Design of Work Equipment According to Human Factors and Ergonomics for Machine and System Safety

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ABSTRACT

The concept of work system design in human factors and ergonomics (HFE) with its interdependent dimensions and respective design requirements and recommendations is crucial for the design of machine and system safety including human-system interaction for safe operations. Therefore, design requirements and recommendations for work equipment and human-system interfaces have been collected and compiled for presentation to manufacturers, users and occupational safety and health (OSH) experts. With an emphasis given on human information processing, design principles for the task, the interaction and the information interface are presented for displays and control actuators according to HFE findings and standards harmonised with the Machinery Directive. The upcoming Machinery Regulation calls for a revision of design requirements in harmonised standards. This must result in addressing the changes and including new HFE findings for the design of safe machines and technical installations providing safe operations for humans in practice.

1 BACKGROUND

The Machinery Regulation (EU) 2023/1230 [1] has been published in June 2023 and will come into effect in January 2027, when without transition period, it will replace the Machinery Directive 2006/42/EC [2]. Even though content is similar, due to few bigger and several smaller changes, it is worth knowing about differences between the Directive and the Regulation [3], especially since rather few standards harmonised under the Directive [2] will soon cover all necessary amendments and modifications required to become harmonised under the Regulation [1]. With regard to human factors and ergonomics (HFE), some differences have significant consequences for the design of safety of machinery such as the consideration of self-evolving behaviour of machinery or supervisory control of highly automated mobile machinery, both closely linked to a long research tradition on concepts of human-automation interaction [4, 5] and the trend to use assistance systems, i.e., for replacing and assisting direct view by camera-monitor systems [6-8], to name but a few.
A structure to systematically address a HFE perspective for safe operations refers to the concept of work system design [9] and standard design procedures in HFE [10]. With the primacy of task design being the core of the HFE design strategy, technical and organisation components of a work system serve task completion, optimise physical and mental workload, and improve overall system performance. The concept of work system design comprises workers performing work tasks (e.g., reliable detection of persons in danger zone, [8]) affected by interacting conditions of work organisation (e.g., continuous shift work), workspace and place (e.g., construction site), work equipment (e.g., camera-monitor system) and work environment (e.g., daylight, frost temperature) [9, 11]. Since the worker is assumed having adequate qualifications for the work tasks, design requirements in work systems refer to work tasks and all other conditions imposed by the system.
With work equipment used in monitoring and control operations being of special interest in the revision of the Regulation [1], information regarding equipment design has recently been added within the platforms' structure on work system design [12]. Information reviewed, selected, and presented on the platform [12] intends to promote an active and constructive discussion of HFE regarding design requirements, recommendations, and solutions to improve safe operations in today and future design of machines and other technical systems.

2 METHODS

The concept of work system design in HFE provided orientation for a structure appropriate for presentation of information [9, 13]. The platform [12] aims to inform, motivate, and support machinery manufacturers, users and occupational safety and health (OSH) experts to apply OSH and HFE when constructing, risk assessing, setting-up and operating machinery. Content on work equipment design was gathered based on reviews of HFE literature (e.g., [14-17]), regulations (e.g., [1, 2, 18, 19]) and standards (e.g., [20]) including information available in varying

subgroups related to OSH activities (e.g., [21, 22]). Content preparation included draft reviews, discussions, and revisions of results for the three-level structure of the platform. While the top level refers to work system components (i.e., work equipment), the second level provides information from work system design towards solutions for early design stages (i.e., display and control actuator design principles). The third level intends to explain what, why, when, and how to apply HFE requirements and to illustrate good practice in machine and system safety by showcases and examples (i.e., visual, auditory, and tactile displays and types of control actuators).
Information about work system design has been internationally presented on purpose because this enables step-by-step composition, allows for flexible adaptations in case of new HFE findings, permits updates along harmonised standards, or facilitates extensions of requirements for work equipment not yet addressed. This is of interest with the upcoming need to provide revised harmonised standards implying presumption of conformity with the Regulation [1]. By complying with harmonized standards, manufacturers and designers can demonstrate that design solutions meet the necessary safety and performance requirements of the Regulation, facilitating market access throughout the EU. However, when design solutions do not follow requirements from harmonized standards, it is the manufacturer or designer required to proof equivalence or conformity with the Regulation.
Among harmonised standards in HFE on work equipment design for safe operation, the standard on ergonomic requirements for the design of displays and control actuators [23-26] is generic and critical because it provides general design principles for human-system interfaces and it emphasises details for several hardware displays and hand control actuators being part of former, latest as well as future devices, machines, and installations. Since the series of the standard misses some details, a review among HFE experts has been conducted to collect information considered relevant in an upcoming revision of the standard, i.e., for software-based representations of displays and control actuators such as touch displays.

