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Human Factors Engineering in System Design: A Roadmap for Improvement

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Abstract

This paper summarises current industrial practices and standards promoting Human Factors Engineering (HFE) at design stage and revise them with an action research approached based on the concrete case studies performed during a European project called TOSCA. The paper highlights how HFE can significantly impact the costs and risk associated with a plant lifecycle and the current gaps and issues encountered. The gaps identified are used to guide industrial practices and standards towards a more valuable inclusion of Human Factors knowledge in structured system design processes to support human performance and reduce the potential for human errors in operations and maintenance.

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Keywords: Human Factors Engineering; Maintainability; Human Machine interface; System Safety Engineering

1. Introduction

Human Factors Engineering (HFE) has a key role in promoting the inclusion of human factors knowledge at design and construction phase in socio-technical systems. Several research projects and programs [1] on system safety engineering and Quantitative Risk Analysis in the last 40 years have offered very strong evidence of the crucial role that human and organizational factors (HOFs) play in major accidents.

A coherent definition of HFE is provided by the International Association of Oil and Gas Producers (OGP), which states that HFE is a discipline exploiting a multidisciplinary approach that focuses on the integration of five elements (“star model”): people, work, work organization, environment and equipment [2]. In other words a suitable HFE application framework should address the whole collection of these contributors with respect to the specific case study, so as to support the human inputs to production and reduce potential for human errors for Occupational Safety and Process Safety. HFE can be interchanged with the terms “Human Factors” and “Ergonomics”. In the Process industry the demands for safe and efficient operations has increasingly shifted the role of the human in the system from primary actor to supervisor of an automated process [3]. This increase in the role of automation highlights the need to properly consider possible hidden hazards when interfacing automation with the process to be controlled and the operators supervising them. In the past the development of new technology was much slower than it is at present and it did allow enough time for the hazards to emerge [4]; hazards that may also originate in the lack of adequate support for operator’s cognitive processing at a rule-based level or at a knowledge-based level [5]. What is now more and more crucial are supports for the diagnostic capabilities of the operator to properly identify deviations in the process, to suitably fix eventual problems coherently with the severity of expected consequence/s. When the complexity of the system increases in fact the ability of the human to control the system and intervene in foreseeable and or unforeseen circumstances with even manual functions such as corrective maintenance) it’s still crucial in helping the system to recover from abnormal conditions [6]; hence the need for Human Factors consideration in designing for operability and maintainability. Simple yet effective choices at both organizational and technical level can be observed to enhance human performance, prevent human error and improve safety and maintainability [7][8]. In relation to Process Safety, a well performed HFE method should account for two different aspects: resilience to human error, and enhancement of human

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performance which means support for direct intervention of operators whenever their tasks are required (e.g. maintenance intervention, calibrations etc.) providing them with better understanding of system dynamics and implications of their tasks. The quality of the human-machine interface (HMI) is critical in this sense. There have been several attempts to tackle this aspect with approaches supporting Human-Centred design [9], intelligent human-machine interface design [10], user needs analysis [11], Safety by Design [12] and Human Factors Integration [13]. Design practices have improved over the years also thanks to the lessons learnt from past accidents and incidents [14]. HMIs need to be carefully designed to meet the operator requirements and provide information and procedural guidance to support his or her diagnostic capability [15]. Boy and Schmitt [16] pointed out the necessity of consideration of human factors at design stage and consideration of the user's needs with new sophisticated methods because safer design requires iterative participation of the operators. Currently the availability and usability of human factors guidance provided by standards for designers and the maturity of practice is an issue [16]. Unfortunately the contribution of safety and human factors experts can only be effective if they can understand the choices made by designers and the reason behind their decisions [17]. That is why participation of designers and human factor/safety experts as a team to enforce knowledge exchange and cooperation can positively impact the quality of the outcome [18]. The value of early HFE integration in design projects is currently supported by some companies in the process industry, which have started to include Human Factors Engineering as a project requirement at procurement stage. In this sense, a EU funded research project TOSCA (Total Operation Management for Safety Critical Activities) [19] has proposed a comprehensive framework for the inclusions of Human Factors knowledge in structured system design processes and a roadmap for further improvement.

