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Human Behaviour Understanding in Relation to Technology and the Environment

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Abstract: The aim of this work is to analyse methods and tools for researching and analysing human behaviour in the context of technology and the environment, using our own observations and literature review. In particular, the paper discusses the evolution of human reliability analysis and identifies challenges in human reliability research.

Keywords: Human, reliability, technology, manufacturing.

1. Introduction

Human reliability issues have been the subject of numerous safety and reliability conferences in the ESREL series. In particular, human factors and human reliability were the subject of 29 presentations at the ESREL 2023 conference (ESREL 2023). At ESREL 2025, 19 presentations were presented, focusing on human reliability analysis, human-machine interaction in Industry 4.0, with a focus on ergonomics, safety and regulatory challenges, and human and organizational factors (ESREL 2025).

The aim of the paper is to analyze methods and tools enabling research and analysis of human behavior in the context of technology and the environment, using own observations and literature analysis.

The authors of the publication (Timpe et al. 2004) estimate that human actions account for 60–90% of all failures in human-technical systems. They also express the opinion that there is no uniform theory of human error, and that taxonomies are necessary to measure it. They state that research and identification of human errors are possible and desirable in the following areas (possible actions):

1. symptoms of possible errors in connection with observable incorrect processes of human-technical system use (human reliability analysis, error frequency estimation),
2. variability of possible errors in the context of human psychophysical (psychological) mechanisms (internal causes of human error),
3. the influence of organizational factors as sources of latent errors (management decisions).

The issue of linking the reliability of HR personnel with risks to their health and occupational health and safety is the subject of publications (Lafontaine 2016).

The human factor has been and continues to be a significant cause of adverse events in the operation of technical systems and in human-mediated management.

As a result of the evolution of technical objects and their operating environments, research on human factors (HF) has become particularly important from the perspective of human reliability in the interaction of the human-technical object/ work machine-environment (HTOE) system. Subsequently, this system evolved into mechatronic systems, and now encompasses complex cyber-physical systems with a machine intelligence component.

Understanding human behavior (taking into account their capabilities and limitations) and related factors that influence

the likelihood of human error and the performance of HTOE systems (French et al. 2011, Laux 2019) remains crucial, taking into account human attributes. Human attributes include sensory abilities, perception, memory, knowledge, and emotional structure.

In complex HTOE systems, performance depends, among other things, on the interactivity between humans, the technical object, and the environment.

2. Human Reliability Analysis Concept

Significant publications in the field of human operator reliability research include: (Reason 1995), (Rasmussen 1997), and (Leplat 1998).

The paper (Reason 1995) found that the characteristics of a human machine operator can be represented in the form of a dynamic, programmable model. The nature of the operator's work is a function of the distribution of their behaviors related to their response to the formulated task. The paper (Rasmussen 1997) found that by analyzing the sequence of operator actions and their deviations from nominal values expressed as human errors, it is possible to build a model of the mechanisms shaping the operator's behavior as a function of possible constraints, work efficiency, and adaptability to change. The issue of implementing safety principles in the operation of human-machine systems was the subject of the paper (Leplat 1998).

The traditional approach to human reliability analysis (HRA) in connection with technical systems has so far most often focused on relational interactions between system structure elements.

Due to the evolution of HTOE, interactions in the human-technical-environment system should also consider the complexity of the system in the relationship between the cyber-physical technical object and the possible human behaviors and organizational culture in a given environment, which may contribute to system failures.

In the operational process of a technical object, its safety and functional reliability are particularly important. The operational process is one of the phases of a technical object's life cycle (processes: concept, design, manufacture/ production, use, maintenance, decommissioning/ disposal), in which humans play a crucial role as operators. Therefore, human (operator) reliability in the operational process of a technical object is crucial for shaping (including assessing) functional safety.

In various phases of a technical object's lifecycle, humans are interactively connected to it in specific ways through various HMI (Human-Machine Interface) tools. This interface facilitates feedback by transforming complex data sets into acceptable visualizations useful for process-specific monitoring and control.

