Human factors in process control systems: The design of human–machine interfaces

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Abstract

This paper deals with selected problems of human factors in the design of process control systems. The argument is that although there are already some legal obligations to take human factors into account, practical experience shows that this is not done adequately and sufficiently. Two types of human–machine interfaces are distinguished, i.e. the task interface and the interaction interface. The design philosophy of process engineers seems to aim at automating all safety critical functions, which is called into question based on the available ergonomics evidence. For the interaction interface examples are presented, showing a further substantial neglect of basic human factors principles, which in turn results in increased operator strain during system failures.

It is argued that there is a demand for immediate action, i.e. for the application of existing human factors knowledge in process control system design, for a professional evaluation of human factors in process control systems, and for research on possibilities of using new technologies that assist the operator in controlling the process control system.

Keywords: Process control; Safety; Workload; Interface design

This paper is based on a presentation (Nachreiner et al., 2003b) at the 20th International Symposium “Man-Safety-Technology” of the ISSA (International Social Security Association) Chemistry Section at the ACHEMA 2003, May 22–23, 2003, Frankfurt/Main, Germany, intended to give an overview of some current problems, without going into any of the details or presenting specific research results. This character of the presentation has been maintained in this paper.

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1. Introduction

“There were too many alarms and they were poorly prioritised”.

“The control room displays did not help the operators to understand what was happening”.

These two quotes from a report (HSE, 1997) on a major accident in a chemical process plant clearly indicate that at least not all process control systems represent the state of the art in ergonomics. This is even more remarkable since according to legal requirements in the EU and its member countries evidence based knowledge from the field of ergonomics or human factors has to be applied to the design of process control systems, and especially to the design of VDU-based control systems (e.g. according to the VDU-directive 90/270 EEC). This does not only apply to the design of the work space, the work station and the work environment, but also to the design of the human–machine interface between the operator and the control system, with the intention of improving the effectiveness, efficiency and safety of the control process as well as optimizing the resulting work load for the operators, which in turn may influence system effectiveness, efficiency and safety. Taking available ergonomic design strategies (e.g. Meister, 1971; Singleton, 1974; Sheridan, 2002) with an emphasis on task orientation and principles (Kantowitz and Sorkin, 1983; Sanders and McCormick, 1993) (e.g. compatibility, consistency, transparency) into account does thus not merely reflect the necessary compliance with legal regulations but also the pursuit of genuine system goals. Designing human–machine interfaces thus becomes a crucial part in the design of chemical plants, especially those with high risks of hazards (Sheridan, 2002).

2. Designing process control interfaces: the task interface and the interaction interface

In designing operator–system interfaces in process control systems two different but interrelated interfaces must be distinguished: the task interface and the interaction interface. Designing the task interface means allocating functions to the operator and/or to the technical components of a process control system. From an ergonomic perspective this should result in tasks for the operators which they can perform safely and efficiently, without any damage to health or any impairment to wellbeing. This requires, first of all and among others, solving problems of adequate degrees of automation, which must not result in left over tasks for the operator; i.e. tasks which cannot be automated or at least not at reasonable costs. Thus principles and criteria for the design of operator work tasks (e.g. Singleton, 1974), and laid down already in international and European standards on task design should be applied, since they are of relevance also within this context.

In the design of the operator–system interaction interface principles of human information processing (Wickens and Hollands, 2000), which can be transformed into design requirements, have to be observed in order to enable the operator to perform the assigned tasks safely and efficiently. This will usually require an analysis of goals, functions, tasks and required activities, and a subsequent analysis of the information required for an effective and efficient task performance, since only a suitable design of the displays and control actuators of the process control system will enable the operator to perform the assigned tasks without compromising operator health, wellbeing, and efficiency as well as system effectiveness, efficiency, safety, and reliability (Kantowitz and Sorkin, 1983; Sanders and McCormick, 1993). By applying ergonomics principles to the design of the interaction
interface substantial improvements in these criteria can be achieved. Besides task analyses, action or time-line analyses should be applied wherever possible for gathering information on how tasks are transformed into activities by the operators. However, it should be remembered that concepts relating to which task should be done by whom (e.g. humans and/or machines) and how it should be performed may differ from the operators’ actions or their actual performance of tasks as shown in activity analyses. This may be due to the fact that activities are dominated or moderated at least by (individual) human coping strategies within the specific setting, sometimes compensating for ergonomic design flaws.