2. Current industrial practices and standards in HFE

In order to provide support for industrial practitioners, a number of standards are available [20]. The standards could require, where appropriate, to take into account the physical and cognitive ergonomic assessments of the operator tasks, the equipment they will use to complete those tasks, and the environment in which the tasks occur. However, the standards need to be generic enough so as to avoid being tailored to any specific design process; this in turns generates a need for more specific guidance for different domains to concretely guide Designers, Operators, Risk Assessors and Project Planners. Safety critical domains such as aviation or nuclear industries, have often developed their own internal standards to provide more specific guidance on HFE assessment and safety by design issues. This section is aimed at providing a brief overview of the HFE standards most commonly used. The ISO: 6385– Ergonomic Principles in the Design of Work Systems [21] outlines how in the design of a work system, the design of the following components shall be addressed: *(a) design of work organization; (b) design of work tasks; (c) design of jobs; (d) design of work environment; (e) design of work equipment, hardware and software; (f) design of workspace and workstation...* Each design stage is described and appropriate ergonomic principles and methods for each stage are listed. The ISO 6385 is supposed to work as a menu to guide further choices but it's to be revised to provide a more comprehensive and structured list of available practices, for example it does not provide any reference to the standard ISO 11064 - Ergonomic Design of Control Centres [22]. This standard offers nine principles for the ergonomic design of control centres and guidance on specific aspects of control room design, including layout, workstation design, controls and displays, and environmental requirements. Another cross reference that is not mentioned in the ISO 6385 is the one to the standard ISO 12100 – Safety of Machinery [23] which suggests a five steps methodology to perform risk assessment at design stage and the overall strategy to take into account safety of machinery in the life cycle, considering usability, maintainability and cost efficiency. Outside the ISO group the EEMUA 191 [24] is an industrial standard developed by the Engineering Equipment and Materials Users' Association to support the design of alarm systems taking into account the requirements of the human operator receiving and responding to those alarms, while EEMUA 201 [25] is focused on the design of HMIs and gives guidance on areas such as display hierarchies, screen formats, and the attributes of the environment which may affect the use of the HMI. These standards define minimum requirements but their systematic approach is fairly generic and does not provide technical support for designers. They offer no guidelines regarding the methodology to conduct this verification. Rapid prototyping and participatory approaches are more and more becoming common practice in design review [18]. The use of 3D models reviews is also often undertaken with the involvement of the final users. The 3D model is a more natural representation that does not require decoding of 2D technical drawings and thus facilitates the operator in identifying potential issues regarding the proposed design. This approach can be considered a concrete example of human centred participatory design, and a more solid starting point for the designers to deliver a safer design. Such participatory design reviews should be facilitated as early as possible. The above-mentioned standards can be used in combination with 3D participatory review, however the process has not been detailed or suggested clearly in any of the before mentioned standards. So while on the one hand ISO 9241-210 [26], Ergonomics of Human-System Interaction, requires participatory human centered approaches it does not provide technical details on what specific aspects should be considered and how to concretely carry out such a process; again even this one does not even refer to more specific standards such as ISO 11064 [22] for the Ergonomic Design of Control Centers and or ISO 12100 [23] on Safety of Machinery. Integration of HFE principles within broader technical engineering and design standards may be one way to achieve assimilation. Too often, only human factors specialists are aware of the existence of HFE standards and the principles contained within them. It is also important to ensure that the HFE standards are aligned with the relevant engineering standards, to ensure that designers are not receiving conflicting guidance. Moreover, it is valuable to underline that the main best practice in HFE is to involve, as much as possible, the actual needs of the end-users in all the design phases to bring in a life-cycle perspective.

