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HUMAN FACTOR RELIABILITY IN SAFETY CRITICAL SYSTEMS: A GLOBAL APPROACH FOR SPECIFIC CONTEXTS

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ABSTRACT

The human reliability evaluation and the risk management of human factor activity have been the subject of several research works for half a century. Many approaches for evaluating human reliability have been proposed as well as predictive cognitive models of operator performance. However, we still observe incidents and accidents on a daily basis that mainly blame the failure of the human factor. In this article, we review the state of the art in the field of reliability of the human factor and the main contributions in that field. We then propose a holistic and operational approach for a global evaluation of the performance of the human factor reliability.
Keywords: *Human Factor Reliability, Safety Critical Systems, Human Error, Human And Organizational Factors*

1. INTRODUCTION

The security of systems in certain environments (industry, civil or military aviation, railways, etc.) remains a major concern for researchers as well as for managers and stakeholders on the professional side. The occurrence of accidents in these contexts can cause significant damage to the safety of people, the environment and the economy.

Technical mastery of production processes and tools has been examined and suspected to be the only mean of controlling safety. This technical component is reflected in the mastery and automation of complex processes, the implementation of maintenance management systems, the drafting and dispatching of detailed procedures...with the aim of preventing and anticipating any accident or undesirable event. Despite progress in this technical aspect, which has made it possible to improve productivity significantly, critical environments have continued to record large-scale accidents.

Years later, the era of the human factor emerged with assumptions about the error of the "human component" as a result of deviation from procedures, standards and technical prescriptions[1]. The human factor has been perceived as a source of accidentality that psychologists and behaviorists have explained by the failure of the cognitive processes of operators. We cite as an example, the Tokaimura nuclear accident in Japan, which occurred on 30th September 1999, which was qualified as the most disastrous nuclear accident since the Chernobyl given the extent of the radiation released. The investigations carried out concluded that the direct cause of the accident was human failure due to an overuse of uranium compared to the quantities prescribed in the operating procedures. Also, let us remember the rail accident in Saint-Jacques-de-Compostelle that took place on 24th July 2013 and resulted in 79 dead and 140 injured. The investigation revealed excessive speed for a section of significant curvature and only the driver and the safety director had been prosecuted and sentenced by the court after being found guilty of the tragedy.

A too simplistic hypothesis to respond to the safety issue of complex systems [2], considering human error in isolation and blaming the reliability of the human factor as an independent source of accidentality. From there appeared the ergonomic studies interested in the coupling of the technical tool to the human factor and taking into account his

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variability. The study of the human factor is therefore inevitable and essential to the safety performance of the overall system [3] and this consideration has allowed considerable progress for safety.

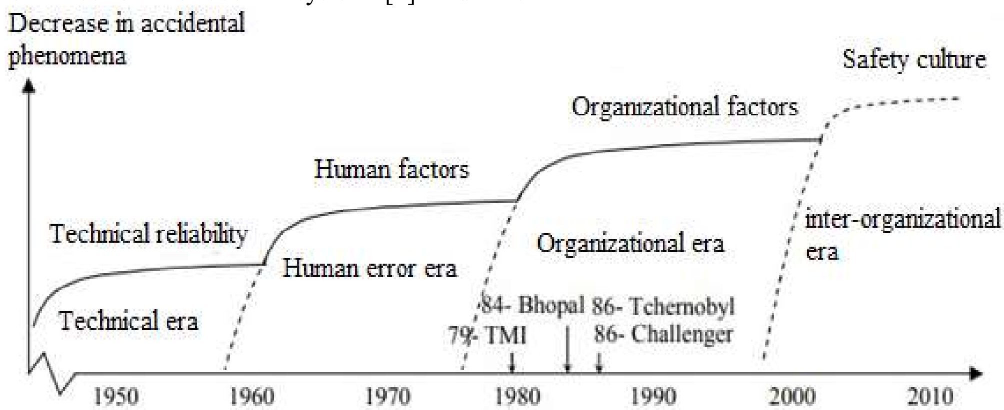

Figure 1: Evolution of safety management approaches (adapted from Groeneweg, 2002)

