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THE HUMAN FACTOR IN RISK ASSESSMENT: METHODOLOGICAL COMPARISON BETWEEN HUMAN RELIABILITY ANALYSIS TECHNIQUES

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ABSTRACT

BACKGROUND - As from 15 May 2008 with the coming into force of Italian Legislative Decree 81/08 that rationalised and consolidated for the first time all the laws on safety into a single piece of legislation, risk assessment (Art. 28) has become more of a cornerstone of company prevention systems and therefore a non-delegable obligation of employers to implement the assessment process, Art. 17(1)(a). A correct method to be adopted in the assessment process must consider the estimate of risks associated with the human factor. This estimate is essential when, for example, in assessing the risk to which operators, and generally workers, are exposed during the use of work equipment (Art. 71).

Human reliability analysis (HRA) techniques have been developed in order to provide human error probability values associated with operators' tasks to be included within the broader context of system risk assessment, and are aimed at reducing the probability of accidental events.

OBJECTIVES - None of the techniques reported in literature can be considered as the best, each one has advantages and disadvantages and can be more or less suitable depending on the context to be analysed and the available resources and skills.

The aim of this study is to review some HRA techniques that have been developed by human reliability specialists and to carry out a methodological comparison in order to highlight the specific characteristics of each technique, so that they may be effectively applied in company risk assessments.

METHODS - This comparison is based on the assessment of the model, taxonomy, data and method that characterise each technique.

RESULTS - A critical analysis has been made of these techniques on the basis of the underlying cognitive model, the associated taxonomy, the reliability of the available data, the ease or difficulty of use, whether operators' tasks were time dependent or not, and the number and type of contextual factors taken into consideration that may influence human performance, also highlighting the limits of applicability to sectors other than that for which they were created.

BOW PO/base indexing:
CIS: Human factors [CIS: Psah], Hazard evaluation [CIS: Qra], Reliability [CIS: Sadr]
EUOSHA OSH: Human factors [EUOSHA: 11321D], Risk assessment [EUOSHA: 19641D], Risk analysis and management [EUOSHA: 08801A]

INTRODUCTION

In recent years, technological development has led to a reduction in accidents due to technical failures as a result of redundancy and protection measures, which have made systems increasingly reliable. However, it is not possible to discuss the reliability of a system without considering the failure rate of all its components, including the human component whose failure/error rate changes the failure rates of the components with which it may interact. Both at a statistical level and in terms of the seriousness of the consequences, there is a distinct contribution of the human factor in the dynamics of accidents. Estimates concur in attributing to human errors 60-80% of accidents [1] and only the remainder is due to technical failings.

Therefore, in order to ensure effective prevention of harmful events, the risk assessment process cannot ignore the role of humans in the dynamics of accidental events and thus the seriousness of the consequences that may derive from them.

The study of human reliability consists in studying internal and external factors that influence the efficiency and reliability of a worker's performance. The internal factors are all those casual technical or systemic events (due to the environment: work equipment, materials used, workplace, work organisation) that influence and alter working conditions, leading operators to erroneous behaviour; the external factors, which are more difficult to foresee since they are tied to individual characteristics, are correlated to psychophysical conditions that, by their very nature, are not easily structured in systemic behaviour models [2]. This makes clear the complexity of the effort made in literature to propose human behaviour models that assign numeric values to error probability in order to foresee and prevent unsafe behaviour.

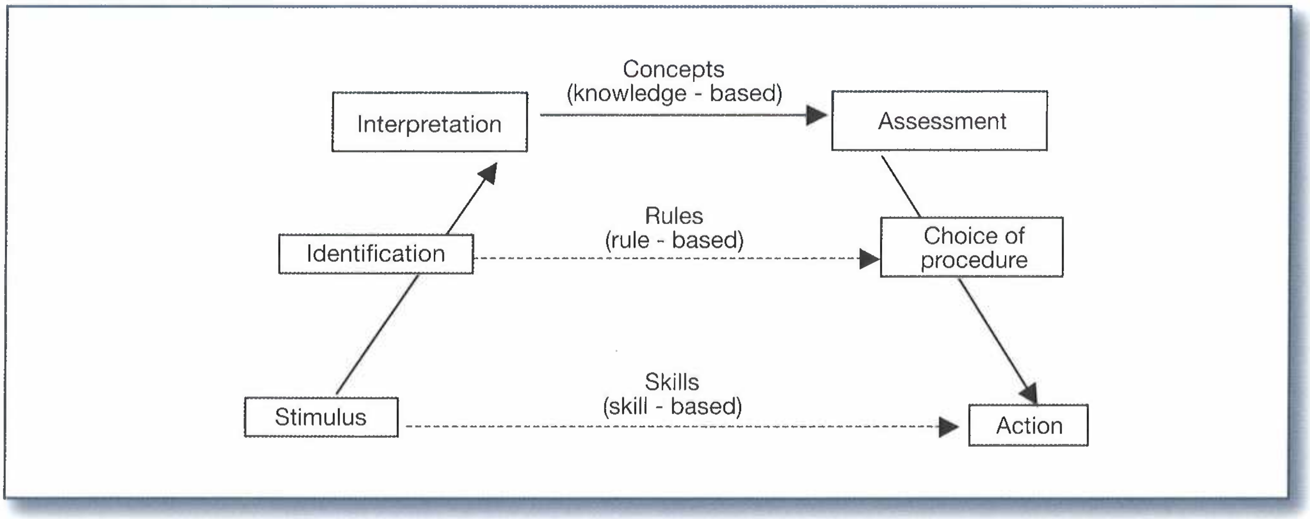
To date, analysis of human factors is a highly interdisciplinary area of study that is still not well defined and for which there is no complete and universally accepted taxonomy of the various types of human error and their causes. One of the first structured representations of human behaviour is based on the assumptions and theoretical principles of cognitive psychology that recognises the cognitive process as the domain in which human errors are defined. This model is based on the information processing system (IPS) paradigm that refers to fundamental cognitive and behavioural functions: perception, interpretation, planning and action [3].