3. Example of applications, design for operability and maintainability: issues and solutions

In Trinity College Dublin, the Centre for Innovative Human System (CHIS) is currently working in a research project TOSCA to map out the best practices for HFE and promote its integration with design engineering & safety engineering and provide a road map for future implementations. In almost all the industrial test beds, TOSCA focuses on introducing human factors at the heart of risk modelling, rather than as a separate and additional analysis. Two examples are discussed below to highlight the importance of Human Factor integration to deliver better designs for both operability and maintainability.

3.2 HFE for the design review of a Gas Insulated Switchgear

The first case study examines the introduction of a Gas Insulated Switchgear (GIS) in an existing facility for an energy company. The term switchgear, used in association with the electric power system, or grid, refers to the combination of electrical disconnects, fuses and/or circuit breakers used to isolate electrical equipment. Switchgear is used both to de-energize equipment to allow work to be done and to clear faults downstream. This type of equipment is important because it is directly linked to the reliability of the electricity supply. A safe, reliable supply of electricity depends on the circuit breakers that protect electricity grids in the event of short circuits. An effective although more costly form of switchgear is gas insulated switchgear (GIS), where the conductors and contacts are insulated by pressurized sulphur hexafluoride gas (SF6). The use of GIS rather than conventional air insulated switchgear (AIS) is enabling the new substation to be housed indoors and condensed into around one quarter of the space. Gas Insulated Switchgear have been gradually changed, moving towards layouts that require less and less space and often translated into having space constraints and awkward situations for the technicians during commissioning and maintenance actions. Figure 1 shows a section of the GIS system (not to scale).

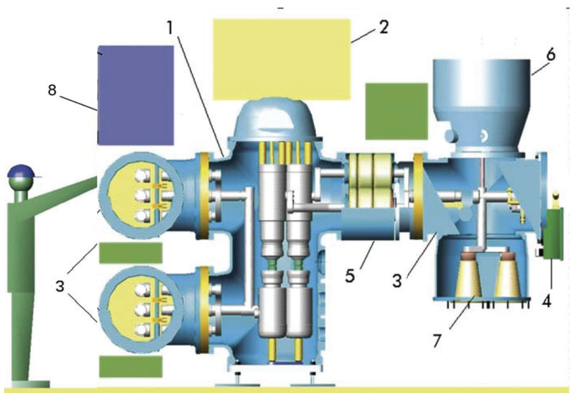

Fig. 1. Cross Section View of GIS

The manufacturers argued that design improvements in GIS make it virtually "maintenance free" and compliant with all the relevant standards (e.g. IEC 62271-1[28], IEC 62271-203[28]). High voltage equipment is indeed mostly designed according to technically prescriptive standards and requirements based on electrical engineering safety principles (e.g. CEI IEC 62271-202 High-voltage switchgear and control gear) [29].

However, those standards do not take into full account aspects related to the human interaction with the equipment, which is limited but by no means negligible. Consequently, this first case study immediately exemplifies the imbalance between the considerable research efforts addressing Human Factors worldwide in the last couple decades [7][8] and the very limited impact on the technical standards currently applied for the evaluation of safety critical equipment and procedures. Besides, this case study highlights clearly that a good design, taking into account all potential risks, helps to ensure safety during repair and maintenance work. Even though manufacturers often refer to GIS as maintenance free, nevertheless commissioning, operational checks and inspections, and the occasional maintenance interventions are activities during which the technician is still required to interface with the equipment. A more compact GIS, in fact, often means technicians adopting awkward postures during commissioning and maintenance actions that are still required. The qualitative analysis has shown that the most significant issues related to this system are: limited and restrictive working areas, the fact that technicians will be required to work in fixed and awkward posture for sustained periods of time, the difficulty (or complete inability) of reading the metrological data, and the slowdown in the emergency procedure. As seen, most of these issues are ergonomic related aspects and they have an important impact on reliability of the whole system and on the wellbeing of the operators. It seems that some basic principles of accessibility were not properly taken into account in the design of the equipment. The lack of basic ergonomics principles in design is reflected in the difficulties encountered by the operators to manually open or close the circuit breakers in case of failure of automatic activation. The risk is that the worker fails to resolve situation in time because he/she must reach the high location and turn the mechanism shaft while standing in an awkward position directly on top of pipe-ducts.