Nevertheless, a level of stagnation in this progress has been reached, and several industrial disasters have followed one another (Three Miles Island, Bhopal, Chernobyl, and Challenger). Posteriori analyzes of these catastrophes cannot explain the appearance of these accidents on the sole basis of human error isolated from its organizational context [4][5][6][7][8][9][10][11]. Following this phase, the importance of the organizational and human factor (HOF) emerged as the third pillar of security. HOF approaches focus on socio-professional components as well as technological components. Interactions between humans, automated and computerized interfaces, interactions within a teamwork, in-depth investigation following an incident or accident are part of the focus of the HOF engineering discipline. Indeed, the inventory and analysis of the causes of incidents and fatal accidents has proven that the investigation of sources of malfunction must go beyond the apparent causes and identify the "root" causes and latent risks. This era was then oriented towards the identification of organizational factors that favor operator error [12][9].

In addition, it has been understood that security is the concern of all contributors, whether at the organizational level (operators, managers, top management, etc.) or inter-organizational (subcontractors, suppliers, customers, etc.) from the design stage of the system and to execution stage by integrating the various daily tasks and operations [13]. The achievement of security objectives is therefore intended to be global under a systemic approach integrating both the technical and regulatory component and the organizational and human factor component.

In this paper, we propose a detailed literature review that evocates different perspectives, theories, qualitative and quantitative studies of human factor reliability. We first start by a delimitation of the scope of interest by defining the performance of a critical system and proposing our vision of a global safety system performance measurement.

The review of the state of the art that we detail in the second section is a critical analysis of key studies in the field of human factor improvement. We aim in this review to investigate a large specter of theoretical and operational studies.

In the last section, we propose a holistic approach of human factor assessment and improvement based on a complementarity between quantitative and qualitative reviewed methodologies. Our approach gives guidance to managers to insure the implementation of different aspects of human factor management and improvement in harmony with the particularity and features of their operational activity.

2. STUDY FRAMEWORK AND LITERATURE REVIEW

2.1. Performance of safety critical systems

Safety critical systems are systems where failure can cause harm to the safety of people or even their lives, significant financial or economic losses, or environmental damage [14].

In the field of safety, several approaches exist for measuring the safety performance of a system:

- A posteriori measurement, which consists on measuring safety performance by analyzing safety results. This assumes that the system is already designed and operational;
- An a priori measurement that focuses on the design stage of the system and the prediction of its behavior. We also talk about measuring the performance of the system by analyzing the project approach used to build it [15];
- The measurement of performance by analyzing its compliance with an existing management reference system from the design stage and during its operation. Often used in the design and auditing of a safety management system and its compliance with existing universal standards: OHSAS 18001 or "workplace health and safety management system", OHSAS 18001 for "Occupational Health and Safety Assessment Series", MASE (Company Safety Improvement Manual) and ISO 45001 for Occupational Health and Safety Management Systems published in March 2018…;

The most common measurement approach is the measurement of safety by results [16][17]. According to this approach, a system is said to be secure if it meets the security KPI's measured a posteriori. The main performance indicators are traditionally related to the number of incidents, accidents or adverse events that have occurred, their frequency and their severity. A safety performance evaluation consists in these cases on assessing the evolution of these indicators over time. This a posteriori measurement method has shown certain limits and disadvantages, including [18][19]:

- Evaluating the "failures" of the system and refraining from valuing and highlighting the "success" carried out;
- A passivity in performance measurement that does not allow action to be taken at the appropriate time to avoid undesirable events;
- Does not allow to detect faults and sources of latent errors at the level of the various components of the system;

This safety approach oriented results measurement should not be considered as a first-line measurement method. It must be supported by continuous evaluation and active improvement of different components that influence "nearly or by far" safety. In order to explain our conception of said improvement approach, we propose in Figure 2 a simplified diagram of the performance measurement process.