After a rather short discussion on task design problems some of the problems and—where possible—solutions associated with the design of the interaction interface will be demonstrated by some examples from existing process control systems as well as from some simulator based laboratory studies. Using both observational and psychophysiological data the relevance of deficiencies in the design of process control interfaces for operator workload, i.e. stress and strain, as well as for the efficiency and operational safety of the control process will be demonstrated.

Since both, the task as well as the interaction interface are more and more often designed, generated, and realized via software, some remarks on software design might seem appropriate here. Software in this context can be described as a tool which an operator uses to perform a given task. From an ergonomic point of view tools are part of a work system which should thus be designed to provide for optimal working conditions and task performance to promote operator well-being as well as work system reliability and productivity. The special point of interest is that by employing software generated interfaces, i.e. using generic technologies, these tools can be designed with high flexibility and adaptability to given requirements, including human requirements. Software design should thus not only consider functionality or effectiveness. In order to achieve a high level of system efficiency it should rather consider efficiency of human performance and satisfying human requirements at the same time—since any operator impairment will also impair system performance; at least as long as there is any operator left in the system. Under such a perspective efficiency of task performance extends beyond financial expenses or time costs. Therefore the operators’ physical and mental workload must become important and relevant criteria in evaluating the quality of work system design and especially the usability of software generated tools (ISO 6385; EN ISO 9241-10 and -11, ISO 10075). Consequently, legal regulations in the EU (OSH directive 89/391 EEC; VDU directive 90/270 EEC) require an evaluation of work stress—which asks for suitable methods for this purpose (Nachreiner, 2002) but which are not yet readily available.

The question thus arises, whether an ergonomic design of both interfaces in fact improves operator and system performance, and how this can be assessed or demonstrated. The following sections will address some of these problems.

2.1. Designing the task interface

Recent developments in computer and automation technology seem to indicate a trend towards increasing automation in process control, allocating more and more functions to the computer, since it promises to be more reliable and less susceptible to errors or failures than humans.

This is one of the reasons why within the chemical industry, at least in some German companies, all safety relevant components of a process control system are under the control
of the computer. The underlying safety strategy thus is to leave all safety critical decision to
the computer, a strategy based on considerations of avoiding human errors in safety critical
systems and relieving operators from any responsibility for safety critical incidents (Kapp-
elmaier, 2002). In such a strategy the computer becomes the guarantor of safety.

This lower error probability of computers may be true but has to be qualified. Whereas
computers might be less error prone (especially in routine operations) they are also less
capable of finding generic solutions for such errors, especially those which are unforesee-
able and for which no solution can thus be programmed (e.g. Wickens and Hollands, 2000).
Responding knowledge based to unforeseen events, however, represents a strength of
human operators and seems to be one of the main reasons why they remain in such sys-
tems. Otherwise the question must be raised why else they should remain in such systems—
if automation is that much superior—apart from problems of acceptance of completely
automated solutions for hazardous systems in the general public (Lee and See, 2004; Muir
and Moray, 1996).

From an ergonomic point of view the question therefore must be raised whether full
automation (or any level near to that on any stage) is in fact an attractive goal, especially
with regard to system safety and reliability. If everything were predictable and determinis-
tic there would be no problem with such a strategy. However, troubles or even worse occur
when automation does not reliably and credibly function as intended. This is not only a
question of the level of automation within the work system in general. It also depends on
the stages of automation (Parasuraman et al., 2000)—referring to different stages of inform-
ation processing. An incorrect acquisition and analysis of information by automation—
even on a high level of information processing—should usually be adjustable by a vigilant
operator before a choice is taken—as long as the operator is allowed to adjust. On the
other hand an incorrect automation choice is hardly—if at all—adjustable by an operator.
The consequences of automation error can thus be severe, and may be irreversible (Wic-
kens and Hollands, 2000).