Human reliability should be focused on actions that are free from the potential consequences of undesirable events, aiming for failure-free operation of operational processes. Human activities constitute part of a specific system susceptible to possible threats to safety and functional reliability.

Human reliability analysis focuses on analysing possible human errors stemming from various causal sources (lack of knowledge, inexperience, momentary emotional state, unknown environmental variability, work ergonomics) and their consequences.

Ergonomics focuses on designing safety, comfort, and convenience for human performance and interaction with the physical properties of technical objects.

Human Reliability Analysis (HRA) is a set of methods aimed at identifying and analysing the causes of events related to human factors. It is focused on risk assessment and safety analysis in various application scenarios.

A key element of the HRA method is the quantitative HEP (Human Error Probability) indicator, which quantifies the probability that an operator will fail to perform a required action correctly within a given time, conditions, and available resources. Determining the HEP indicator is linked to the analysis of factors influencing error-free operation/ human performance as a technical object operator PSF.

The following Probabilistic Safety Assessment (PSF) factors were distinguished:

1. complexity,
2. experience and training,
3. operator's ergonomics with HMI,
4. operator's access to operating procedures in various exploitation process scenarios,
5. operator's required psychophysical fitness for duty,
6. time available,

7. operator stress level,
8. local process management system.

HRA analyses utilize qualitative and quantitative methods to assess human influence on the occurrence of potential risks (hazards) during the operation of a technical facility.

Research is focused on assessing the impact of human actions on system reliability and explaining internal failure mechanisms involving human factors (Jackelynne 2016).

Research includes: identifying human actions, modelling significant human actions, assessing the probability of human actions that are subject to error, and identifying performance-shaping factors (PSFs) of the human-technical system (taking into account organizational and contextual factors).

3. Evolution of the Approach to Human Reliability Analysis

HRA tools have evolved over the years and three generations of their development can be distinguished (Jackelynne 2016) with a focus on:

1. analysis of the impact of possible human error on the observed performance, combined with a decomposition of the system's structure and functions, followed by an assessment of potential risks (generation 1): HEART, PSA, THERP,
2. analysis of the impact of possible human error on the observed performance, taking into account the cognitive context of the performance (cognitive processes) and the system management methodology (generation 2): ABM, ATHEANA, CAHR, CES, CREAM, SPAR-H,
3. analysis of the evolution of human behaviours that result in performance errors using digital modelling (generation 3).

The first HRA-oriented tools are focused towards probabilistic PSA safety assessment of the human-technical object system, and the dynamic interactions between the operator and the work environment are not taken into account.

The THERP (Technique for Human Error Rate Prediction) method was one of the first tools for analysing human errors (HRA) in industrial applications (Swain & Guttmann 1983, Kirwan 1996, Kirwan 1997). In the THERP method, a human is an element of a human-technical system, and their reliability was estimated as for a machine with a specific structure designed to perform specific tasks under specific conditions.

To assess the probability of human error (HEP), the HEART (Human Error Assessment and Reduction Technique) event tree tool was used, which is a prototype for methods for investigating the causes and effects of failures and for analysing risk and reliability of systems, such as Fault Tree Analysis (FTA) and Event Tree Analysis (ETA).

The analysis utilizes the decomposition of human actions and the construction of event trees and success or failure paths, focusing on the decision-making process related to the operation of the technical object (system). This approach utilizes relational databases (catalogues) relating specific actions and the probabilities of failure for specific scenarios, environmental conditions, and technical objects.

The THERP method allows for the implementation of changes to improve safety, taking into account identified weaknesses in human-machine interaction.

Human Reliability Analysis (HRA) tools subsequently evolved towards event-oriented analyses of potential errors and interactions between factors influencing human performance (PSF). In particular, the following methods can be distinguished: Cognitive Environmental Simulation (CES), Standardized Plant Analysis of Risk-Human Reliability Analysis (SPAR-H), Cognitive Reliability and Error Analysis Methods (CREAM) (Hollnagel 1998), and CAHR.