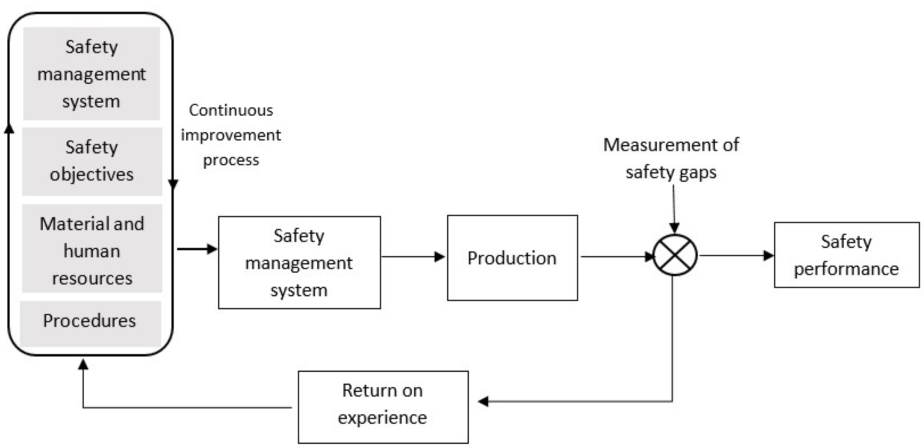

Figure 2: Safety System Performance Measurement

This schematization is based on a set of input elements such as the safety objectives, the human and technical resources, the procedures as well as the components of the safety management system. These elements are subject to continuous improvement through, for example [20]:

- Field missions and accompaniment;
- Continuing education;
- The establishment of an internal innovation process;
- A technological and regulatory watch;
- Safety auditing and inspections;
- A regular schedule of events, meetings (strategic, management and operational committees) reserved for security;
- A multidisciplinary team dedicated to the implementation, monitoring and inspection

of the components of the safety management system;

We represent on the same diagram (figure 2) the measurement of return of experience and feedback that are essential to ensure a process of continuous improvement of safety performance.

2.2. Human Factor reliability

2.2.1. Human error

Human work in complex safety-critical processes continues to attract the attention of researchers as a major issue. Indeed, erroneous or inappropriate human actions in this context can have disastrous consequences on human life, on the environment or at least affect the economic aspect in terms of performance (Examples: Three-mile island accident). Research and studies in the field of human error have evolved over the decades. Considered for a long time as a source of poor human performance, it subsequently became, for certain authors and researchers in cognition (Daniellou, Reason), a precious source of reliability of systems and rectification of deep and undetectable failures.

> *"An error is often the result of a situation where an operator and/or a team could not implement their skills for reasons related to the design of the systems, the interface, the organization, to training. . . (...) "An error is a situation where a planned sequence of actions fails to achieve its goals. It is a deviation from an internal or external reference (objective, model, standard, rule, etc.), when the person did not intend to deviate from this reference.* ***An error is never intentional****". [13]*

The diversity of definitions as well as interpretations of the concept of error has led several researchers to distinguish between many types of errors and to work on their classification. Several classifications have been proposed, we will focus more on those of the cognitive domain. Reason [4] proposed one that focuses on the conceptual mechanisms at the origin of error production according to a model that he named Generic Error Modeling System (GEMS). This model distinguishes two types of errors: errors that precede the detection of a problem (mistakes and lapses that occur at the level of automation) and errors that follow the detection of the problem: misunderstandings based on the rules (Roules Based RB), or on knowledge (Knowledge Based KB). According to this, two families of errors are distinguished; they are defined according to the stages in which they occur: planning errors and execution errors.

The new point of view considers "human error" not as a conclusion that satisfies the realization of an investigation following an accident or as a cause of failure for safety, but rather as the starting point for the investigation of deeper dysfunctions within the organization. Rather than focusing on what the operator should have done to avoid the accident, the new point of view tries to understand decision making processes to take the appropriate action in a specific work situation and a given organizational context [6][21].

2.2.2. Systemic approach for Human factor analysis

The concept of deep defenses and barriers has emerged to understand the reel causes of accidents and to prevent hazardous events. This concept aims to secure a system by setting up a set of successive and independent measures that prevent from possible incidents and limit their consequences (INERIS 2009).

Many researchers have proposed the theory of linear causation of accidents. Heinrich's domino model [25] proposes series of dominoes that each triggering the next to represent the linear effect of each causal event.

The more recent and much used Swiss cheese model (SCM) proposed by Reason [4][26] also represents accident causation as a linear process. We propose a version adapted to the version of James Reason in figure 3.