The reference model most commonly used in the field of human reliability is Rasmussen's skill-rule-knowledge (SRK) framework, [4] which, together with the associated error taxonomy, is a specific representation of the IPS paradigm. Rasmussen proposes classifying human behaviour into three different types:

1. *Skill-based behaviour:* routine behaviour based on learnt skills. The cognitive commitment required is very low and reasoning is unconscious, i.e. the operator's action in response to an input is carried out almost automatically.
2. *Rule-based behaviour:* behaviour guided by rules that the operator has to follow to carry out well-known duties. It is a matter of recognising the situation and applying the appropriate procedure to carry out the task. The cognitive commitment is higher since it implies a certain level of reasoning.
3. *Knowledge-based behaviour:* behaviour aimed at solving problems in situations that are not routine or known, but new or unexpected, for which there are no specific rules or procedures. This type of behaviour is defined as knowledge-based for the very reason that it requires a high cognitive commitment in seeking an effective solution.

Rasmussen's classification can be simplified as per the model in Figure 1.

FIGURE 1 - Staircase model



Each operator action is preceded by a series of cognitive processes that are carried out in accordance with a structure in various levels, each of which contains different cognitive functions. The sequence is almost never linear or complete, but is arranged according to a "staircase" where horizontal "jumps" are sometimes made to avoid higher and more tiring steps.

The cognitive process, which leads from stimulus to action, envisages three different procedures of increasing complexity that require increasing levels of attention and cognitive resources.

At the base of the model there is the skill-based behaviour by which the operator, stimulated by an event (input: signal, noise, etc.), reacts almost instantaneously by carrying out an action linked to a procedure that has been thoroughly internalised. At the intermediate level there is rule-based behaviour by which the operator, on the basis of the information received and possibly, following a skill-based behaviour, orders a series of actions through the use of procedures and carries them out. At a higher level there is the knowledge-based behaviour in which the operator is required to creatively and independently use the available information and his/her knowledge (i.e. without using procedures or instinctive behaviour), in order to assess and decide which will be the appropriate actions to take [5].

On the basis of Rasmussen's model, three different types of error have been identified:

- *Slips:* execution errors that occur at the skill-based level. This category includes all actions carried out differently than planned, i.e. the operator knows how a task should be performed, but does not do so, or inadvertently performs it in the wrong way.
- *Lapses:* execution errors caused by memory failure. In this case the action achieves a different result from that expected due to a memory failure. Unlike slips, lapses cannot be observed directly.
- *Mistakes:* errors not committed during the actual execution of the action. In this case it is the plan itself that is not valid, despite the actions are carried out as planned. They can be of two types: *rule-based* and *knowledge-based*.
    - *Rule-based mistakes:* errors caused by choosing the wrong rule due to an erroneous perception of the situation or, in the case of a mistake, in applying a rule.
    - *Knowledge-based mistakes:* errors due to the lack of knowledge or its incorrect application. The negative outcome of the action resides in the incorrect knowledge that determined it. This type of error is inherent in limited rationality or in any case in the difficulty of responding to problems that have a broad range of possible answers [1].

1. METHODS

1.1 Human reliability analysis techniques

The literature shows various human reliability analysis (HRA) techniques aimed at assessing work risk from human error. These techniques have been developed to meet the needs of probabilistic risk assessment (PRA) in order to quantify the contribution of human error to the occurrence of an accident. In this light the HRA approach may be seen as a specialisation of PRA on the significant factors of human reliability, an approach that provides a more detailed assessment of the risks, inherent in the system, that are associated with the human factor. A probabilistic risk assessment identifies all the risks, including human errors, to which the system is exposed, provides their quantitative estimate and includes this information in a fault or event tree. The development of HRA techniques was closely linked, for better or for worse, to that of industries exposed to the risk of serious accidents as seen in Seveso (1976), Three Mile Island (1979), Bhopal (1983), and Chernobyl (1986), to mention just some of the worst, where the substantial contribution made by human fallibility to their occurrence was highlighted.

