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Human Reliability in Man-Machine Systems

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Abstract

This paper discusses the state of the art in the reliability analysis of human operators. Such analyses generally comprise human reliability assessment (HRA) in Man-Machine Systems (MMS) and involve the description of available human behaviour models. In the given context, man-machine systems represent the actual interaction between a human operator and a technical system. The authors introduce systems where the human factor plays an essential role and the failure of a human being could lead to a safety hazard. Currently, the quantitative evaluation of human reliability is based on the total probabilistic safety analysis (PSA) of the entire MMS.

Keywords: Man Machine System; quantitative reliabiity analysis; HRA; THERP

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1. Introduction

The aim of this paper is to analyse the procedures characterising the reliability analysis of man–machine systems. In general, all live systems are denoted as probabilistic: their behaviour can be anticipated with a certain probability according to the previous state. It is obvious that a human being with his or her brain and mind constitutes the most complicated live system, and therefore, in any MMS, the human element plays an essential and often dominant role because the operator-controlled machine is used to satisfy human needs. Importantly, the human factor encompasses several major disciplines, for example engineering, biology, cognitive psychology, and biomechanics. Only a comprehensive knowledge of all aspects of the human factor can be regarded as the main precondition in the process of evaluating human behaviour.

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A large number of methods are applicable for the reliability analysis of technical systems. These techniques are classified into qualitative and quantitative; in the former case, the value of a reliability indicator can be calculated to a high degree of accuracy. The result is then valid with a certain probability. Further, in technical systems with a human operator, it is also necessary to analyse the influence of the human being on the relevant technical system.

2. Reliability in Man-Machine-System

The reliability of technical systems is viewed as the ability of these systems to perform a required function. This reliability is not a mere number but rather a complex property of systems. Reliability is commonly expressed by means of appropriate indicators. The related analyses are regularly based on creating a reliability model and calculating one of the reliability indicators through the use of certain rules. The quantitative analyses are a suitable instrument facilitating the expression of total reliability (the value of areliability indicator), lifetime, and other aspects. As already indicated above, another set of tools for reliability examination comprises qualitative analyses. These analyses are usually used in the proposal phase to enable the detection of critical elements. The relevant methods for reliability analysis are defined by the international standard IEC 60300-3-1; the most widely used approaches are Fault Tree Analysis (FTA), Failure Mode and Effects Analysis (FMEA), Hazard and Operability Analysis (HAZOP), and Event Tree Analysis (ETA). Furthermore, the Monte Carlo statistical reliability analysis has recently become a very popular option.in the discussed field.

Previous evaluations of MMS reliability were principally focused on the examination of technical subsystems, and the influence of a human being on the system reliability was not considered from the quantitative perspective. The reason to start new research in evaluating the human factor and human reliability consisted in failures affecting nuclear power plants or chemical factories, with air and sea disasters being another central subject of investigation. The results obtained within the novel branch of research have shown that it is very difficult to design universal evaluation procedures, mainly because conditions in the examined field are very stratified and varied. Each type of human activity exhibits specific working methods which cannot be unified, merged, or assigned the same tabular values. There exist fundamental differences between technical and human reliability, especially in the way of information (data) processing and goal reaching. The probability of wrong execution of certain human activities can be high; however, the probability of not achieving the end result is still very low. The authors of references [1], [2] presentplausible definitions of human reliability, describing the concept as the ability of humans to carry out a task under certain conditions and observingthe given time interval; moreover, the researchers also emphasise the significance of performing an assignment within an acceptable range and highlight the human capability of bringing to the working process a suitable qualification and appropriate physical and psychological performance preconditions.

Fig. 1 shows the basic procedure of interaction between a human operator and a technical system composed of several subsystems. The diagram also indicates possible external influences on the performance parameters of the human and technical components of man-machine systems.

3. Human Reliability Assessment

Human Reliability Assessment (HRA) is a section of the reliability discipline where the overall human performance in operating actions is studied. The majority of human reliability assessment techniques are partially based on behavioural psychology. These methods have been derived from empirical models and via statistical calculations but are not always adequately validated; they are also dependent on expert judgments which may be subject to bias. Importantly, reliable and practically useful results can only be expected from a high-quality predictive analysis. In this connection, the actual degree of quality depends on the application of relevant findings in psychology or ergonomics and on the employment of conclusions previously drawn from incorrect actions, for example through evaluating operational experience or by means of simulator experiments.