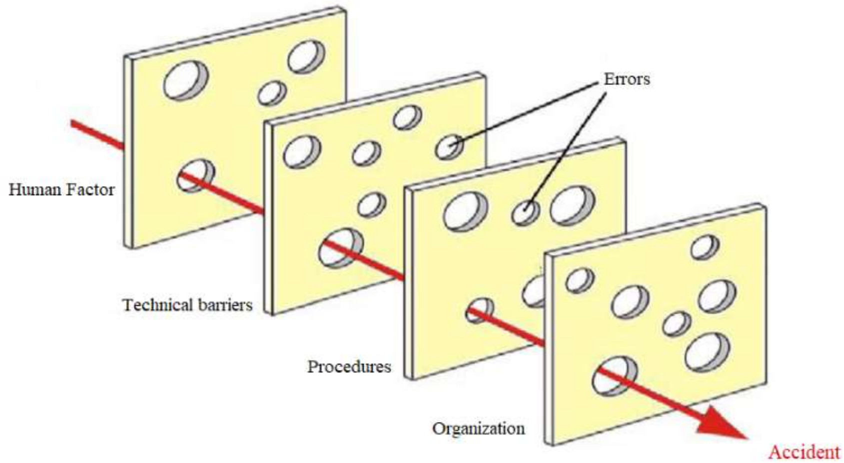

Figure 3: Swiss Cheese Model Adapted From Reason (2008)

The wholes of the Swiss cheese layers represent latent errors in different barriers of the system: technical barrier, organizational barrier, human barrier… The alignment of failures with respect to each barrier can cause an undesirable event or even an accident.

Latent errors are assimilated by Reason as pathogens that exist in the human body. These agents are present and do not cause visible symptoms but their affluence in the body can lead to serious consequences.

This metaphor or analogy between the human body and the safety system essentially brings us back to the following main observations:

- The defenses and barriers of a system are the main tools for preventing accidents, they form between them catch-up loops to prevent the occurrence of an accident;
- Latent errors are detectable and preventive approaches are necessary at all hierarchical levels in relation to the various security components;
- The search for the causes must focus on a deeper understanding of the true causes (analogously to the treatment of the causes and not of the symptoms in medicine);

The crash, according to Reason, occurs when failures or errors at the various barriers line up. The different defenses of a system allow in this case the passage of an undesirable element in relation to security.

2.2.3. Human and organizational factors

Human and organizational factors (HOFs) represent an operational side of the concept of deep defenses. We cannot discuss safety-critical systems without focusing on organizational and human components. HOFs have become indispensable for high-risk businesses such as the nuclear, aviation, mining and rail industries. Indeed, the analysis of the most serious accidents which have taken place during the last decades in organizations with very complex socio-technical systems revealed the existence of close correlations with the human factor, organizational elements, management, procedures and technicalities, as well as the social and environmental components of the company [27][28]. In such contexts, HOFs support the principle that any abnormal behavior of the system and any error, even that which may seem small or insignificant, must be considered a threat of great magnitude to the system as a whole.

Overall, there is no normalized or standardized HOFs approach. According to INERIS [20], an HOFs approach contains a set of tools that can be structured along the following main axes:

- Background management models that concern human behavior, security management and the organization;
- Data collection techniques and tools such as questionnaires, interviews and observations,
- Implementation principles and the formulation of applicable procedures and targeted prescriptions;

Concretely, at the operational level, the employees and teams designated for the application and monitoring of HOFs use tools and practices including:

- Training and impregnation with Crew Resources Management

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- Behaviorist methods and Behavior Based Safety
- Safety management system
- Checklists, golden rules, questionnaires,
- Investigations and systemic analyzes of accidents and incidents, causal tree for analysis adverse events
- Feedback process (REx)
- Analysis of workplace/workstations, analysis of activity,
- Support for change,
- Audits, inspections and safety visits

2.2.4. Situation awareness modeling and evaluation

The study of the performance of the human factor in similar contexts was initiated in military aviation in the United States of America about thirty years ago. Air Force pilots are confronted with complex situations with a big set of data and for which a non-adapted decision could lead to fatal accidents. Ergonomists, engineers and psychologists belonging to this organization have therefore studied the processes and elements that influence decision-making with the aim of maximizing the performance of the human factor in this context, and subsequently reducing the number of accidents. From this was born the concept “situation awareness”. Considered essential for understanding the performance of the human factor, the concept of situational awareness continues to receive the attention of the scientific community [29][30][31][32].

