF, assuming independence and linearity [16]. Consequently, man-machine systems' reliability is not addressed in a deep cognitive level and human performance has no proper treatment.

HRA theoretical basis should have [4]: (1) a paradigm of human behavior, (2) a taxonomy of human actions or errors, (3) a set of information and correlations from the real work environment, (4) a process for applying the methodology to different types of analysis and complexity levels.

One of the theoretical questions concerns the meaning of terms and their lack of specificity. The term "human error", widely questioned, should be replaced with "failed interaction" [15] to capture contributions of both human and machine. The study of human error is the systematic application of information about human characteristics and behaviors to improve human-machine performance [17]. In other words, human reliability analysis is a method used to quantitatively assess the impact of potential human errors in the proper functioning of a system composed of humans and equipment [18].

The definition of human error refers to human capacity to *incorrectly* perform a task under certain conditions, for a given time or at a given time; and perform additional tasks that can affect human-machine system in terms of safety, quality, productivity, workload, etc. However, human error is not a well-defined category of human performance [5].

The definition of theoretical constructs that are the heart of many models is a particularly complicated problem [19]. Coincidently, Sheridan [20] states that there are models that consider verbal propositions and hypothetical theories that are not framed in any specific information (for example: situation awareness, workload and level automation). The use of phrases like "people can do many things and achieve their goals in many different ways" creates the false idea that issues of common sense and intuitive knowledge of human behavior are included in the model, which is not done in a systematic way and has no relevance in those models´ quantification methodologies [8].

Many taxonomies include, due to the theoretical attention to erroneous human behaviors, expressions from psychology as "workload", "stress", "fears" and demonstrations of erroneous behaviors as "delays", "omissions", "repetition", nor defined with precision and clarity [4].

The theoretical basis must come from psychology: an improved HRA methodology must formally incorporate cognitive and psychological theories as the heart of human performance model [21]. On this point Cacciabue [4] had already anticipated that any model should be able to emulate cognitive processes, including the process of decision making based on reasoning skills. As discussed in Section IV many authors emulate cognitive processes with fuzzy logic. Cognitive models represent rational and logical operator´s processes, summarizes dependences both on personal factors (stress, lack of competition) and contextual factors (abnormal conditions, emergency conditions, etc.), and they model the human machine interface. Any attempt to understand human behavior should include the role of cognition [12].

Among the first attempts to model human cognition was the information processing models. They had the overcome notion of cognitive serial processing [5]. Instead recent cognitive models, as COCOM model [22], are based on two premises: the cyclical nature of human cognition and the dependence among cognitive processes and the environment and work context [12].

Is necessary to include psychological and ergonomic models in HRA studies: (1) psychological studies describe the effects of mental stress, ambient noise, etc.; (2) ergonomics research addresses the impact of PSF in human machine interfaces. The operator mental load is a key element in complex sociotechnical systems´ safety, reliability and efficiency [7]. For example, HEROS [9] is limited to classify human behavior in Rasmussen´s (RSK) categories. This limitation is due to poor inclusion of ergonomic studies about the impact of factors such as motivation, training, education, safety culture and team composition; and the assumption that these factors are considered in HEROS classification.

Many models of HRA not have enough theoretical and experimental bases for its key ingredients [12]. The paradigm that models human-machine interactions should simulate the plant, its interfaces and control mechanisms, operators´ decisions and actions [4]. Additional ergonomic and psychological studies are required to determine and identify the weaknesses of systems, e.g. design errors that may cause human error. These analyses are difficult to be performed with traditional methodologies [9].

As stated by Parry [3], HRA models must have a theoretical basis for the set of parameters used to associate PSA (probabilistic safety analysis) stage and probabilities estimation.

In addition, the parameters selection is not a casual process, it must be substantiated theoretically. Some of these parameters come from individuals and teams. HRA should model the individual operator, the team as a whole and the dynamic interaction of the plant with its physical and organizational environment [21]. There are two options for modeling the team: (1) the team as a unit of analysis and (2) individual operator as the unit of analysis upon which the team's response is modeled. Most industries have no formal methods for organizational and human factors quantification. In fact, these factors continue to be monitored by traditional measures of quality control [23].

The remaining modeling parameters come from environment or context. Human error does not occur in vacuum, is determined in part and largely permitted by operational context [15]. Context gives meaning to information that the operator receives, guides formulation and revision of goals and intentions, determines and limits knowledge and attention to successful problem solving. Since the beginning of HRA, performance shaping factors were used to quantify contextual factors (see paragraph B).