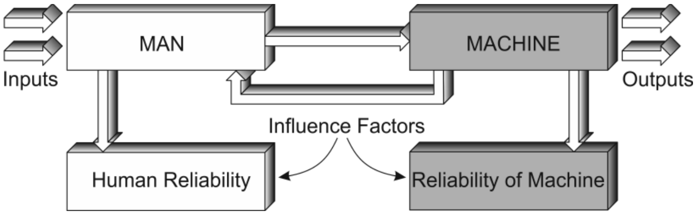

Fig.1. Human and technical reliability in MMS

HRA methods are designed to recognise that the cognitive human behaviour is not related to external properties of the situation (i.e., the procedures do not always involve rule-based behaviour). Human operators are typically able to accommodate themselves to different situations; they learn the required behaviour and acquire the related skills if they perform an action repeatedly [3]. If the action is carried out frequently and on a regular basis, the individual behind it may become highly trained, practising their tasks subconsciously. Such practice enables the human being to reduce the input information load, as already indicated. Hence, the application of an inappropriate procedure may be a knowledge-based decision error as well as a skill-based error of the individual. This depends both on the situation (external information cues) and on the experience or habit of the human operator [4], [5].

4. Review of HRA methods

A number of HRA techniques (many of which are freely available) have been developed for use in a variety of industries. Currently, there are more than 50 different types of HRA approaches, and these methods differ in several key aspects. In general terms, HRA tools calculate the probability of human error for a particular type of task while taking into account the influence of performance-shaping factors.

4.1. Qualitative and quantitative evaluation of human activities

Quantitative HRA techniques refer to databases of human tasks and associated error rates to calculate the average error probability for a particular task. These methods are focused on identifying an event or error and defining the common result of task analysis or incident investigation. Any quantitative evaluation of human reliability is based on the total probabilistic safety analysis (PSA) of the whole MMS system [1]. A part of this analysis consists in human reliability assessment (HRA), which brings information about the following problems:

- the degree of safety and readiness of the investigated technical system with respect to human interventions;
- the range and magnitude of human faults compared to technical faults;
- the possibilities that lead to an increase of the reliability and the safety of the system.

Quantitative HRA methods are focused on translating an identified event or error into Human Error Probability (HEP).

Furthermore, qualitative HRA techniques guide experts through structured discussions to develop estimates of failure probability, given the specific information and assumptions available to the specialists with respect to the related tasks and conditions. These methods are based on verbal description of the activities, and the specific output is a tree event.

4.2. First generation methods HRA

The first generation of HRA methods utilises simple error taxonomy. The techniques within this class were the initial tool developed to help risk assessors predict and quantify the probability of human error; they encourage the assessor to break a task into component parts and then consider the potential impact of modifying factors such as time pressure, equipment design, and stress. These compound analyses allow us to determine the potential for a nominal human error. The discussed methods focus on the skill and base rule level of human action and exclude the factor of cognitive abilities and consciousness. The model of human behaviour characteristic of the above-described HRA procedures is shown in Fig. 2.

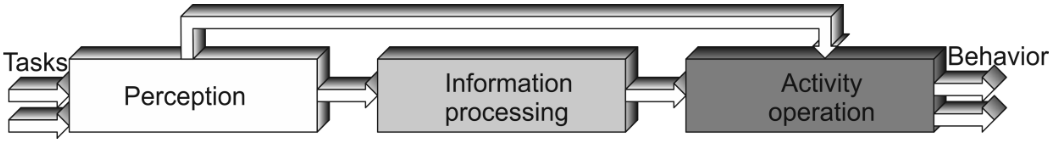

Fig.2. A model of human behaviour in HRA methods of the first generation

The most widely used HRA methods of the first generation are as follows:

THERP (Technique for Human Error Rate Prediction) [6] - a method for predicting human error rates and for evaluating the degradation of a human-machine system likely to be caused by human errors in association with factors such as equipment reliability or procedures. The method exploits performance-shaping factors to make judgments about particular situations.

HEART (Human Error Assessment and Reduction Technique) [8] - a cross sector tool applicable to any domain where human reliability is important. The presented instrument has been successfully deployed in various industries, including the nuclear, chemical, aviation, rail, and medical fields, and it constitutes a pre-processed form of HRA designed for fast use. The method is generally easily understood by engineers and human factor specialists.

4.3. Second generation methods HRA

The second generation of HRA methods uses theory–based error taxonomy, often coincides with the cognitive model of human behavior, and employs a complex match of scenarios to facilitate error identification and quantification [7]. These procedures are characterised in that they consider the cognitive behaviour of the human operator. The operator’s activities are assumed as performed for a specific purpose (Fig. 3). The development of the second generation tools began already in the 1990s; the most notable methods within this group include ATHEANA, CREAM, MERMOS, and CAHR. At present, however, the only technique that remains in regular use is MERMOS.

ATHEANA (A Technique for Human Analysis) [9] is a second generation tool described as a method for obtaining qualitative and quantitative HRA results. The instrument is based on the weighted average of the conditional probabilities of all unsafe acts which contribute to Human Failure Events (HFE), and it is exploited as a function of all the Error Forcing Contexts (EFC) for a specific scenario. The premise of the method is that significant human errors occur as a result of Error Forcing Contexts (EFC), defined as a combination of plant conditions and other influences that render an operator error more likely to happen.