Pilots had to build synchronized and assimilated image in order to be able to make the right decision and take the appropriate action in relation to their complex and dynamic surroundings. A good awareness of the situation is therefore evocative of a good mastery of the situation as well as a good ability to anticipate events. However, low situational awareness signifies confusion about a complex situation and the operator is considered “carried away” or “out of step” with the actual situation.

Several definitions have been proposed in the literature to describe the internal process of an operator in such critical situations without one of them being unanimously approved by the scientific community. The definition most used and most quoted by the authors remains the one proposed by Mica Endsley [33][34][35][36]. Endsley defines situational awareness as:

> *“The perception of elements of the environment in a volume of time and space, understanding their meaning, and projecting their state into the near future”.*

Three main theories of situational awareness are developed: the three-level model of Endsley, the interactive sub-systems approach of Klein **Error! Reference source not found.**, and the perceptual cycle of Smith et Hancock [37]. These theories present a mainly divergence on the nature and the schematization of the concept of SA. SA is represented on one hand as the product of a three levels process (Endsley [33]), on the other hand SA is considered as a continuous dynamic process of the acquisition of consciousness [37] or on a combined point of view which proposes a mix of the two models **Error! Reference source not found.**.

We think that SA theory can be considered as a basis for a deep understanding of human factor performance in complex systems. Figure 4 represents a modeling of how SA can be a part of a global analysis of human performance [39]. Indeed, the understanding of factors that affect SA acquisition is an important way to apprehend and improve the whole system so that human performance can be optimized.

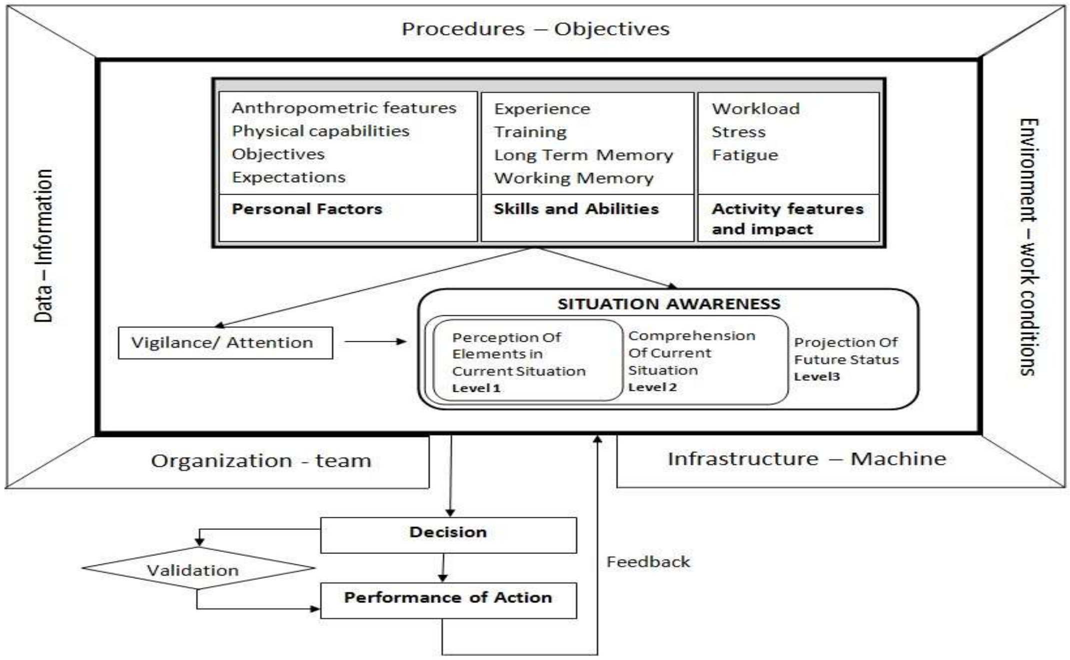

Figure 4: Model Of Action's Determinants Based On Endsley's SA Process (Ouahli Et Al. 2018)

Since situational awareness is an important concept for the assessment of human factor performance, the problem of SA measurement has been studied since the emergence of the SA concept. Several methods have been developed, all of which have advantages and disadvantages in terms of their representativeness.