Increasing automation—even in single stages—changes the nature of the tasks for
human operators (e.g. Bainbridge, 1983; Parasuraman and Riley, 1997; Woods, 1996),
since more and more tasks are allocated to the computer, leaving only leftover tasks to the
operator in the end. Allocating more and more functions to the machine has resulted in a
complete change of tasks for human operators, from performing actions to controlling
them, and from direct control to supervisory control (Sheridan, 1994, 2002) and finally to
monitoring tasks. The issue to be addressed next, however, is, what has to be monitored:
performance, control, or the monitoring performance of safety critical automatic monitor-
ing (sub)systems, as for example in an increasing proportion in the nuclear power genera-
tion and the chemical industries. The question is whether such tasks can at all be
performed (effectively and over the required time span) by humans—or whether this is
beyond human capacity. Leaving such tasks to the operator at the ‘sharp end’, i.e. close to
calling at potential losses (Reason, 2000), and resulting in a severe risk of system failure
would thus seem to be an unacceptable strategy.

Ergonomic evidence supports this argumentation. Bainbridge (1983) has argued years
ago that such requirements cannot be fulfilled by humans. Taking them out of the loop
under normal conditions and thereby avoiding the development and testing of experience
based mental models must result in inadequate performance under abnormal conditions.

As long as human operators remain in process control systems they must therefore be
provided with tasks for which they are suited and which will not overtax them in any
This is not a problem in the design of process control systems in particular, but a rather common problem in systems engineering. Therefore certain characteristics of well designed tasks, as shown in Table 1, have been specified in European Standard EN 614-2, as well as a general procedure and some more specific methods to be used in the design process in order to achieve them.

Considering practical experience with operator tasks and jobs (to which those criteria apply as well) in process industries will most probably lead to the conclusion that these characteristics have been met to widely varying degrees. We would like to leave it to the reader to judge whether these requirements have been fulfilled or at least not violated in the process control systems she or he is aware of. In our experience there is a majority of jobs for which we would be able to demonstrate violations of these criteria. For the future we would therefore urgently advise to follow the methodology (from system analysis via function analysis and function allocation to task design) and the criteria specified in EN 614-2 when designing process control systems. In particular, special emphasis should be given to opportunities for dynamic function allocation (nowadays often called and integrated in adaptive automation, when applied in an automated systems context). Dynamic function allocation allows for the operator to decide on the assignment of different tasks to the computer or herself/himself (Singleton, 1974; Sheridan, 2000), depending on her/his experience, constitution or work load, and thus making use of the advantages of software generated and modifiable task allocations. It should be mentioned, however, that the concept of adaptive automation also includes the possibility of the system to take over/give away tasks from/to the operator, e.g. based on a system’s diagnosis of the operator’s functional state (e.g. HFM, 2004; Hockey et al., 2003). This would seem to raise the question again, who is and who should be in control—in the end; an exciting question for the future, as we see it.

Adhering to ergonomics standards can help to serve two purposes: first, incorporating at least basic ergonomics into the design, and second, being thus able to demonstrate that minimum legal requirements have been fulfilled.

2.2. Interaction interface design

Task and interaction interface design are of course closely related since an appropriate interaction interface—appropriate for completing the tasks—must depend on the tasks of the operator (primacy of task design, Ulich, 2001). Since in process control control systems
are mostly software generated this again allows for flexibility and adaptability—adaptability towards the human operator. Thus some further ergonomic concepts might be helpful for evaluating the adequacy of the design of a process control system, i.e. mental work load, comprising mental stress, mental strain and the effects of mental strain, e.g. fatigue, monotony, or reduced vigilance, as defined in ISO 10075. ISO 10075-2, dealing with design guidelines with regard to mental work load, specifies some principles which should be observed in system design in order to avoid dysfunctional or impairing effects on the operator or to optimize her/his mental work load—with the final goal of optimizing total system performance. These principles relate to task characteristics (e.g. complexity of task requirements) as well as to characteristics of human information processing (e.g. signal discriminability or compatibility of information presentation).

Applying these guidelines in the evaluation of process control systems clearly reveals advantages and deficiencies of specific design solutions. Fig. 1 (based on Nachreiner et al., 1998) shows some results of such an evaluation of different process control systems based on different technologies. As can be seen from this figure an appropriate use of new technologies can reduce problems of mental work load—although there is still room for improvement. Whereas mental work load due to task complexity is a little bit higher with new technologies (NT), mental work load due to adequacy of information presentation or decision support has been rated much more favourably for those systems using more recent technologies (OT).