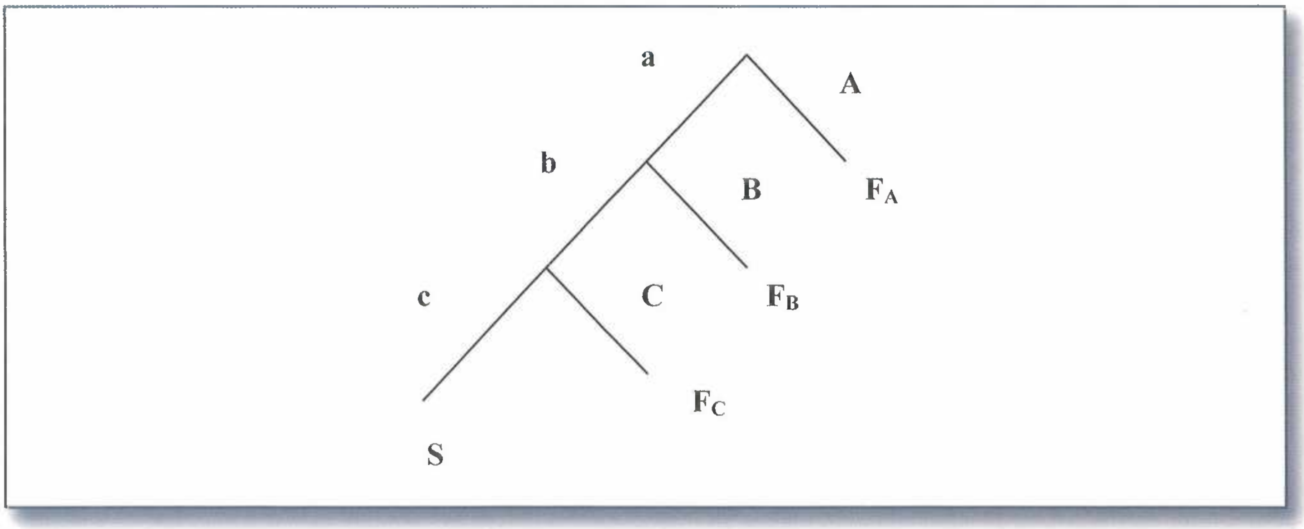
1.2 The technique for human error rate prediction (THERP)

The technique for human error rate prediction (THERP) is the most complex and complete effort made to produce methods and data for the systematic analysis of human error. This method, which was set out in the *Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications* by Swain and Guttman, enables to "predict human error probabilities and to evaluate the degradation of a man-machine system likely to be caused by human errors alone or in connection with equipment functioning, operational procedures and practices, or other system and human characteristics that influence the system behaviour" [6]. The main characteristic of the method - and of many HRA approaches - is the technique of breaking down a task into sub-tasks, the human error probability for each of which is provided within corresponding confidence limits.

The underlying assumption of THERP is that of positioning the success/error of humans on the same level as the success/fault of any component of the equipment (where error translates into a fault). Indeed, each task of the operator is analysed in the same way as the reliability of the components is assessed, with additional adjustments to take account of the particular nature of human performance.

Operators' incorrect actions are sub-divided into errors of omission and errors of commission. The former relate to an assigned action that is not performed at all, the latter to the incorrect performance of an assigned action. The basic analytical tool is a binary HRA event tree with the appearance and symbols as illustrated in Figure 2.

FIGURE 2 - Model for constructing an HRA event tree



In a HRA event tree, each node corresponds to an action, whose sequence is represented from the top down. Two limbs originate from each node. The limb on the left side and marked with a small letter, indicates success; the limb on the right side marked with a capital letter indicates failure. Each action is thus identified with a letter in alphabetical order, excluding the capital letters S and F, used to indicate success and failure respectively.

Once the qualitative part is complete by applying the HRA event tree method, the quantification part consists in associating a nominal probability of human error to each node of the tree. Nominal means that these values are independent of the specific situation under consideration and must therefore be adapted to it.

In order to account for the particular characteristics of the case of interest it is necessary to move from nominal human error probability (HEP) to real HEP. This happens by taking account of the so-called *Performance Shaping Factors* (PSFs).

The method identifies seven PSFs and subdivides them into three main categories:

- *external factors,* which include the physical characteristics of the work environment, the procedures required and the information available and the quality of the human-machine interface;
- *internal factors,* which indicate the personal characteristics of the individual operator: skills, experience, motivation and expectations;
- *stress factors,* which include the type and number of stressful elements that may be found in various situations.

Indeed, the factors making up performance represent the most substantial concession made possible by THERP for considering the operators' human nature and at the same time allowing to explicitly solve the work context issue.

The *Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications* provides numerous nominal probability values grouped into 27 tables, and models to guide the selection of the most suitable table for the specific case. In this way the data can be easily consulted and selected, but to use it correctly it is essential to know the context to which it refers. Each table is subdivided into the minimum components of the task and, for each of these components, usually two numerical values are given: the nominal HEP and the error factor (EF) (the square root of the ratio of the upper (UUB) to the lower uncertainty bound (LUB), on the basis of a lognormal distribution of the HEP). On the basis of expert opinion, HEP will increase (up to a maximum given by the nominal HEP x EF) if the operating conditions are worse than the nominal conditions, or, on the contrary, will decrease (up to a minimum given by the nominal HEP/EF) if the operating conditions are better than the reference conditions. As for the HEP uncertainty bounds, the value of the LUB, corresponds to the 5th percentile of a hypothetical lognormal distribution of the HEP, and the value of UUB, corresponds to the 95th percentile. The median of this distribution is the nominal HEP.