The CES method focuses on understanding and modelling the operating environment of a human-machine system, examining how humans process information regarding hazards (assessment and interpretation) and their related reactions and potential stressors. The SPAR-H method focuses on assessing human reliability as a function of the probability of operator error (HEP) in conjunction with diagnostic and operational errors and the PSF performance of the operator of a complex technical system. The CREAM method focuses on the analysis of cognitive reliability and human error, aimed at risk assessment in complex technical systems, taking into account the situational context and the operator's cognitive functions (in particular,

their capabilities in perception, interpretation, planning, and action).

The CREAM method is based on:

1. assessment of the impact of the operator's working conditions in the natural environment on their actions and behaviours,
2. cause-and-effect analysis of the error category and possible causes of its occurrence.

A new challenge for the engineering community was the implementation of human-robot collaboration (HRC) systems and cognitive robots (CR). HRC systems have built-in functions for safe operation in specific environments, to a certain extent. It is crucial for such systems to reduce risk in operational processes while maintaining operational flexibility (Yang et al. 2025).

The current trend is to build models using ABM (Agent-Based Mode) digital agents, which take into account the evolutionary nature of human error related to their psychophysical state, behavioural variability, and operating environment. At the same time, machine intelligence mechanisms are being increasingly effectively utilized in decision-making processes.

The aim of the ATHEANA (A Technique for Human Error Analysis) method (Thomson et al 1997) is to analyze probable error events in relation to their sources (triggers) and to estimate the Human Error Probabilities (HEP) in risk assessments.

The SPAR-H (Standardized Plant Analysis of Risk-Human Reliability Analysis) method is focused on assessing human reliability with a focus on determining the probability of a possible HEP operator error in relation to the PSF performance of the operator of a complex technical system.

The CREAM method, combined with ABM, shifts the approach from the traditional model of technical object operation to scenarios of use and maintenance processes that consider possible failures, human errors, and technical object malfunctions. This approach enables a better understanding of the dynamics of possible errors, which impact effective operation mechanisms. It enables optimization and ensuring the functional safety of a system under conditions of specific resources and operating in a specific environment. It also enables integrated dynamic analyses of human reliability, focusing on efficiency, accuracy, and safety.

The CAHR (Connectionism Assessment of Human Reliability) method (Jackelynne 2016) is inspired by the biological functioning of the human brain. It focuses on parallel processing of distributed information within a network, preserving the relationship between an action/stimulus (a change resulting in a response as a result of the interconnections of several causal and situational factors/events) and the reaction/event effect (a second-generation tool). The method's features include: information is distributed throughout the network's connection structure (expressed as weights); information is processed in parallel across various connections between system structure elements; and system behavior is trained by adjusting the connection weights (relationships) between selected system structure elements in response to potential errors (also using backpropagation algorithms). These potential relationships are strengthened by rewards and weakened by dereliction.

The essence of next-generation HRA tools (Ciani et al. 2022) is to study the evolution of human behavior that results in error, using digital modelling for cognitive purposes and building relational databases (catalogs) between specific actions and error probability for specific scenarios, environmental conditions, and technical facilities. Generation 2 tools/ methods are being developed as the generation 3 new more advanced tools.

Current industrial evolution requires a holistic approach to the design and operation of complex, mixed systems in a changing environment. At the same time, there is an urgent need to develop communication between the technical and humanities communities to address new civilizational challenges and develop useful methods and tools aimed at understanding human behavior in interaction with technology and the environment.

The Industry 4.0 model focused on digitalization and automation combined with the Internet of Things (IoT) concept. Industry 5.0 is evolving toward social and environmental aspects. Humans are being placed at the center of attention (HCA, human-centric approach), people are collaborating with machines (cobots), products are being personalized, humans are being more closely integrated with technology,

sustainable development is being promoted, and systems are being designed to quickly adapt and function in a threat environment (resilience). The Internet of Everything concept is being utilized, resulting in a system that is complex and diverse in terms of structure and functions.

4. New Challenges in Human Reliability Research

Human reliability is perceived and directly linked to their characteristics (potential), which are subject to evolutionary change. Human evolution is strongly linked to their living environment and activities, which are focused, among other things, on the cycle of formulating dreams (actions). Dreams beyond human capabilities are expressed through new needs, with the pursuit of achieving them as a result of research and analysis using available knowledge and technology. With human participation in the process of action (implementing a specific mission), new solutions are created, expressed through products (including machines, technical objects, and services). Humans play various roles in these lifecycles, from concept through implementation, to use, maintenance, and disposal.