The most mentioned methods in literature that received much attention are SAGAT by Endsley [34], SART by Taylor [40] and SPAM by Durso et al [41]. These methods can be summarized in the following types:

- Questionnaires: This method is based on the administration of questionnaires to operators and supervisors about different elements of the situation;
- Evaluations: The principle of these methods is that the operators or observers are required to rate the level of situational awareness according to defined graded axes;
- Performance assessment: This approach assumes that situational awareness is strongly correlated with performance. The level of SA is assessed in relation to the performance achieved.

2.2.5. Human reliability assessment

Human reliability assessment attempts to assess the potential and mechanisms of human errors that can affect the safety of systems. Activity analysis is a central step in assessing human reliability. It is a necessary element to take into consideration the specificity of each workstation as well as the important factors related to the activity in question.

Models for taking the human factor into account are based on different objectives:

- Quantify to assess risks and predict reliability (Predictive Quantitative stream). This 1st generation methods consists of evaluating the probabilities of occurrence of human errors in order to integrate these data into the assessment of the overall safety of the system and to establish databases allowing a priori analyzes of human reliability. The THERP method (Technique for Human Error Rate Prediction), introduced by Swain [42], is one of the first attempts in this direction;
- Describe in order to analyze, model and categorize (Analytical Description stream). This approach aims to address the error in its genesis and to provide tools for reliable collection and analysis of errors. The most known methods are ATHEANA, CREAM, MERMOS and CAHR but MERMOS is the much used method [44].
- Describe to predict and prevent. Combinatorial methods aim to describe and analyze in order to prevent but also to predict errors. They therefore combine the prediction of error rates while being based on models of the mental functioning of operators.

A very large number of quantitative methods are referenced in the literature but few of them have been validated or tested in sensitivity studies and fewer are actually implemented [43]. Although other more recently developed methods make it possible to respond to some of the criticisms usually addressed to PEHR methods (Probabilistic Evaluation of Human Reliability): uncertainties attached to the evaluations, sensitivity to expert judgment, etc. Human factors specialists agree that knowledge of the mechanisms of human error is important enough today to better design interfaces, but they are still only simplified models of mental activity, and complex realities.

2.2.6. The Human Factor Analysis and Classification System

The Human Factors Analysis and Classification System is a taxonomy that describes the human factors that contribute to an accident or incident. It is based on a sequential or chain-of-events theory of accident causation and was derived from Reason's [4] accident model (cited in Wiegmann & Shappell, [45]).

The US military first developed the Human Factors Analysis and Classification Sustem (HFACS) System to aid in investigations and evaluate data mishaps [46].

The HFACS is a framework for analyzing human error in complex systems. It is based on the idea that human error is a result of the interaction between the individual and the system they are working in. The HFACS categorizes human error into four levels: Unsafe Acts, Preconditions for Unsafe Acts, Unsafe Supervision, and Organizational Influences. By understanding the underlying factors that contribute to human error, organizations can develop strategies to reduce the risk of error in human tasks execution.

This taxonomy allows to build a causal relation across a large number of incidents, facilitating the identification of dominant and recurring failure factors [47], causal and contributory factors over time [48]. HFACS is a fundamental tool to develop effective accident database and reduce human factor errors through systematic data-driven investment [46].

3. GLOBAL APPROACH FOR HUMAN FACTOR RELIABILITY ASSESSMENT AND IMPROVEMENT

3.1. Analysis of the literature review

The preceding literature review revealed general limits and criticism of the evocated studies. Main detected gaps are resumed in the following:

- Dispersed studies in different fields with diverse local objectives in the domain of human factor activity in critical safety areas.
- The need of complementarity between these studies and approaches.
- A need for operational implementation methodology and guidance to improve human factor performance in organizations.
- Difficulties in generalizing these studies because they are often conducted in laboratory settings, which can limit their ability to be generalized in real world situations.
- Complexity and special characteristics of studied processes which make it challenging to apply general approaches

Based on these findings, our purpose is to contribute in filling these gaps and proposing a new global approach to assess human factor reliability. Our methodology try to combine different approaches detailed in the first session. We give guidance for human factor performance improvement in operational context in respect with specifications of each process.