Having defined the EF as:

$$EF=\sqrt{\frac{UUB}{LUB}}$$

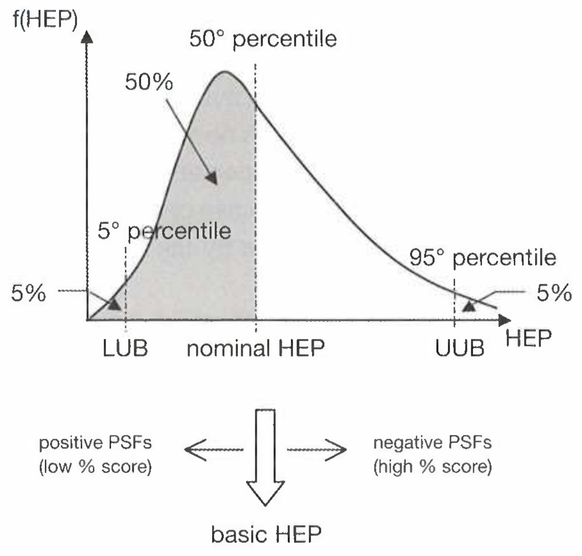
HEP can be obtained by modifying the nominal HEP through the EF depending whether the PSFs improve or worsen human performance, so:

$HEP={}_{nominal}HEP \times EF$ if the PSFs are unfavourable

$HEP=\frac{{}_{nominal}HEP}{EF}$ if the PSFs are favourable.

Figure 3 shows the lognormal distribution of the HEP. The LUB corresponds almost to the best condition for performing the task (all the imaginable PSFs are optimised), and the UUB corresponds to the worst condition (all the PSFs worsen).

FIGURE 3 - Hypothesised lognormal probability density function of HEP and of the variation in nominal HEP



1.3 Empirical technique for estimating operator errors (TESEO)

The Empirical technique for estimating operator errors (TESEO) [7] is a typical example of an indexed model of simple and immediate application aimed at assessing the error probabilities of an operator who is responsible for controlling a complex system.

The TESEO method determines the error probability, Pe, of the operator through the product of five factors, each of which characterises an aspect of the system (human, plant, environment, etc.):

$$P_e = K_1 \cdot K_2 \cdot K_3 \cdot K_4 \cdot K_5$$

where:

K_1 is the factor based on the type of activity that quantifies the degree of routine: if the activity is normal routine, the probability of a possible operator error leading to an accident tends to be low.

K_2 is the stress factor based on the time needed to perform the activity (whether routine or non-routine) and on the time available: an increase in stress leads to a higher possibility of risking an accident.

K_3 is the factor based on the type of operator assigned to the task according to the employment level, experience and training: greater work experience means a drastic reduction in the possibility of error.

K_4 is the anxiety factor based on the activity that depends on the work situation, a serious emergency, a potential emergency or not real, but possible, conditions.

K_5 is the factor that takes account of the environmental conditions and the ergonomics of the machinery-equipment used by the worker.

The five factors basically represent the Performance Shaping Factors (PSFs) quantified in correspondence to differing situations. Here below are extracts of the tables with the values of some factors for application of the model.

If $P_e > 1$, then it is assumed that $P_e = 1$.

TABLE 1 - Factor values in the TESEO model

Type of activity factor *(K_1)*		
Type of activity	K_1	
Simple, routine	0.001	
Routine, requires attention	0.01	
Non-routine	0.1	
Stress factor for routine activities *(K_2)*		
Time available (seconds)	K_2	
2	10	
10	1	
20	0.5	
Stress factor for non routine activities *(K_2)*		
Time available (seconds)	K_2	
3	10	
30	1	
45	0.3	
60	0.1	
Factor relating to environmental conditions and ergonomics *(K_5)*		
Microclimate	Interface with plant	K_5
Excellent	Excellent	0.7
Good	Good	1
Acceptable	Acceptable	3
Acceptable	Poor	7
Unacceptable	Poor	10

Source: Vestrucci, 1990 [5]

1.4 The technique of reliability with reference to time (OATS)

The *Operator Action Tree System* (OATS) was developed by John Wreathall [8] specifically to consider the errors of operators when they are required to intervene due to abnormal conditions. OATS has been developed to provide a categorisation of the types of error and associated probabilistic values that may be used in the PRAs.

The method is based on a logic tree, the so-called basic operator action tree, which identifies the possible operator failure modes following an accident.

OATS identifies three types of errors that are clearly cognitive in nature:

- *error in perceiving* that an accident has occurred;
- *error in diagnosing* the nature of the accident and in identifying the necessary remedial actions;
- *error in the temporal* assessment of implementing correct behaviour.

The estimate of the nominal probability of error is closely linked to the time interval needed to take a decision when an anomaly is discovered. This interval may be formally described as follows:

$$T = t_1 - t_2 - t_3$$

where:

T is the time interval needed to take the decision;

t_1 is the time interval between the start of the accident and the end of the actions related to it;

t_2 is the time between the start of the accident and the mental planning of the intervention;

t_3 is the time needed to implement what has been planned in t_2.

1.5 The method of Human Cognitive Reliability (HCR)

The *Human Cognitive Reliability* (HCR) method, developed by Hannaman, Spurgin and Lukic [9], is specifically oriented to modelling tasks (or actions) for which the time available, T, is the main restriction and whose correct application implies cognitive aspects.