First generation models describe events in which only external and formal aspects are observed and studied, without considering the reasons and mechanisms at different cognitive levels [12]. Most of HRA theories assume the independence of PSF [24], this assumption, as discussed below, is very questionable.

Related to terms definition problem, the absence of accurate and precise definition of PSF causes subjectivity and inconsistencies among analysts [25]. The consistency problem is one of the major objectives in improved HRA models and motivates the use of mathematical tools for the treatment of uncertainties associated with subjective information.

There are many reasons for human errors [17]: misdistribution of equipment (layout), poor written procedures, complex tasks, harsh working environments, fatigue, outdated textbooks and inadequate training or experience. Also human errors arise from inadequate system design, such as complexity of tasks or error-prone situations [26]. It can be strongly argued that improved HRA methodologies should consider human error causes; in fact according to Parry [3] there are no models for modeling human error probabilities (HEP) indicating errors causes, despite the numerous attempts to achieve this objective. In addition, traditional HRA models do not adequately address the cognitive bases of possible errors team during accidents [27].

Another important theoretical aspect is the errors taxonomy or classification [28], in which most HRA authors also agree on the theoretical basis importance. Many authors uphold using a human performance underlying model (human behavior or human cognition) to support human errors classification [5]. HRA models require a taxonomy that aims to maintain consistency between the different elements of the man-machine interaction [4] but not necessarily has to be error taxonomy [28]. Models based taxonomies, such as Wickens´ multiple resource model [29], do not provide strong responses when cognitive constraints are evaluated [20].

Despite the described importance of the theoretical basis, HRA must not ignore the importance of observational and historical information. The actual information and field observations are essential to reduce uncertainty, to validate models and to adapt each method to a particular domain [4]. HRA analyst should be familiar with the real system through careful plant visits. An example of observational data sources are accident reports, which are not excluded from the acute criticism of researchers: most accident reports are not designed on the basis of any human error theory [5]. Therefore, a sufficiently substantiated method for collecting or obtaining and processing this information must also be included in HRA methods.

Another important information source is from expert judgment. Expert judgment suffers from vagueness, subjectivity and incompleteness due to absence of empirical evidence correlation, this weakness is not taken into account usually by HRA models [24]. As stated by Konstandinidou et al [8] is necessary to build a model that can incorporate subjective information.

Fundamental limitations of HRA methods can be summarized [8]: (1) insufficient information, (2) methodological limitations referred to analyst and expert's judgment subjectivity, and (3) uncertainty about the actual individual's behavior in a specific situation. Additionally, old reliability problems become new when HRA is applied to modern complex systems and their operational tasks [23]: (1) system representation and modeling, (2) model quantification, (3) representation, propagation and quantification of uncertainty in system behavior.

In this line, Gertman et al [27] suggest improvements that should be included in HRA methods: (1) better treatment of context dynamics, (2) better treatment of crew cognition including multiple decisions possibilities; (3) better treatment of cognition influences on team. Cacciabue [4]

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lists the basic theoretical requirements of any HRA model: (1) a cognition model, (2) an error taxonomy, (3) observational data and (4) probabilistic quantification method. Mosleh and Chang [30] enumerate the following five components as method expectation: (1) human error identification, (2) human error probabilities estimation, (3) error causes identification, (4) causal model of human errors with roots in cognitive and behavioral sciences, and (5) data support and experimental validation.

Later, Mosleh [21] adds the desirable attributes of an improved model: (1) content validity (plant, equipment, cognition, action, errors of commission, omission, etc.); (2) explanatory power, causal model error mechanisms and context relations, theoretical foundations; (3) ability to cover human error events and their dependencies and recoveries; (4) clear definition of analysis units and detail levels for various applications; (5) PSF´s experimental validity; (6) model reliability: reproducibility, intra- and inter-analyst analyst consistency; (7) traceability and transparency; (8) testability; (9) different degrees or levels of analysis: initial or screening analysis, fast or scoping results, detailed analysis; (10) practical use.

Finally, Cacciabue [6] specifies the 5 basic elements of any HRA model: (1) retrospective and prospective analysis (whose consistency is ensured by the availability of a human-machine model or paradigm [31], (2) task analysis, (3) data and parameters identification, (4) human-machine interaction model and (5) dynamic reliability model.