Applying basic ergonomics evidence to a closer inspection of today’s process control interaction interfaces very soon reveals that there are a lot of violations of even the most basic principles (e.g. Nachreiner, 1990; Nachreiner et al., 2003a), not to mention an appropriate state of the art design of displays and controls making full use of the currently available technologies or even recent developments in interface design (e.g. Burns and Hajdukiewicz, 2004). Examples for such violations of basic principles can be found.

![Fig. 1. Evaluation of process control system design based on guidelines from ISO 10075-2 (scale 1 = no problems (preferred) to 9 high risk of problems due to mental work load (to be urgently redesigned)).](image-url)
abundantly in the process control industry but cannot be demonstrated here for copyright reasons. For comprehensible reasons manufacturers of and companies using systems with design flaws usually do not grant permission for publishing such examples via documentation materials, screen shots, or even details of the interface. Design problems are therefore very rarely documented in the literature, the internet or brochures (some examples, however, can be found in Kutscher and Radek, 2003).

Common violations of basic ergonomic design principles range:

- from negative polarity, presentation with illegible information due to lacking colour contrast, insufficient character font sizes and line formats,
- via overloaded displays with digital presentation of information where analogue presentation would definitely be required, presenting numerous displays of set points, and actual and effect values in an unstructured order and thus leaving the task of searching and detecting such deviations to the operator (and thus affecting the task interface), instead of directly showing deviations of actual values from set points,
- to static information presentation where a presentation of past dynamics (e.g. trends) and future developments of process parameters (prediction) would be required for an effective task performance.

Figs. 2–10 illustrate some of the above mentioned design problems. Examples are drawn from the feed section of a benzene/toluene distillation from a full scale real time simulator in our usability laboratory at the University of Oldenburg, Germany. This control room is equipped with a commercially used real process control system (Invensys Systems GmbH) and commercial work stations, and furnished as in process control industry. The original presentations of the flow charts use colour coding which has been reduced here to greyscale reproductions for printing purposes. Some of the above mentioned problems will be illustrated in more detail in the following sections.

Usability studies with this process control system have been carried out using walk-throughs (Nielsen, 1993) as preliminary task analysis by human factors specialists experienced in process control operations (Meyer et al., 2001). This resulted in a record of design flaws with several of them quite obvious to identify. Some of these are presented next in order to illustrate some of the ergonomics problems in interface design. In the meantime several improvements have been implemented in order to compare different solutions with regard to their effects on performance and operator work load.

Fig. 2 shows the feed section, with the flow diagram and the completely digital coding of information concerning pressures, temperatures, set points, and actual values. The representation as it is requires the operator to memorize what the operational and alarm limits are, to calculate the relative position and any variation of process parameters over time—or to select and open the faceplates or the available trend overlays to get the relevant information, with the consequence that these will hide essential parts of the display.

Alarm lists usually are completely unstructured; if there is any structure at all, this is based on the time stamp, but not on a (logical) structure suitable for a fast diagnosis of system failures (see the quotes from HSE (1997) presented in the introduction). Alarm displays thus often simply represent a printed alarms list displayed on a VDU without any additional support to the operator for failure diagnosis. Fig. 3 shows an example of such an alarm list.
Alarms are not presented according to their importance or priority or demand for action, but only on a very simple level of severity ranking (in this case 3 levels, 2 of which are used, next to last column, in Fig. 3, with ‘R’ standing for returned). Causal relations are not observed at all, so that a failure in one part of the plant may be indicated by a (sequence) alarm in a completely different part, and this may happen long before the alarm for the underlying failure is displayed. An intelligent alarm management system could be conceived of presenting the alarms in their causal order or in an order for appropriate action (Bransby and Jenkinson, 1998; EEMUA, 1999). Nothing applies here. Clicking on Top Priority only leads to a block diagram of the component in alarm, and “Alarm 1 of 13” only tells the operator that on top of the display is alarm 1 of 13 alarms.

In addition, Fig. 3 shows a complete mixture in language (English/German) on the display, leading to inconsistencies between control devices and the information displayed as well as to inconsistencies within the information displayed. Furthermore negative polarity is used in the presentation of the alarms—which is inconsistent with the design of the flow charts and, even worse, incompatible with usual environmental conditions (e.g. lightning) in process control rooms, leading to reflected glare and diffuse reflections.