The evolution of human integration with the product (technical object) they shape throughout their life cycle is required to better understand the mechanisms that ensure the required level of functional safety and reliability. Integration of human systems (HSIs) (Jackelynne 2016), utilizing their communication receptors, is also essential, focusing on purposeful collaboration combined with openness to multidisciplinary learning in the context of meeting a specific need or goal.

The reliability of technical objects has been shaped over the years using models originating from systems engineering and systems theory, and then evolved into models such as a system of systems (SoS).

A system can be subject to dynamic change and task-based relationships with other systems (the system of systems formula). Currently, key challenges include adopting a human-centric approach to digital technologies, including artificial (machine) intelligence and related regulations, digital twins, and augmented reality, upskilling and reskilling people with digital skills, and a cost-effective and sustainable, circular industrial model. Advanced mechanisms are currently being developed that integrate physical components and operators with decision-making mechanisms supported by real-time digital computational processes, resulting in autonomous monitoring, control, and optimization of physical processes (cyber-physical systems, CPS).

A system of systems (SoS) is a collection of heterogeneous, independent, and distributed systems (of purposeful use) collaborating toward a common goal that cannot be achieved by a single system.

SoS systems are characterized by their evolutionary nature and complexity, and also by their potential: their own dynamic structure, the ability to act independently, possessing their own goals, the ability to cooperate and share resources, the lack of central management, and the ability to operate in diverse environments.

A system (e.g., operators, technical devices) of systems (SoS, system of systems) is a purposefully (task-wise) configured set of independent, autonomous systems connected into a larger system with specific required properties, which can then be subject to further purposeful reconfiguration. The systems approach aligns with systems engineering, which utilizes the principles of systems thinking, an interdisciplinary field of research in the field of product engineering and management throughout its lifecycle.

The SoS model is evolving to address new challenges in cyber-physical system modeling. The SoS concept is applicable in dynamic environments where integration and coordination are crucial for adaptive capabilities (Ashfaq 2026).

As technology advances and becomes increasingly equipped with devices for information acquisition, processing, and internal and external communication, it has become possible to build purposeful, action-oriented networks, known as the Internet of Things (IoT). Integrating human systems (HSI) with the IoT has led to the concept of the Internet of Everything (IoE).

IoE operation, expressed through a purposeful mission, is a complex, interactive function between elements of a structure encompassing humans, technical objects/machines, software/digital models, communication, and the environment. IoE systems are characterized by high complexity, are subject to evolution, and require purposeful analysis throughout their lifecycle, also for reliability reasons, including HRA, but from a new perspective.

The essence of IoE systems is communication using tools such as interfaces between various actors: humans, technology, and the environment, as well as understanding the attributes of these possible interactions. The goal of IoT systems is to design and operate safe, reliable, effective, and efficient systems that align with sustainable development strategies.

Furthermore, the HCD (Human-Centered Design) approach, which places humans, with their needs and characteristics, at the heart of the creative process in the lifecycle of SoS systems, is imperative. It seems that humans will continue to be the essence of every SoS system in terms of criticality, coupled with the need to ensure functional safety, which requires the development of a supportive environment.

The HCD (Human-Centered Design) approach focuses on analyzing human needs, particularly the user of a product (technology, most often digital) and its (human) possible interactions, taking into account psychophysical properties, emotions, and constraints. The complexity of systems in terms of structure, function, required communication, and the existence of limited human resources results in a growing demand for machine intelligence and digital twins.

Human-Centered Design (HCD) is evolving towards a human-centric approach (HCA). HCA leverages digital twins and machine intelligence to address new challenges in the design and operation of cyber-physical systems. An example of an intelligent system design combining human cognition and machine control, expressed through human-centered technology (HCT), and then implementing purposeful human-machine collaboration (HMC), is presented in (Sun et al. 2026).

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