SLIM (Success Likelihood Index Methodology) [10] is a set of procedures for making expert judgements when developing Human Error Probability (HEP) estimates. The method is used for the purposes of evaluating the probability of a human error occurring throughout the completion of a specific task. The method uses expert judgment to quantify Performance Shaping Factors (PSF). Such factors are used to derive the Success Likelihood Index (SLI). The factors (PSF) are chosen by experts and comprise mainly those elements regarded as most significant in relation to the context.

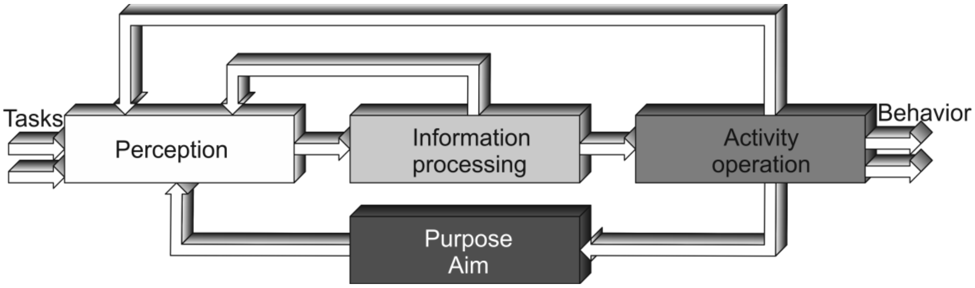

Fig.3. A model of human behaviour in HRA methods of the second generation

CREAM [11] can be used as a screening process to decide whether or not to continue with an HRA. The next stage of extended analysis requires a cognitive demands profile to be built. This involves describing each cognitive activity in terms of observation, interpretation, planning, and execution. The CREAM method is fully bidirectional; it can be applied for retrospective analysis as well as performance prediction. The method is employed in the nuclear industry and within railway crash scenarios.

5. Probabilistic Risk/Safety Assessment

HRA methods are based on the Probabilistic Risk /Safety Assessment (PRA/PSA). Human reliability is usually defined as the probability that a person will correctly perform some system-required activity during a given time period (if time is a limiting factor) without carrying out any incorrect activity that can degrade the system reliability [1]. To determine the probability of human error (HEP), we exploit the following resources or processes:

- scientific references to similar comparable activities (generic data),
- an observation of incorrect actions in the analyzed system or a similar MMS.

There exist many methods for the probabilistic assessment of human reliability [12], [13] and they pursue virtually the same goals; these aims prominently include the quantitative analysis of human behavior, the identification of possibly inappropriate activities, and the identification of weak points in the system together with creating preconditions for suitable intervention.

Human Error Probability (HEP) is the probability that an action will be performed out of tolerance during the observation period. Mathematically, a human error can be quantified as:

$$HEP = \frac{n}{N} \text{ where} \tag{1}$$

n – the number of incorrectly accomplished tasks,
N – the total number of accomplished tasks.

Human Success Probability (HSP) is the probability for an action to be performed correctly during the observation period, see (2):

$$HSP = 1 - HEP \tag{2}$$

Many practically important distribution functions can be described with only two parameters; for example, we know the expected value and standard deviation for the normal distribution. In the evaluation of human reliability, a lognormal distribution is assumed. The distribution is determined by the median *M* and kurtosis coefficient *K*. For the 5th and 95th percentiles, the corresponding formula is defined as shown below (3):

$$\begin{aligned} 5.\ percentiles &= \frac{M_{HEP}}{K} \\ 95.\ percentiles &= K \cdot M_{HEP} \end{aligned} \tag{3}$$

M_{HEP} – the median probability of human error (*HEP*),
K – the kurtosis coefficient of lognormal distribution.

6. Human Reliability Analysis Using Technique THERP

THERP is currently the best documented and most widely accepted method for the assessment of human reliability. As regards its main characteristics, let us note that the approach offers the advantage of simplicity but does not consider human performance reliability in time.

The technique comprises five basic steps [14] and these are outlined as follows:

- Define the system or process.
- Identify and list all the human operations performed and their relationships to the system or process tasks and functions.
- Predict the error rates for each human operation or group of operations.
- Determine the effect of human errors on the system or process, including the consequences of the error not being detected.
- Develop and recommend changes that will reduce the system or process failure rate.

Tab.1 shows some sample operator errors and their nominal failure rate values. The error factors recommended by Handbook of Human Reliability [1] in connection with error probabilities are based on experimental variability.