B. Performance shaping factors

The biggest differences between methods relies on PSF selection and quantification, but there is little scientific basis for choosing them [3]. First generation models don't emphasize in PSFs [32] and they arise from environment impact on operators [12]. None of them tries to explain how PSFs exert their effect on performance [8]. In contrast, second generation PSF emerge by focusing on the operator´s cognitive impact [32] [12].

Three problems are associated with performance factors [33]: (1) many methods use PSF but there is no standard set among all methods; (2) PSF aren't specifically defined which creates consistency difficulties between methods; and (3) there are few rules that govern the creation, definition and use of PSF.

Kim and Jung [25] conducted an extensive and meticulous review of all contributions related to PSF and therefrom propose a new taxonomy, classifying PSF into 4 groups: human (personal characteristics and labor capabilities of the human operator), system (man-machine interface, plant physical characteristics), task (task procedures and characteristics) and environment (workgroup factors, organizational factors, physical environment of work).

As developed in the previous section regarding the definition of model´s concepts and constructs, precise and specific definition of PSF is also a requirement to achieve the expectations of improved HRA. Similarities can be established between PSF of different methods, but such factors could have different levels of specificity [34]. For example, in ASP (Accident Sequence Precursor) method the PSF "poor ergonomics" is similar to HEART´s (Human error assessment and reduction technique) "unreliable instruments"; but they have different levels of detail being the second a subset of the former.

The specificity problem is more intense in cognitive and organizational factors. The different terminologies in HRA show deficiencies in capturing the operational context and operator cognitive characteristics that causes the failures [15], first generation models do not include cognition within PSF and do not model human abilities [32]; in fact, with few exceptions (e.g. Rasmussen RSK model) taxonomies of human error don't consider the potentially adverse mental or psychological conditions (e.g. fatigue, illness, attitudes, etc.) [5]. The most important human factors are related to mental processes (interpretation, planning, decision making) and not simple perceptions and reactions to physical events [6].

Organizational factors create many modeling problems. The classification of organizational factors is not comprehensive, no specific, and there are duplicated, crossed, abstract and complex categories [35]. However, it is very important to consider the organizational environment and organizational processes in HRA modeling [14]. Detection of organizational external factors is easier than internal operator mental states, and can be [4]: cooperation between operators, managerial and organizational aspects, noise, systems failure, hidden signals, ambiguous procedures, etc.

Methods limitations regarding the inclusion of organizational factors are [35]: (1) there are no general and acceptable principles to classify organizational factors for their complexity, fuzziness, variety and unclear boundaries or limits (nonspecificity is particularly noticeable in these factors); (2) is difficult to establish a causal model that represent organizational effects on human reliability due to interactions complexity in organizations; (3) it is difficult to consider and define relationships and degrees of correlation between human activities and internal or external performance factors; (4) is very difficult to obtain accurate information of organizational factors in the industry, in databases is little relevant information about organizational factors. In other words, Mohaghegh, Kazemi and Mosleh [36] explain that main problems in organizational factors are: (1) constructing a set of all organizational factors that affect risk, (2) how they affect risk, i.e. a causal model of human error and (3) both contribution to risk, that is, a quantitative method. Organizational factors and cognitive functions affect risk more than physical and behavioral performance [6].

A more relevant role should be assigned to HRA with a focus on cognitive and organizational factors [6]. Working environments have become much more demanding in terms of cognitive skills and reasoning than sensory and motor or physical skills. Human performance is the result of deliberate use of skills adapted to specific working conditions, and no a sequences of predetermined response to certain events [37]. Therefore, human individual abilities must be modeled (including cognitive, physical and social skills).

For the third problem Spurgin and Lydell [10] state that it is highly unlikely that a human action can be represented by a set of normal PSFs linearly independent, this makes suspect on using PSFs in any formulation especially in those who rely on expert judgment.

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PSF should be objectively measurable [3]. There should also be a way to establish correspondence between failure modes and PSF, and a method to classify hierarchically error mechanisms and failure modes based on PSF relative strength for each scenario [3].

One of the major weaknesses of models is the absence of modeling interactions and interdependencies between PSF. Kirwan [13] proposes to develop an understanding of the interrelationships between external failure modes, the psychological mechanisms of error and PSF.

PSF classification isn’t completely separate and orthogonal, certain mutual influences among PSF lead to the possibility of double counting in HEP calculation, which reduces the accuracy and quality of the analysis [35].