3 WORK EQUIPMENT DESIGN ISSUES

3.1 Human information processing in design principles

Work equipment is one among other dimensions in work systems to be designed according to HFE principles for facilitating and improving human task performance. In the given context, design issues rather refer to the design of the interfaces of equipment for human-system interaction (e.g., on/off-switch, graphical user interface) than to the design of the whole equipment or tool (e.g., circular hand saw, excavator).

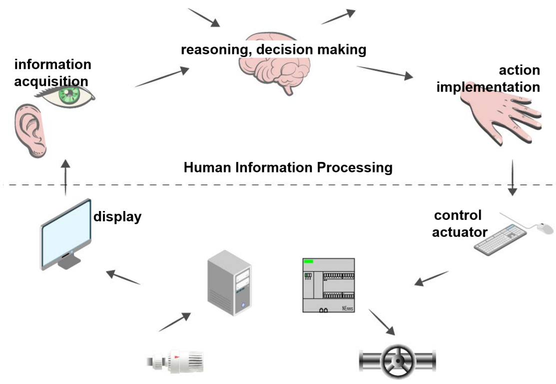


Figure 1. *Human information processing interfaces with work equipment for human task performance.*

The design of the work equipment shall fit to and serve the human tasks in the system. Human task performance follows cycles of human information processing (see Figure 1) [6, 17] beginning with

- Human information acquisition (and perception) through human senses (e.g., sight, hearing, touch, smell taste), followed by
- Human information processing (and reasoning and decision making) through the human brain (e.g., attention allocation, working memory, anticipation of consequences), resulting in
- Human action implementation through human body parts (e.g., fingertips, hands, legs, whole body).

During this process humans interact with work equipment or machines through human-machine interfaces at

- The side of machine output designed to facilitate and improve human perception (e.g., visual display presented in human binocular view) and
- The side of machine controls designed for input and to facilitate and improve human action implementation (e.g., repeated activation of emergency stop avoids reverse activation).

Steps in the process of human information processing (i.e., perception, reasoning and decision-making, action implementation) form design requirements to be matched by work equipment design (e.g., feedback, compatibility,

controllability [14, 15]). Work equipment design intended for human-system interaction includes three different but interrelated interfaces, i.e., the task interface (i.e., feedback design), the interaction interface (i.e., controllability), and the information interface (e.g., detectability) [27, 28].
Task interface design allocates functions to operators and/or to technical components (e.g., machine) in a work system [27] and is required to result in tasks for workers which they can perform safely and efficiently without impairment for health. As an example, this includes designing appropriate feedback for the worker about task performance [10, 17]. Deducing interactions from tasks results in interaction interface design, e.g., when function, movement, and position of elements of a control console corresponds to workers' expectations and thereby pick up on population stereotypes [23]. Information interface design addresses information modalities (e.g., visual), objects (e.g., text) and passive or active impacts (e.g., label, control, feedback) to improve "detectability" as one among several design principles, when drawing attention to warnings (see e.g., [23, 26, 29]).
Presented design principles for the task, the interaction, and the information interface are examples taken from sets available in context relevant standards (e.g., [30, 10, 31, 23-26, 11]) representing several scientific findings in HFE (e.g., [17, 32, 14]). As the selection below can give only suggestions about how to select generic principles and translate them to the application domain at hand, information about how to include the principles in the design process are provided by example references.

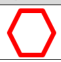
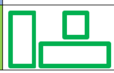
3.2 Principles of displays design

Relevant information about principles of display design have been collected and discussed by working group members [12] and refer to above mentioned sources. Displays as work equipment are devices for presentation of information relevant for human task performance to workers. In the context of machinery safety, display design according to design principles of HFE serves safe operations by supporting human sight (visual displays), hearing (auditory displays), touch (tactile displays) and smell (olfactory displays), to name but a few, if necessary for human task performance. While generic design principles are available across different types of displays, specific design principles are available for

- Visual displays such as tank level indicators, trend presentation, machinery status signals,
- Auditory displays such as warning signals, feedback of normal operation, communication device, and
- Tactile displays such as position of switches, surface of controls.