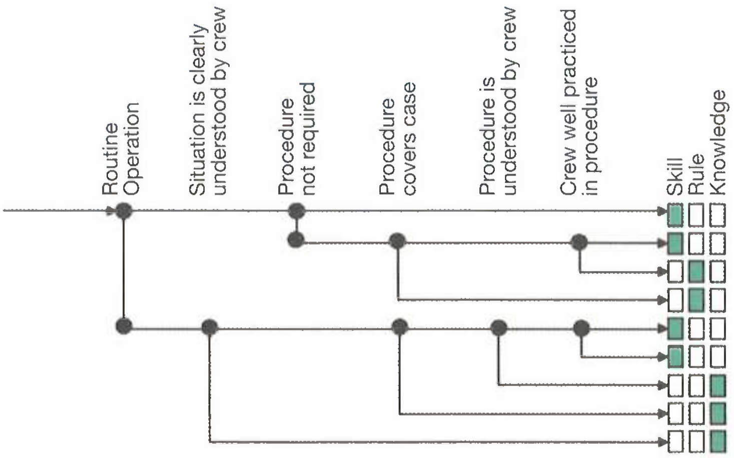
In particular, the method provides the probability of error (also known as the probability of non response within the available time T), $P_e(T)$, due to performing the assigned task too slowly and does not include the error in perceiving the anomaly or the error in choosing the initiative to take.

The method adopts the following steps:

1. classification of the task;
2. determination of the nominal value of the median time $T^*_{1/2}$;
3. conversion of $T^*_{1/2}$ with the PSFs into $T_{1/2}$;
4. determination of the time T available;
5. application of the HCR method to obtain $P_e(T)$.

Having established the HRA event tree, the level of breakdown and with it the subtasks for which the time factor is essential, it is necessary to classify each subtask on the basis of the type of cognitive process that it implies. This classification is facilitated by the use of a logic tree as given in Figure 4. By replying to the questions at the start of each node, starting from the beginning of the tree, the cognitive process of interest is classified based on Rasmussen's SRK classification, which provides a classification criterion of types of human error.

FIGURE 4 - Logic tree



Source: Hannaman, Spurgin, Lukic, 1985 [10]

The second stage involves establishing the nominal median time, in other words the available time value that gives exactly 50% probability of success and failure in carrying out a particular task. The adjective nominal indicates that the value refers to an average situation and not a specific one for the case under consideration. The ways of determining $T^*_{1/2}$ are the usual ones: operating experience, simulators, judgments of experts, etc. The nominal value is corrected to take account of the specific nature of the situation under consideration and this correction is made by using three PSFs: *training, stress, quality of the plant*. Each PSF is associated with a coefficient K_i, i= 1,2,3 and the median time $T_{1/2}$ is estimated by the equation:

$$T_{1/2} = T^*_{1/2}(1+K_1)\,(1+K_2)\,(1+K_3)$$

The value of the coefficients, which are determined experimentally, and the criteria for their choice are set out in Table 2 [10].

By choosing the most appropriate values of K_1, K_2 and K_3, the described correction of $T^*_{1/2}$ into $T_{1/2}$ is achieved.

Table 2 - PSFs and values of coefficients to determine $T_{1/2}$

i	PSF_i	Situations	Criteria	K_i
1	Training	Advanced	Qualified staff with more than 5 years experience	-0.22
		Good	Qualified staff with more than 6 months experience	0.00
		Initial	Qualified staff with less than six months experience	0.44
2	Stress conditions	Serious emergency	Situation of great stress; emergency with staff under pressure	0.44
		Heavy workload/ potential emergency	Average situation, potential emergency, with high workload required	0.28
		Excellent/normal conditions	Staff are engaged in making minor adjustments and interventions	0.00
		Vigilance problems (very low stress)	Attention problems; staff must face unexpected emergency	0.28
3	Quality of control room and plant	Excellent	Advanced tools available to help staff in emergencies	-0.22
		Good	Information is well organised and supplemented	0.00
		Sufficient	The displays are well planned, but staff must supplement information	0.44
		Poor	Displays are available, but are badly designed (they are not planned with human reliability criteria)	0.78
		Extremely poor	The displays to alert staff are not directly visible to operators	0.92

Source: Vestrucci 1990 [5]

For each situation it is necessary to determine the time available T to the operator to carry out the action before a significant and undesired change in the status of the system occurs. The time available T may be determined from transitory analysis of the plant, from similar situations that have already occurred or that have been examined, and from the judgment of process experts.

The HCR model is a mathematical correlation of the data obtained through a simulator and refers to the context of nuclear power plants. It consists of three curves, each of which relates to a type of cognitive process (SRK). The experimental data were approximated with the (accumulated) distributions of Weibull, which provide the probability of non response in relation to the time available T (Table 3):

$$P_e(t) = exp - \left(\frac{t/T_{1/2} - \gamma_i}{\eta_i}\right)^{\beta_i}$$

where:

t is the variable regardless of time,

$T_{1/2}$ is the median time,

$\gamma_i, \eta_i, \beta_i$ are the correlation coefficients associated with the type of predominant cognitive process.

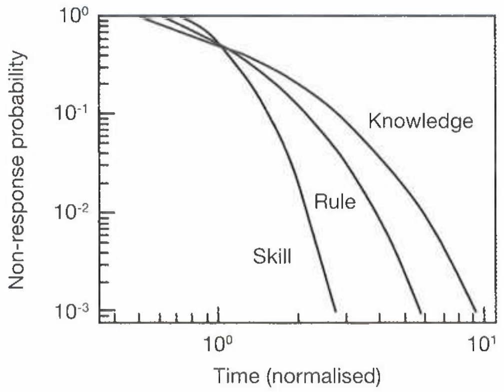
TABLE 3 - Regression coefficients for the HCR model

Type of cognitive process	β_i	γ_i	η_i
Skill	1.2	0.7	0.407
Rule	0.9	0.6	0.601
Knowledge	0.8	0.5	0.791

Source: Vestrucci 1990 [5]

Figure 5 shows the three curves of the model (which may be used to graphically estimate the probability) in relation to the normalised time and therefore to $t/T_{1/2}$.