Fuzzy mathematics and bayesian networks have made contributions in modeling PSF. For example, Ramos Martins and Cohelo Maturana [38] consider PSF directly in the construction of a Bayesian network, which allows: (1) a representation of interdependencies between relevant factors in initiating event; and a (2) quantitative determination of PSF influences in accident event (i.e. relative impact of each PSF in accident probability). The Bayesian network model of mentioned authors, proposes the inclusion of operator´s internal factors: concentration, motor control, creativity; external factors that directly affect the ability of the operator when executing the task: environmental factors, individual attitudes; other external factors: personnel management, availability of physical resources, organizational culture are defined as constants because they are unlikely to change over the task. Other internal factors that are not skills such as personality, fatigue, emotional state impacts the state of skill at task execution.

C. *HRA quantification*

The objective of most HRA model is to obtain HEP (or its complementary human reliability probability). It is also one of the expectations of improved models as discussed in the previous section. To do this, models have a methodological module or component that performs this calculation numerically, based on probabilistic techniques or others mathematical tools.

It is important to highlight the differentiation performed by most HRA authors about model and method or methodology: the model underlies methodology and gives meaning and theoretical basis to parameters and constructs that are used later in the methodology. The methodology is the specific procedure for evaluating HRA, desirably quantitative. Given the large differences in the scope of human reliability methods and their underlying models, there is substantial interest in evaluating HRA methods and ultimately validate theories (models) underlying these methods [39].

These quantification methods are usually the main points of criticism of any model. Most methods agree, from a qualitative point of view, with the intuition of which tasks are more likely to be performed with errors, but the assumptions and methods that quantify that prediction are often very questionable. There is no consensus on methods for estimating HEP [3].

According to Cacciabue [6], two conditions must be fulfilled in order to quantify the risk associated with certain system: (1) an appropriate database or at least a consolidated data collection technique, and (2) an appropriate methodological paradigm.

The quantification schemes do not have a good scientific basis [3], as examples include [10]: (1) "the idea of adding the HEP of THERP has not been demonstrated" [10]; (2) the PSF and their weights in SLIM (Success Likelihood Index Methodology) must be determined by a group of people relatively poor trained so these methods are often problematic; (3) EPC (Error Producing Conditions) from HEART are difficult to be substantiate; (4) CPCs (common performance conditions) of CREAM limits the application scenarios.

First generation models quantification have a primary factor: task characteristics (modeled through HEP); and a secondary factor: context (modeled through PSF) [12]. However, it may be stated that first generation models don’t reach the desired quantification in risk analysis [32]. The basic methodology is the determination of a nominal HEP (from historical statistics database) and modified through PSF according to the situation. There is no systematic method for modifying nominal HEP in a specific situation [18] and HEP application may not be feasible or practically effective in very complex tasks [2]. Another element used in most of the quantification methodologies is expert judgment, in order to capture the common sense or intuition about HEP in a given task.

Applying HRA methodologies involves numerous judgments expressed in natural language, for example in THERP: degree of stress, quality of operating instructions and training should be qualified verbally; or in HRC (human cognitive reliability) is based solely on verbal evaluations [9]. In this line, most of reviews suggest that quantification by expert judgment introduces biases that should be avoided. Incorporating expert judgment in HRA models is usually done with no formality; therefore it is sometimes impossible to distinguish the source of the information. To overcome this weakness, for example, Podofillini and Dang [40] use Bayesian networks theory to incorporate expert judgment.

IV. CONCLUSION AND DISCUSSION

There are cross-cutting aspects in the three issues described, mainly the precision, nonspecificity and clarity in constructs and concept definitions. Thus suggests using a human abilities theory based on cognitive theories and psychometric tests, and a mathematical tool that allows the uncertainties treatment. These human abilities theory should include the Cattell-Horn-Carroll taxonomy of cognitive abilities and Fleishman social and interpersonal skills.

Human abilities theory simultaneously addresses the described HRA issues. First, it provides a theoretical basis for causal cognitive model of human error with a strong experimental support specifying their interrelationships and dependencies. It´s a quantitative theory derived from psychometric studies therefore facilitates the parameters quantification required in quantitative HRA. It also reduces the analysis subjectivity.

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The inclusion of the underlying cognitive abilities in human reliability analysis involves a theoretical base and punctually the Cattell-Horn-Carroll theory is largely experimental based. This theory also facilitates the later quantification since it is based on psychometric tests, while addressing the problem of strong dependence on expert judgment: psychometric tests are devolved to be an objective measure. This contribution should also be utilized in human resources administration: personnel selection, operator's evaluation, training programs and training requirements.

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