Referring to the task interface design, analysis and design of the workers task determine, e.g., whether a display is required, what type of display this should be, where to localise a display, and how to arrange many displays for information presentation in the field of view, hearing or other type of sensation of the worker [24, 17, 14].
To allow for safe operations during task performance, human interactions call for interface design presented appropriate in location and time while serving human information processing. With the human field of view being limited, for monitoring operations, when employees must actively search for information, it is necessary to display information in the central area of view, especially if colour vision or stereoscopic depth perception is required [24, 6, 14]. The area outside the central field of view may contain displays which are not critical for safe operations. For detection tasks, when employees must be warned by the system, workers attention shall first be attracted to consult visual displays in line of sight (by e.g., combinations of acoustic and visual alarms) and next informed about changes in system status by clear structures and indications for critical changes in information by, e.g., highlighting. Human interaction with visual displays is possible only when presented in the field of view, whereas auditory displays are omnidirectional with interactions requiring sound characteristics contrasting to the environment and haptic displays allow for interaction only with human contact providing with high/low capacity and sensitivity under salutary/adverse conditions (e.g., attention, vibration).

Table 1. *Scheme for coding visual, auditory, and tactile signals [24, 29].*

Meaning	Coulour codes	Shape codes	Auditory codes	Tactile codes	Operator action
danger, emergency, fault state			sweeping, rising/falling tone frequency or amplitude, bursts, explosive sounds	high intensity vibration	act urgently, take immediate action
warning, abnormal, non-nominal, limits reached			short tones, alternating constant tones	medium intensity vibration	caution, take care, be alert, monitor and intervene
command			sequence		mandatory action
safe, normal, all clear			prolonged, continuous tone with constant amplitude	low intensity vibration	no need to take action

Information interface design of displays supports safe operations when image quality is high. This enables high contrast of at least 1:3 (better 1:6) between display background as well as ambient environment and all display elements (e.g., characters, symbols, indicators, lines) to be identified due to task and interaction requirements [33, 32]. Contrast shall allow for readability and discriminability in accordance with speed and accuracy required by the workers' task. Suitable means for distinguishing one display from another (e.g., different shapes, colours, labels) shall be used to discriminate between different displays (see Table 1). Information presentation serving standard identification and reading requirements of Latin characters, numbers or specific symbols ask for height of at least 18 arc min [24, 34, 33]) or detection of objects and persons of at least 10 % screen height [35], however, safe operations call for reliable identification and reading with required levels and height being higher [24, 33, 1, 2]. Viewing distance, ambient environmental factors such as illumination and vibration, display quality of characters and objects, contrast between characters or objects and background, human task load and time available will all affect minimum size and proportion. This should result in design of modifications of character or object height on display to enable for safe operations, if not alternatively modifications of human tasks allow for different information presentation.

3.3 Principles of control actuator design

Relevant information about principles of display design have been collected and discussed by working group members [12] and refer to above mentioned sources. Control actuators as work equipment are devices for implementation of information towards the end of the human information processing cycle. In machinery and system safety, control actuator design shall follow design principles of HFE to support human activities (e.g., shifting control) with specific body parts (e.g., hand), in time, location, and quality and serving human tasks [25, 6, 14]. Designers and manufacturers are required to actively design and describe human tasks to be performed while interacting with prospective control actuators [25, 17]. A detailed task description requires documentation about

- The person involved (e.g., the worker operating the machine),
- The machine or device addressed (e.g., the kneading machine),
- An interaction activity of the worker (e.g., powering the motor of the machine on and off), and
- About each (sub)task a short sentence (e.g., worker powers off the machine with a control actuator).

Following a standardised procedure for selection of control actuators according to human task requirements [25], the task needs evaluation to inform about interaction qualities such as the accuracy in positioning the control actuator. Once this accuracy is determined (e.g., moderately accurate for emergency stop) information about discrete or continuous control movement is crucial. A discrete control actuator moves across a limited number of fixed positions. The error in selecting the correct position increases with the number of discrete positions. Accuracy can be improved by clear information on the current value of the controlled variable, by clear labelling or by placing the actuator where it can be easily seen and moved [25, 6, 14].

As regards specific task requirements, visual feedback about control actuator state shall be provided. Acoustic or tactile support is recommended, however, never to substitute visual feedback. In case of uncertainty, repeated activation of the actuator should not reverse activation. For smooth operations, avoiding inadvertent operations would be desired (e.g., albeit emergency stops shall always be located within easy reach and for direct access for the worker). The surface should provide friction to avoid hand slipping from the actuator. Easy cleaning is required since the actuator shall always be within sight and clearly to be identified [25, 6, 14, 32].