FIGURE 5 - Non-response probability according to HCR model



Reliability curves used in HRC

Source: Hannaman, Spurgin, Lukic, 1985 [10]

As can be seen from the figure, the curves are defined from a specific time value. Indeed, it can be immediately seen from the analytical expression that $P_e(t)=1$ per $t_0=\gamma\ T_{1/2}$, so-called dead time. The physical meaning of this time must be related to the completely manual part of the task; in other words, it represents the time that is needed to perform the task regardless of the more purely cognitive aspects.

At this point, it will be sufficient to insert the time T in the analytical expression of the model and to determine the y-coordinate corresponding to $T/T_{1/2}$ in order to obtain the value for the probability of non response.

1.6 The cognitive reliability and error analysis method (CREAM)

The cognitive reliability and error analysis method (CREAM), which has been developed by Hollnagel [11], is a second generation method compared to those presented so far. The difference between second generation methods and those of the first generation is evident in the emphasis the former place on the influence of context on human performance. In addition, while in first generation methodologies error definition is based on the omission/commission dualism, which derives from the logical function of success/failure that describes the behaviour of mechanical elements in reliability analyses, second generation methodologies are based on a model that takes account of the cognitive functions of the operator. In addition, the CREAM cognitive model can be easily adopted to both retrospective and prospective analysis. A retrospective analysis starts from the assessment of events such as: accidents, near misses and dangerous situations, seeking to reconstruct the sequence of events to trace the primary causes in order to develop prevention measures. A prospective analysis consists in predicting and assessing risks and the consequences deriving from accident sequences of various levels of seriousness, deriving from various initiating events and from various human-machine interactions, with the aim of contributing to the development of plant control and protection systems. One of the aims of the prospective analysis is to provide a quantitative value for human reliability in the context of the PRA.

In order to outline the work environment in its more general sense, the CREAM method identifies nine common performance conditions (CPCs). Table 4 provides a checklist in which each CPC is given a qualitative level and shows which contextual factors have a negative influence over human performance.

TABLE 4 - Common performance conditions, CPCs

CPCs - Common Performance Conditions	Qualitative level
Adequacy of organisation	Very efficient
	Efficient
	Inefficient
	Inadequate/Deficient
Working conditions	Advantageous
	Compatible
	Incompatible
Adequacy of human-machine interaction and operational support	Adequate
	Tolerable
	Inappropriate
Availability of the procedures and plans	Appropriate
	Acceptable
	Inappropriate

(Table continued on next page)

Table 4 *(Continued)*

CPCs - Common Performance Conditions	Qualitative level
Number of simultaneous goals	Fewer than capacity
	Adequate
	Matching current capacity
	More than capacity
Available time	Adequate
	Normal
	Temporarily inadequate
	Continuously inadequate
Time of day when the task is performed	Daytime
	Night time
Adequacy of training and preparation	Adequate, high experience
	Adequate, low experience
	Slightly inadequate
	Inadequate
Level of cooperation and interaction among department staff	Very efficient
	Efficient
	Inefficient
	Deficient

Source: Hollnagel, 1998 [11]

The cognitive model used in CREAM is the contextual control model (CoCoM) that is based on the hypothesis that human behaviour is regulated by two fundamental principles: the cyclical nature of human cognition and the dependence of cognitive processes on the context and work environment.

The model refers to the information processing system (IPS) paradigm and considers separately cognitive functions with their connection mechanisms (skills model) and cognitive processes that regulate their development (control model) [12].

The skills model takes into consideration the four fundamental cognitive functions of human behaviour and includes knowledge and ability of the individual. It represents the most classical part of the CoCoM model, since it is basically the IPS paradigm in its entirety, but is differentiated by the cyclical nature present among the cognitive functions.

The control model represents the most innovative part of CoCoM since it is a kind of metacognitive model that manages the evolution of decision-making and behavioural processes on the basis of the contextual conditions in which they occur. Four different levels of control are associated with the model: strategic, tactical, opportunistic and scrambled. These represent the attitudes of an operator in regard to his/her skills and ultimately determine the sequence of cognitive processes and actions. The evolution of the environmental context influences the control model through two independent and essential parameters: the result of the actions or previous tasks and the subjective notion of the time available.

In the taxonomy associated with the CoCoM model, a logical subdivision is rigorously maintained between the essential elements of the process leading to wrong actions, i.e. the subdivision between causes, effects-manifestations and consequences of human errors. The consequences are the result of the human-machine interaction and are implicitly obtained from real events. The causes of incorrect behaviour, also called genotypes, are the reasons that determine the occurrence of certain behaviour. These can be further divided into internal causes, which depend on the individual, and external causes, which depend on the human-machine system. Finally, the effects and manifestations, also called phenotypes, are represented respectively by the incorrect forms of the cognitive process and by the real external expressions of incorrect behaviour, i.e. of inappropriate actions. The distinction between the causes and effects-manifestations must be clearly respected in the analysis of human-machine interaction, so as to enable a logical connection between them in looking for and identifying the primary reasons that gave rise to the incorrect manifestations in terms of human actions.