3.2. Global approach for human factor reliability assessment and improvement

In this session, we present a new methodology that takes into account qualitative and quantitative approaches described in the literature review in the previous session. This evaluation approach considers the specificity of each process and requires the analysis of tasks. We suggest a methodology that assess the probability and the mechanisms of human error in critical tasks performance. The aim is that the system can be improved by developing safety barriers that avoid hazardous events.

3.2.1 Qualitative analysis

The overall assessment begins with a delimitation of the studied process (example: part or all of the production process). Thus, it is necessary to analyze the studied process in order to break it down into activities. These activities can be considered as the workstations of the process. Each activity or workstation is to be broken down into tasks for which the requirements must be defined based on a functional breakdown structure.

Indeed, task analysis is a central step in assessing human reliability. Task analysis in the proposed methodology is mainly based on following aspects:

- Identification of potential sources of errors related to the execution of the task. This through repeated simulations of the task, referring to the database of the analyzed incidents/accidents, and possibly through the administration of anonymous questionnaires administrated to the operators for feedback on the errors made that may not be declared or observed.
- Task analysis involves breaking down a task into small steps to identify potential sources of human error and track critical steps. This can be made through functional task analysis, and decomposition.
- Error-cause analysis by examining past incident and accident to identify patterns and common causes of human failure. This can be made through a deep analysis of root causes of human errors. The understanding of previous errors is an important way to improve the system and develop strategies toward error prevention.

By understanding the performance of tasks in its details, organizations can identify the potential points representing risk of erroneous acts such as complex instructions, poorly designed tools or inefficient communication. The output of this qualitative step is the identification of critical tasks and risky points of the operator activity.