Since controlling a process control system can—at least in part—be considered a dialogue between an operator and the process control system via a software generated interaction interface software ergonomic principles related to dialogue design should—at least in principle—be applicable to the design of process control dialogue interfaces. The German association for process control in the chemical industry (NAMUR) has consequently
acknowledged that in principle these principles, as specified in ISO 9241-10 and developed for office systems, apply to the design of process control systems. Table 2 presents a list of these principles (for details see ISO 9241-10).

Mental work load is not directly addressed in this standard. However, it will be shown that there is a direct relation between (some of) these dialogue principles and certain aspects of mental work load.

The most prominent principle is the one specifying suitability for the task. This can be directly applied to the example of the feed section from Fig. 2. In order to be able to reliably monitor system performance in the feed section under normal conditions or in case of any component failure the operator has to rely on the pressure in the feed system. This pressure will change in case of a failure of a pump motor, a filter, or a valve in the feed

Table 2
Ergonomic requirements for human–machine dialogue design

<table>
<thead>
<tr>
<th>Suitability for the task</th>
<th>Self-descriptiveness</th>
<th>Controllability</th>
<th>Conformity with user expectations</th>
<th>Error tolerance</th>
<th>Suitability for individualization</th>
<th>Suitability for learning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source: EN ISO 9241-10 Ergonomic requirements for office work with visual display terminals (VDTs), Part 10: Dialogue principles.</td>
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section. This essential information, however, is displayed digitally as P 401 (with P for the English word “pressure”, used in a German dialogue system and corresponding to the German word “Druck”) in mbar as an absolute value, offering no further information about any normal or critical values. Instead the operator has to keep those in mind, adding to mental work load (since there are a lot more parameters to be remembered). Fig. 4 shows a detail of this display.

One first improvement towards suitability for the task would be an analogue display of this parameter, with the actual value, the set point and the alarm limits shown. Such a display can actually be opened by double clicking on the numeric value of P 401, an action which will result in the display of the overlay shown in Fig. 5 (which in turn leads to hiding all information from the temperature control system). Fig. 5 does not show any high alarm limits, though it could be configured to do so, nor does it show a set point. So every value above the low alarm limit seems acceptable, which is definitely not true.

However, a display improved in this way would only be a small step towards reducing mental work load and improving safety. The operator would now find it easier to relatively locate the actual pressure level in the feed section and to decide whether this is OK or not. In order to be able to diagnose as early as possible any dynamic changes within the process which could indicate a breakdown of the system in the near future, e.g. a creeping soiling of a filter, information on earlier stages must be provided with which the actual value can be compared, e.g. by providing a time related presentation of the information via a trend display. Fig. 6 shows such a solution, where the required trend, which was not normally available to the operator in the original layout, can be displayed by double clicking on the now permanent analogue display of P 401. This facilitates task performance for the operator and makes it more effective.

Another example showing the interrelatedness of task and interaction interface and its relation to mental work load is presented in Fig. 7. From an engineering point of view flow controller FC 201 is a correct representation of this controller, showing the set point (W), the actual value of the measure (X) and the effect value (Y), in this case the opening position

Fig. 4. Detail from feed section, showing digital pressure display.
of valve V9. A failure of this valve must be detected by comparing all three values: if the actual value is below the set point and the opening of the valve is beyond normal values (e.g., 100%) this indicates the failure. From an ergonomic point of view solutions can be imagined which make a fast detection of such a problem easier, e.g. by moving the task interface more towards the process control system by leaving the required comparisons to the machine and having it indicate the malfunction directly. This could reduce the workload of the operator considerably and facilitate the detection of valve failures and timely operator responses.

Moving on to consistency or compatibility with user expectations or stereotypes, another principle to be observed in dialogue design, Fig. 8 shows an obvious violation of this principle. Moving from left to right usually an increase in values is expected. In Fig. 8, however, the temperature declines from left to right. This is where human errors must be expected, resulting from a human error in display design.

Fig. 9 shows another quite common example of lack of compatibility or consistency. There is a mixture of German and English naming for components, and abbreviations are used ambiguously, e.g. P for “pressure” (P 401) as well as for “pump” (P 102). This definitely does not contribute to clarity or consistency.