1.7 Limits of human errors analysis methodologies

In light of the above, the development of a methodology to analyse human errors requires the combination of four essential elements:

1. the development and/or application of a reference model for human behaviour;
2. the development and/or application of a classification, or taxonomy, of incorrect behaviour, to be coupled to the reference model of human behaviour for a structured representation of human errors;
3. the availability of sources of data on human reliability that are qualitatively and quantitatively significant;
4. the description of a method where the steps to be followed in applying the analysis are set out.

The above techniques are based on models of human behaviour that seek to describe the cognitive process of humans and to highlight its link with human performance.[13].

The cognitive model, which acts as a reference paradigm for the representation of human behaviour, requires the support of a corresponding taxonomy that can represent incorrect actions in an ordered and structured manner. A taxonomy is a classification, i.e., a set of categories in which data is collected. Harwood and Sanderson observed that there is a compelling need for an interdisciplinary vocabulary to communicate on the role of humans [14]. In order to model human behaviour various classifications of incorrect actions have been proposed in the literature but, as shown previously, Rasmussen's classification seems to meet this need better than others by providing a universal set of verbal models.

To produce valid results, a model or a method requires significant input data, in the sense that each item of data should be correlated to a series of attributes that specify the environmental conditions, the characteristics of tools, and the training of staff. The data on human error probability can be obtained from historical statistics, from laboratory experiments or from judgments of experts in the sector. In the first case the data is taken directly from plant operating experience, and so it is the most realistic data but also the most complex and costly to obtain and process. A more controlled and cheaper way to produce data on human reliability is that based on laboratory experiments. The main limit to the data thus obtained is the significant degree of artificiality compared to the real environmental and human conditions in an industrial and operative context [5]. As an alternative to the two previous approaches, which although different are both experimental (in the field or in the laboratory), there is sometimes a preference to produce data on human error through expert judgment. This method, on the one hand, avoids the use of data that cannot always be easily sourced and is difficult to apply, on the other, it encourages subjectivity in assessing a specific case.

In the analyses of human-machine interactions the formalisation of a method is an essential methodological step for putting into practice models of human behaviour, taxonomies and data collected in the work environment.

A characteristic to be considered in the assessment of a method is its ability to encompass the complexity of the factors that influence human behaviour within relatively simple models.

Therefore, it is possible to order the various models in a hierarchy of complexity: low complexity when, by choosing a particular model, part of the type or of the quality of information will be lost. In addition, there are two types of distinct models, those that consider time as an essential parameter for estimating human error and those that achieve this estimate by considering the factors that mainly influence human actions (difficulties, PSFs, environmental conditions, information, etc.). This distinction is based on the consideration that human error does not only depend on incorrect actions, but may also relate to correct behaviour that is too slow. To this end, a distinction is made between stationary conditions, i.e., situations in which the probabilities do not depend on the time available (e.g., routine tests) and conditions that depend on time, i.e., situations in which a given task must be carried out within a preset time in order to avoid unwanted consequences (e.g., decisions to be taken in the case of emergency).

Nonetheless, the limit of human behaviour models remains that of being unable to give due consideration to the influence of context on human performance. Almost all the models presented in this paper, try to take account of so-called contextual factors, in varying degrees, by introducing coefficients that in some way weigh the influence of one factor more than another on the performance of a task by the operator. Obviously this occurs every time that the specific working context is considered.

2. RESULTS

Here below the advantages and disadvantages for each of the techniques examined are highlighted, including explanations on how the techniques may be more or less suitable for application to one case or another.

2.1 THERP

Scope of application

The THERP method was created as a tool for planning and analysing reliability and risk within nuclear power plants. Currently, the THERP method is considered one of the most complete methods, in addition to being the only source of data available in reference to human error probability.

Limits/Advantages

One of the limits of this technique is that it models (considers) human behaviour as any mechanical component, because it is structured like the risk analysis and assessment techniques used for components and plants.

The THERP technique also ignores what are normally defined as cognitive task errors, i.e. the set of mistakes that derive from cognitive processes such as reasoning, the formulation of solutions, and the selection of strategies, by considering only omission/commission errors. For this reason Swain and his assistants have subsequently sought to re-elaborate the original technique so as to take account of higher level cognitive errors, thus moving away from the exclusively behaviourist position.

One of the advantages of the THERP method is that it is possible to develop it in the form of procedures and so it lends itself to being applied in differing sectors (nuclear, chemical, healthcare).

As for the human reliability assessment in reference to procedural tasks, THERP, as it is structured, may be considered a reference method, even if, in order to use it, it requires the training of expert personnel and considerable resources.

2.2 TESEO

Scope of application

The TESEO method can be used for the rapid classification and assessment of error probability. Indeed, although it is applicable to the individual action and thus, following a well-developed qualitative analysis and with the task under analysis already broken down into all its elementary actions, it can be profitably used for global assessment of error probability of an overall task.

Limits/Advantages

The mathematical structure of this model lends itself to quantify the level of reliability of human operators in specific situations. It is relatively simple to use and its output data is reasonably in agreement with the assessments provided by expert judges. In this case too, however, the numerical values on which the technique is based are taken from assessments provided by experts.

Among the disadvantages is the lack of a real theoretical base, above all in relation to the data used to develop the method, and the fact that the five factors are defined once and for all.