Since interactions such as movements with linear characteristic are the easiest type of movement, they shall be provided. The axis of movement shall be compatible to normal operation levels, i.e., the z-axis when working on tables, the y-axis when working on walls and the x-axis to be avoided because it tends to be out of sight. Grips with contact characteristics are the easiest and fastest and shall therefore be preferred. When it is possible to use the whole hand for activation, the preferred method of force shall continue hand movement towards actuator, i.e., normal forward [25, 32]. Based on selections among requirements and levels required, results for control families [25] shall be identified and selected to conform with HFE requirements and serve safe operations.

Information interface design of control actuators supports safe operations when multimodal information for selection, implementation, and feedback is provided. While visual information about control actuators shall always be provided for information, recognition, orientation and feedback about control functions or positions (e.g., visual check), acoustic information presentation is omnidirectional when above environmental thresholds, helpful by itself and useful if vision is not possible (e.g., acoustic click). Haptic or tactile information presentation requires body parts being in contact with control actuators and supports control activities, e.g., when changing switch position or select controls by location or shape (e.g., tactile touch). Proprioceptive information about control actuators, e.g., by perception of changing muscle tension or arm position over a movement path [25, 6, 14].

3.4 Modification suggestions for principles of display and control actuator design

Several HFE requirements for the design of displays and control actuators in the context of machinery safety are presented in a series of harmonised standards [23-26] and several HFE textbooks. Even though the standards provide valid design principles, a revision seem inevitable according to a selection of suggestions for modifications from HFE experts working in context of OSH including machine and system safety or in HFE standardisation referring to the Machinery Directive. The benefit of the given series of standards is that it provides general design principles for human-system interfaces, and it emphasises details for several hardware displays and hand control actuators being part of former, present, and future devices, machines, and installations. In addition to the benefits, there are several advantages of this series of harmonised standards:

- These standards are harmonised with the Machinery Directive with a chance to harmonise the series after revision with the Machinery Regulation.
- As harmonised standards within this series, they serve requirements for safe operations according to the Machinery Directive, different to other standards with similar content on the face on it, but neither harmonised nor considering safety in design requirements and recommendations.
- As the standard series is on design principles of HFE, it is valid for a broad range of displays and controls, including former, present, and future solutions.

Nevertheless, the series of standards misses topics and details, with some of them to be discussed whether suitable for safe operations (e.g., touch screens, gesture control due to ambiguity of interpretations), and others required (e.g., software-based displays):

- Please include design of software-based displays (hardware displays only) for safe operations,
- Hand controls only (missing foot controls, virtual controls, etc.),
- Inform about touch screens, special displays (e.g., for VAM realities, XR),
- Solve ambiguity of interpretations for gesture control,
- Direct versus remote control, direct versus remote view; display/image quality, control/actuation quality,
- Reality view in 3D displayed on 2D monitors,
- Combination and integration of displays and control actuators,
- Respect HFE for safe operations is going far beyond usability or user experience design,
- Work system approach taking into consideration interdependences with other dimensions (e.g., task-equipment, place-equipment, equipment-environment); display design affects task design,
- Provide quantitative measures (e.g., anthropometrics [36]); include diversity of European population [36],
- Include whole body or foot impact on control actuators (e.g., foot pedal).

4 DISCUSSION AND CONCLUSIONS

HFE requirements and recommendations for the design of displays and control actuators have a long tradition in facilitating and serving machine and system safety including safe operations (e.g., [23-26, 14, 15, 17, 6, 32]). With standards available on the topic while being harmonised with the Machinery Directive, manufacturers of machinery, operating companies, and companies placing machines on the EU market are informed about specific HFE requirements of the Directive (see Annex Z in [23-26]) and are supported in how to fulfil requirements of the Directive, and how to design. Since these standards provide only a selection of information, a literature review in HFE disclosed additional sources for information acquisition, scientific findings, and knowledge about the design of displays and control actuators.

Some of the findings match suggestions for modifications from HFE experts working in context of OSH including machine and system safety or in HFE standardisation referring to the Machinery Directive. This provides an initial bases for an upcoming revision of the series of standards [23-26] to adapt to required changes for harmonisation with the Machinery Regulation. HFE experts with interest in machine and system safety are invited to contribute by providing experiences about application of the standards and by suggesting modifications for a revision.

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