Tab. 1. Important operator errors, database THERP [15]

Operator error	Nominal HEP_i (-)	Error factor (-)
Incorrect accident diagnostics	0,00001 – 0,0001	30 - 1
Omission of data reading from the panel, or display alarm not detected	0,00005 – 0,0005	10
Misreading or failure to note information in observing the system state displays	0,001 – 0,1	3 - 5
Failure to respond to an audible alarm	0, 0001 – 0,25	10
Performance of a procedure without using the relevant written document	0, 005 – 0,3	10 -5
Omission of a step in performing a procedure	0,001 – 0,05	3 – 5
Error of selection in actuating a component (switch; hand valve) or in reference to the system state display	0,25	10 – 5
Omission of selection in actuating a component or in reference to the system state display	0,25	5

A key aspect of the THERP approach is the determination of the probability that an error or class of errors will result in a system or process failure. The partial (joint) probability that an error will occur and that the error will lead to a system failure is expressed as HEP_i. The probability that an operation will be performed that does not lead to a system failure (HSP) is then denoted as $1\text{-}HEP_i$, and the probability that a class of errors will lead to a system failure is given by [10]. We have:

$$Q_i = 1 - \left(1 - HEP_i\right) \tag{4}$$

Q_i – the partial probability of errors.

The total system or subsystem failure rate [10] let us express the following formula:

$$Q_{HUMAN} = 1 - \left[\left(\prod_1^n \left(1 - Q_i\right)\right)\right] \tag{5}$$

Q_{HUMAN} – the probability that one or more failure conditions will result from errors in at least one of the n failure classes.

The aim of this paper is to perform a reliability analysis of the human operator and to show via a model example how the overall reliability of a subsystem can be affected by the operator's misreading of the data on an analogue indicator. The THERP procedure was chosen as a suitable tool for human reliability analysis. As already proposed above, the correctness of the human operator's actions may be compromised by erroneous interpretation of data or unsatisfactory performance of his/her operating asks. The relevant problems are classified in the following manner:

- Group A – omission of data reading from the analogue indicator;
- Group B – misreading or failure to note an item of information while monitoring the analogue indicator;

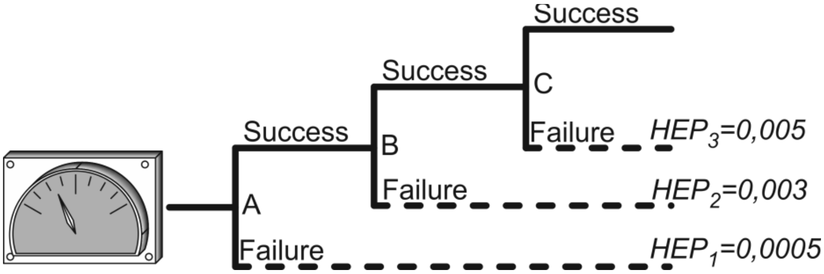

Fig. 4.THERP: the event tree for a human operator's activities within a subsystem (analogue indicator reading).

- Group C – incorrect control action on the analogue indicator.

Based on an analysis of the human operator's activities, an event tree is designed (Fig 4).

The knots A, B, C represent the interaction between a human operator and a subsystem comprising an analogue indicator. The classes subsume human activities that may lead to the probability of failure *HEP$_i$* or are correctly executed within the probability 1- *HEP$_i$.* The total probability Q_{HUMAN} that the human operator will perform an incorrect activity during his or her interaction with the analogue indicator is given by (6)

$$Q_{HUMAN} = 1 - \left(\prod_{1}^{3} \left(1 - HEP_i\right) \right) = 0{,}008481 \tag{6}$$

The calculation of the total probability QHUMAN is based on the nominal values of *HEP$_i$* specified in Tab. 1 without an error factor. For various complex subsystems and interactions with the human operator, the error factor can be used effectively. Selecting the value of the error factor depends on the previously made qualified estimation.

Conclusion

The complex reliability of an MMS is a function of all the elements which define the system operation; in particular, for technical systems, it is necessary to consider all the involved aspects of information technologies and human interactions in addition to the underlying reliability function of the system components. In general, the human contribution to the overall system performance is considered to be more important than that of hardware and software reliability. Estimates of human error probability and the consequences resulting from such an error are the principal products derived from performing human reliability analysis.

Humans actively use their brains to reach an aim or to accomplish an objective, and they adjust their behaviour to satisfy the partial conditions leading to the desired target. On the basis of the actual state analysis, an individual can choose also tools or procedures different from those originally recommended or adopted. As already indicated, a human being has the ability to monitor and modify their behavior permanently; he or she can correct wrong or unpremeditated steps to avoid hampering the system performance. Although a technical system, too, can carry out certain monitoring activities, the related functions may easily become inoperative in any failure of some specific functional block.

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