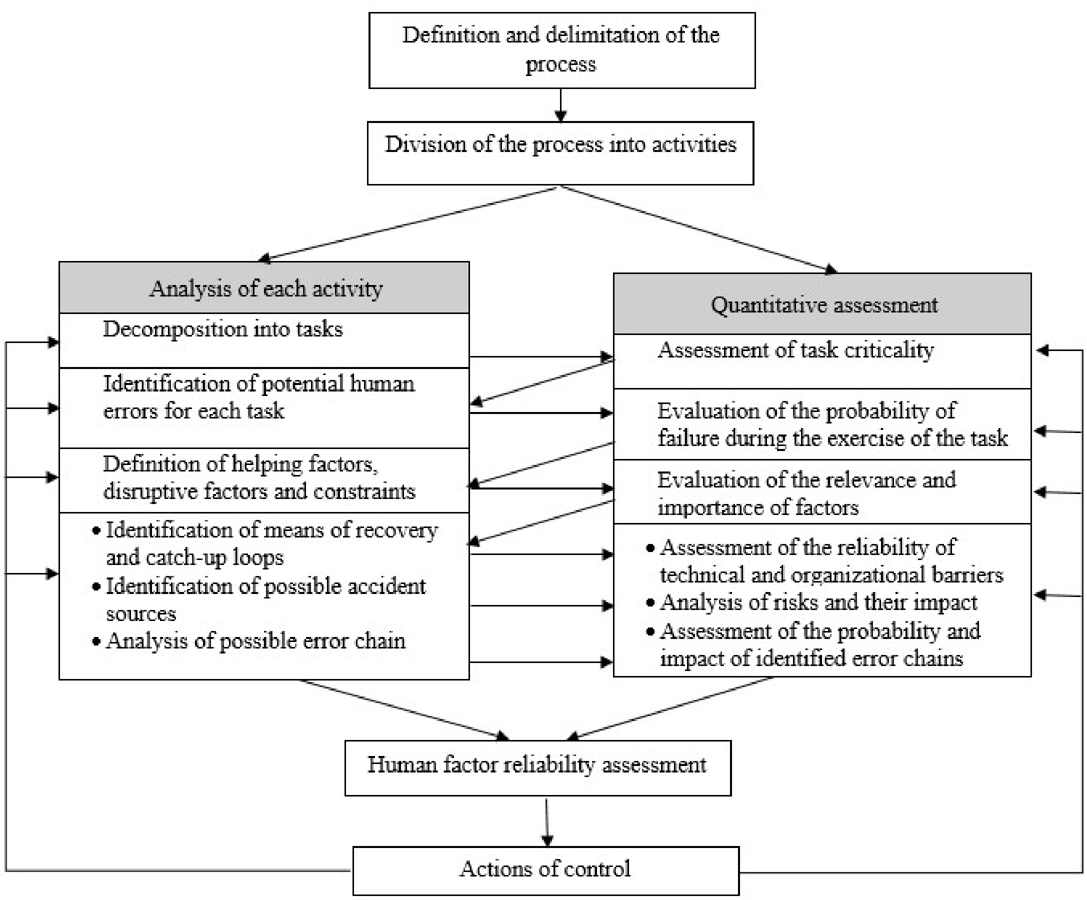

Figure5: Global Approach For Human Factor Reliability Assessment

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3.2.2 Quantitative analysis

For all aspects of task analysis, it is important to carry out a quantitative study based on probabilistic data. Mainly, we propose to realize a risk assessment including frequency analysis for critical tasks. In the following we evocate principle methods for evaluating the probability of human factor in exerting critical tasks.

- Frequency-based approach: estimating an error occurring rates in the future based on collected data on the frequency of the error in studied task. This estimation can be done by tracking errors over time and incidents reports analysis.
- Expert judgment: Human factor specialists and operational managers in an organization are able to identify most likely sources of errors in studied tasks and estimate their probability of occurrence.
- Predictive models that use statistical analysis to predict the likelihood of errors occurring in a task. Statistical methods as regression tree or decision tree identify relationships between predictor variables and the error rate.

The choice of the method depends on the specifications, context of studied tasks and available data. We preconize a combination of these methods to get an optimized benefice. The output of this analysis is a quantitative prioritization of critical tasks and a global evaluation of the reliability of the studied process.

3.2.3. Improvement of the system

To implement corrective and improvement actions we propose to start by identifying helping and disruptive factors. The use of Human Factor Analysis and Classification system in this step is an important operational tool. Collecting data related to the identified factors in order to highlight the importance of these factors affecting the performance of the critical tasks entrusted to the operators.

Once we have identify and evaluate the critical tasks, potential risky points, helping and disruptive factors that influence the performance of human factor, it is necessary to detail an action plan that faces vulnerabilities and enhance safety performance of the global system. Means of recovery and catch-up loops for critical errors is an important step in human failure prevention. To achieve it, we propose the detailed actions bellow:

- Identifying Recovery Options: For identified critical tasks, the first line actions are about eliminating the root causes of potential process failure and identifying potential recovery options. This step could be radical as a global modification of the process, automation of the risky tasks or by implementing only additional checks, audit and supervision.
- Setting-up catch-up Loops: Catch-up loops are processes or systems that are put in place to identify and correct errors after they occur or mitigate their effects. This could include actions like implementing quality control checks, conducting regular audits, or using technology to monitor the process in real-time and identify errors quickly.
- Continuous Improvement: Once recovery and catch-up loops have been put in place, it's important to continuously monitor and improve the processes. This could include regularly reviewing the effectiveness of the recovery and catch-up loops, and making changes as needed to improve their effectiveness.

4. CONCLUSION

In this paper, we propose a general methodology for assessing human reliability that can be applied in any safety critical context.

The proposed methodology makes it possible to draw up a qualitative analysis combined to a statistical evaluation for a global assessment. This methodology allows to define the different failure scenarios by a deductive approach supplemented by an inductive approach based on simulator or site experience feedback to evaluate the different failure scenarios identified (the quantification relies on statistical data based on hazardous events, simulator, site observations as well as expert judgment).

The basis of our methodology is a global approach that provides guidelines for professionals to carry out a human factor reliability assessment that considers a variety of quantitative and qualitative studies. Also, we propose general axes of improvement that could be detailed per each case study.

We look forward our works to detail a use case of the methodology with numerical and process details. The use of a reel world situation in different domain of safety critical systems can demonstrate the utility, detail the operability and detect limits of the proposed approach.

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