The estimation of the impact of Human Factors on risk assessment for the system was performed using an ad hoc Failure Mode and Effects Analysis (FMEA) template where the functional analysis included the human tasks as well as the technical aspects. Once the qualitative analysis was completed the next step was the evaluation of the appropriate reliability data to be used for the quantitative assessment. Information about the order of magnitude of the likelihoods of the events was obtained using equipment reliability data (when available) and the Technique for Human Error Rate Prediction (THERP) [30] for relevant human errors whilst the severity was assigned using expert judgment based on the classifications guidelines used by MIL-STD-882 [31]. The study showed that taking human factors into account changes the level of risk significantly, in some cases of an order of magnitude going from acceptable risk to undesirable, or in the worst case to unacceptable [20]. Generally, the results show the importance of taking into account human factors at the design stage of a piece of equipment where modifications are easier to carry out and less expensive than they would be once the plant is built.

The results were discussed in a review meeting with operational personnel and the safety supervisor of the company owning and operating the equipment. They approved and confirmed the problems highlighted by the analysis and will use them to try and identify feasible solutions for future procurements with the management.

3.2 HFE and the design review of a gas processing facility.

The second case study concerns the design review of a new Gas Condensate Stabilization Plant processing plant to be connected to an existing plant. Natural gas is a mixture of many compounds, among which the main constituent is methane (CH_4). When natural gas is extracted from an underground well, it is saturated with water vapour and it usually contains heavy hydrocarbon compounds and non-hydrocarbon impurities. In this raw state, natural gas cannot be marketed and therefore must be processed to meet certain specifications before it can be sold. There can be different equipment configurations for the processing required to separate natural gas condensate from a raw natural gas. The one considered consists of the following facilities: (the actual configuration cannot be displayed for IP issues)

a. Extension of inlet pipeline from each plant.
b. Installation of pre-flash vessel facilities including water coalescer and water filters
c. Installation of a condensate stabilizer facility including, reboilers and heat exchangers for heat integration.
d. Installation of 3-stage flash gas compression facilities.
e. Installation of produced water system.
f. Installation of off-spec condensate system.
g. Installation of all associated utilities for condensate plant (hot oil, fuel gas, flare and drain system)

One of the main drivers of the HFE inclusion in the project was the direct request of the client that wanted to make sure that the actual physical layout, operations and control room environment and procedures connected to the design were reviewed to identify possible issues connected to process and personnel safety and operability/maintainability of the equipment itself. Such an attitude in organizations provides evidence that the benefits of HFE screening at design stage is becoming more and more evident to the industry. Likewise, this example is useful to merge the main issues related to HFE in this specific context in order to explain in more detail the main proposed approaches to deal with them. The project has benefited from an initial Human Factors screening: the tool used was aligned with Oil and Gas Producers' recommendations [2]. However, these standards lack a set of more concrete guidelines for Human Factors Engineering activities, so that proper integration between different standards and the strengthening by expert elicitation was required. The basic needs that emerged for the use of HFE principles applied to that design project were the following:

- The Ergonomic Review for Physical layout and plants area was achieved reviewing the 3D model of the unit at 30%, 60% and 90% stage of finalization using checklist design on the basis of the ISO 11064-4 [22] and the MIL-STD-1472F [32];
- The Ergonomic Review of the control room and the Human-Machine Interface (HMI) was performed taking into account those cognitive and physical aspects relevant to support the effective control of the plant through the information provided by the control panel. This review relied on the guidelines provided by ISO 11064-5 [22], which presents principle and gives requirements and recommendations for displays/controls (and their interaction) in the design of control-centre, and ISO 9241[26]. The procedures has been formalized with the Basic Ergonomic Review Report, which includes the 3D model of the plant (at various level of completion), the Control room Layout and the DCS Graphics Print Out;
- The Alarm Rationalization Study provided requirements and recommendations for the prioritization and the settings of alarms connected to plant monitoring to reduce information overload, and prevent possible human errors in control room tasks. The objective of the alarm study was to capture and document all information relevant to the proper design of an alarm system and to define alarm suppression strategies. Not all alarms and messages should necessarily be routed to the operator; other recipients of alarms and messages should also be considered. To do this a Variable Table Construction (via Initial Setup - ISU) was used to understand the boundaries of the process, setting the safe operating limits correctly, provide sufficient time to respond and adopt a consequence based approach. Alarms are always linked to human follow-up. Therefore, the foremost principle in reviewing alarm is the recognition of the human task and the human factors involved. It is also important to avoid a situation with huge information overloads. The following documents need to be issued at least "for comments" as they are basic inputs to the activity: I/O List, Alarm Philosophy and Distributed Control System architecture;
- The analysis of possible human errors also referred to as "Human Reliability Analysis" in this case was qualitatively performed as a review of main critical possible errors. The output of the study was a report specifying possible recommendations aimed at reducing Human Error or mitigating its effects. As part of the Human Reliability Analysis an initial task criticality screening and a more detailed task analysis for highly critical task was carried out. The following documents were used as basic inputs to the activity: main operation procedures (start up and shut down procedures for the facility) or the operating philosophy, main maintenance procedures or maintenance philosophy for critical equipment, interview with process engineering designing the plant to capture elements not described in the above documentation or to elicit the information if the documentation above is not available, main control room and or field operator actions expected in response to critical alarms and areas that require modification and providing them with possible mock-up solution. Using a standard method [4] the tasks were reviewed and ranked based on criticality level. The final result was a critical task inventory, with recommendations on each critical task to be used for further screening and input into the design of manuals and procedures. The identified tasks that are ranked critical could be further analysed for procedural reviews and for special training purposes.

Parts of these studies overlapped with each other and have been considered together. For example the Alarm Management study can be an input to HMI design review but this point is not clearly mentioned in any of the available standards. The overall outcome of the HFE intervention in the design project was a report covering different aspects from physical ergonomics to work load assessment and maintainability of the system.

The experience of the HFE study was not optimal due to the late involvement in the project and the lack of integration with the design team; however the HFE input was well appreciated by both the design team and the end users. Nevertheless, this experience can become a very convenient means to share some lessons learned, for further developments of HFE discipline.

4. Example of benefits and suggestions for improvements

The case studies discussed in the previous paragraphs are aimed at emphasizing the importance of the inclusion of Human Factor Engineering at the very early stage of systems design and at presenting some existing approaches to do so. The benefits to be gained from the adoption of a proactive approach towards Human Performance in industrial systems have direct implications for the improvement of system operability and maintainability during its whole life-cycle. Basically, HFE offers the opportunity for screening and ranking the potential human related-issues in each status of the system, e.g. normal operations and maintenance. Next, it provides the required guidelines to deal with these human-related issues and to properly address them. The immediate benefits are in terms of preventive measures and mitigations against human performance degradation. Indeed, a design coherent with HFE supports the direct interventions of the operators, meaning that it proposes valuable solutions to prevent human error perturbations on the system and also the enhancement of human performance during the required tasks. Current standards in use for system design are necessarily broad in order to deliver their support to the widest possible range of end users. However, companies are often using additional internal material to allow the specification of guidelines better tailored to their operational realities. This may be the sign of a widespread need for more detailed HFE guidance to support the design process. Table 1 summarises issues and gaps previously highlighted in some of the available standards whose importance has been confirmed by the case studies.