2.3 OATS

Scope of application

This method was created with the aim of considering the errors committed during an accident and in emergency conditions, in particular assessing the time available to the operator to implement the procedures for correcting the malfunction. Together with HCR, it is different from the other methods in that it considers the dynamic aspect of the human-machine interaction and the time dependence of the probability of failure events or human errors.

Limits/Advantages

According to Hannaman, Spurgin and Lukic [9] the OATS assessment procedure has the major benefit of providing error assessments that are unconnected to the type of operator task and therefore, generally, can be transferred to similar work environments, is simple to use with defined values, and has an application guide. This method and THERP are considered the best hypothesis, in that the data is obtained from expert judgments or from laboratory studies. The biggest deficit is that it does not adequately consider the natural time differences in terms of t_1, t_2 and t_3, between different work activities: this makes the prediction of the risk of injury, which may be derived from intervention effectiveness calculations, rather fragile data.

2.4 HCR

Scope of application

The HCR technique was developed in the nuclear sector in order to quantify, based on time, the probability of non-response to an accident situation.

Limits/Advantages

The limit of this method is therefore that of being calibrated on data that refer to the context of the nuclear industry and so its use in other situations is arbitrary. It emerges from an analysis of HCR literature that it is probably one of the best techniques for the quantification of intervention times but, on the other hand, does little to predict the possibility of error. Its biggest deficit is in giving too much weight to cases in which the worker does not activate the correct accident procedure, disregarding cases in which the worker activates a procedure at the wrong time or deliberately violates the established safety procedures. The number of PSFs considered to modify the nominal median time is very limited.

The model, however, has the advantage of being relatively simple to acquire and use. Time dependency is modelled explicitly and significantly and enables connection with the phenomenological evolution of the plant.

2.5 CREAM

Scope of application

The CREAM method is one of the so-called second generation techniques for human reliability assessment, since it focuses on the operational context and is based on task analysis.

Limits/Advantages

The model enables a precise, detailed and, above all, dynamic representation of human-machine interactions, since it can follow the temporal and logical process that leads to manifestations of inadequate behaviour. However, it cannot encapsulate an entire accident sequence, in which differing episodes of error and/or malfunction occur and that combine to give rise to the undesired consequences of an accident.

Being one of the second generation techniques of human reliability assessment, which are based on task analysis and focussed on the operating context, CREAM is a sufficiently flexible technique to be able to be also applied to risk assessment in contexts other than technologically complex plants. Table 5 compares the various HRA techniques discussed in this paper.

TABLE 5 - Comparison between HRA techniques

Method	Model	Classification actions	Contextual factors	Dependence on time	Data	Complexity
THERP	SKR	Omission/commission	7 PSFs	No	Huge databank	High
TESEO	Not present	Success/failure	5 Well defined factor	No	Numerical values are based on expert assessment	Low
OATS	Not present	Success/failure	None	Yes	Data obtained from experts or from laboratory studies	Media
HCR	SKR	Slips, Lapses, Mistakes	Limited no. of PSFs	Yes	Does not require defined values	High
CREAM	CoCoM	Phenotypes/genotypes	9 CPCs	No	Does not require defined values	High

3. DISCUSSION

After examining some of the human reliability analysis techniques, the uncertainties that still exist when choosing this type of approach to the human factor must be highlighted. Indeed, component reliability principles and methods are used, which puts estimating human error probability at the same level as estimating failure probability.

In addition, these methodologies, by favouring psychologically based models, remain anchored to the interior stage of the cognitive process, and do not highlight the link with external conditions. In considering the influences that the context exercises over human performance, it is necessary to give adequate weight also to those that are considered "latent system errors". These are leaks in the system that remain latent for a certain period of time, but that in relation to other etiological factors may give rise to an accident of which the human operator is the final random link in a chain of errors and deficits relating to the context in which he/she operates.

A further consideration in the study of human behaviour and propensity to error relates to the value system and to the stereotypes that each individual bears as his/her own cultural baggage and that are reflected in his/her perception of risk: since this perception is an amalgam of sensorial data that reach the subject after processing by the subject him/herself in the light of his/her knowledge (training/information) and experience (culture/values), it is inevitably subjective. Hence the difficulty in exactly foreseeing the reactions of each individual who perceives, or fails to perceive, that he/she is in a hazardous situation; hence also the difficulty in overcoming the propensity to those behaviours that are intrinsically unsafe but anchored to the culture of an individual.

It would therefore be desirable that for a correct measure of company prevention systems, human reliability analysis techniques be applied as part of an integrated process in planning, on an increasingly human scale, workplaces and in widely spreading the sharing of safety values by the whole organisation.

Indeed, many of the most advanced behavioural science studies, in particular Behaviour Based Safety (BBS), concerns the possibility of exactly forecasting the reactions of individuals subject to particular stimuli. The aim of this scientific methodology is to promote, as part of the company organisation, a culture of safety that does not aim so much to punish incorrect behaviour as to reward - and therefore reinforce over time - sometimes with verbal acknowledgment, sometimes with tangible benefits, all behaviour that helps to limit risks [15]. By putting itself forward as a science, BBS claims to be able to: study a company system to the point of understanding why in particular situations workers did not adopt correct behaviour; modify such behaviour by activating real collaborative processes and reciprocal valorisation between individuals. Without entering into the merits of BBS, certainly company choices that consider humans (with their baggage of knowledge and values) and the relationship between individuals as elements of primary importance in finalising company processes, must be considered as favouring the safety of the whole system.

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