Although much of the standard guidance is available to engineers and design teams (it is often specifically targeted at these groups), the authors would stress that their experience of the duration and frequency of detailed review sessions reveals that these groups are not fully assimilating HFE information. It is also important to ensure that the HFE standards are aligned with the relevant specific technical engineering standards, to ensure that designers are not receiving conflicting guidance from the two sets of guidelines. In order to best achieve this, engineers and designers should be provided with basic training in HFE to ensure that they understand the basic principles and are capable of correctly interpreting the information contained within the standards and applying it to their designs. These limitations highlight the possibility of further improvements of Ergonomic standards, to become more practicable and effective for designers.

Table 1. Summary of HFE issues in system design standards [3]

HFE Area of Design	Related existing standards / best practices	Possible issues/ gaps
Design of physical built environments	ISO 6385 (2004) Ergonomic principles in the design of work systems	The standards do not provide any practical guidance on how to actually review the built environment at the design stage involving users (such as 3D reviews)
Design of machinery / electrical systems	ISO 12100 (2010) Safety of machinery / EEMUA 178 (1994) A design guide for the Electrical Safety of Instrument Control Panels	The standards are seldom applied in the industry and they do not specify to what machinery they should apply
Design of control rooms, HMI for information systems	EEMUA 201 (2010) / ISO 9241-210 / ISO 11064 (2006) Ergonomic design of control centres	How to review the mimics of control centres is not specified and the use of task analysis is not clearly suggested
Design of information systems and alarms	EEMUA 191 (1999) / ISO 11064 (2006)	As above
Workload assessment for design	ISO 11075-3 (2004) Ergonomic principles related to mental workload	Not really applied in the industry
Design of manuals and procedures	ISO 12100 (2010) / ISO 18152 (2010) Ergonomics of human-system interaction – Specification for the process assessment of human-system issues	The standards specify how to assess processes but not how to translate them in to good instructions and procedures
Risk assessment at design stage	ISO 31010 (2009) Risk management – Risk assessment techniques	Little guidance on what standards are available for human reliability analysis

5. Conclusions and roadmap for the future

The most valuable contribution to be gained by good Human Factors Engineering practices is the improvement of the likelihood of Business Continuity for a system related to reduced outages and the time requirements for maintenance interventions which leads to enhance the results of a certain company in terms of avoiding loss of production.

This is the final goal of TOSCA project that is striving to develop appropriate guidelines for effectively introducing HFE as part of Total Quality Management (TQM) for the industrial partners selected as test beds within the project. The project has highlighted gaps with existing standards and industry guidelines that will be addressed by providing an example of industry tailored Human factors engineering review methodology for the review of project in system design especially tailored fro the process industry. However the applicability of the methods (such as task analysis and risk assessment review for critical operations) could be extended to other domain such as manufacturing and robotics. The main milestones for improvement can be summarised as follow:

1) Review of educational program for engineers to include some basics HFE elements for system design.
2) Integration of HFE principles within broader technical engineering and design standards.

3) Set up reviews with end users as a systemic approach in design processes and collect feedback from operations.
4) Structured risk assessment at design stage for operability and maintainability including analysis of issues related to processes and tasks for which the system is designed or connected to the system being designed.

While the key benefits to be achieved are:

a) Improving the quality of the end-products. So as to provide more effective and quicker intervention in processes through a clear panel layout. Improved personnel performance with respect to man-machine interface thus resulting in a higher quality product.
b) Preventing damage/risk to plant. By improving access for the use of required equipment and tools it's possible to reduce the risk of damage to, piping and instrumentation.
c) Preventing illogical valve position indicators, etc.
d) Reducing/preventing errors. An example of this an HMI able to enhance diagnostic operations to support more effective intervention in the event of potentially undesirable deviations, reduction of waste through increased reliability, preventing unintended actions, etc.
e) Reducing/eliminating physical/mental stress. Reduce pulling, pushing, lifting, bolting effort, fewer adverse working postures, more convenient operation of equipment, etc., improved presentation of information
f) Reducing training costs (requirements/time) due to simple and logical designs, making it easier to delegate work to less trained personnel ensuring participation of the end-users in the design process

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