Fig. 10 shows an example for an error message which is not as informative as it is requested to be. At least the operator is informed that her/his control action has failed—by
announcing a “bad set”—but no information is given as to what the error was. The operator may now try to see whether this was an error of interaction with the system, e.g. not switching the control to manual (as in this example) or an input which was beyond limits, e.g. due to a typing error.

This could easily be continued and in particular using examples from interaction interfaces from different commercial process control systems, showing that there is a

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**Fig. 6.** Detail from feed section showing permanent digital plus analogue pressure display and additional selectable faceplate with trend display for pressure.

**Fig. 7.** Valve failure, to be detected by comparing mismatch of X, W, and Y of FC 201.
need for implementing ergonomics principles into the design of process control systems. The examples presented, however, would already seem to indicate that these design flaws must have an effect on system performance and reliability, either directly via operator errors (of omission as well as of commission) or indirectly via influencing the operator’s mental work load and degrading her/his functional state. These effects might be especially grave in cases of emergencies, when adequate fault diagnosis and operator

Fig. 8. Incompatibility in temperature display.

Fig. 9. Inconsistencies in naming and language.
responses must be performed under—sometimes quite substantial—time pressure. This raises the question whether such design flaws do in fact influence operator performance and work strain.

3. Usability studies of process control software

In order to address these questions we have conducted several studies in our usability laboratory (see Meyer et al., 2001; Nachreiner et al., 2002; Nickel et al., 2004a,b; Nickel and Nachreiner, 2002, 2005; Schomann et al., 2001, as well as Meyer, in preparation). All studies were performed with the above mentioned process control system, using different versions of the interaction interface, with some studies still under progress (it should be mentioned that such studies are simply not possible under real life conditions due to the associated risks or losses).

Operators for these studies were either chemists or engineers (males as well as females) with a background and practical experience in process engineering and process control operations (e.g. Figs. 11–13), or students (e.g. Fig. 14 and 15) which had to be intensively trained to become sufficiently acquainted with the process control system as well as with the chemical process underlying the simulation in order to be able to monitor and control the process. It should be mentioned that taking real process operators does not solve the problem of representativeness of operators, since this would have to be operators with experience with the available process control system and the process to be controlled.

In contrast to typical laboratory tasks, operators had to monitor and control the process, responding to experimenter interventions (e.g. component failures) as well as to the simulation’s reaction to operator interventions. So the operators were able to control the course of events to a great deal, as under real life conditions. This, however, results in special problems for data analysis, for which solutions are not readily available. For a demonstration of the effects of deficiencies in interface design we will therefore present here typical results using typical examples from individual operators only. Recently finished studies (Meyer, in preparation) have provided tests of significance for comparisons among
different interface design solutions, supporting the hypotheses/results presented here. These results would indicate that there are complex interactions between different states of the process (e.g. normal vs. emergency conditions) and the effectiveness of different design characteristics. Conclusions drawn here are thus not only based on the examples presented but on a set of related studies.

Indicators used to check for effectiveness, efficiency and satisfaction with process control include:

- general measures for multiple purposes such as video and audio taped behavioural data (operator activities) mainly in order to conduct activity and time-line analyses, think aloud verbal protocols yielding procedural information and interviews in order to yield information by way of explanation (Bowers and Snyder, 1990), e.g. to perceived problems with process control using the process control interface,
- rating scales on aspects of mental work load and on stress responses,
- performance measures such as time to detection and/or solution for experimenter induced failures (some of them in the form of creeping failures), stability of process control, quality of production, and
- psychophysiological data (e.g. heart rate and heart rate variability) as real time indicators of mental—or more specifically emotional—strain when controlling the process. Although its psychometric properties are rather low (Nickel and Nachreiner, 2002, 2003), the 0.1 Hz component of HRV is described as one among other measures recommended for the assessment of mental workload in the evaluation of process control systems and adaptive automation (e.g. Parasuraman, 2003). However, this measure rather seems to indicate general activation or specific components of mental workload such as emotional load (but is definitely not sensitive for cognitive workload). Nevertheless, assessing general activation or emotional operator responses might perhaps be a suitable first step to investigate the adequacy of working conditions, here the interaction interface, with regard to operator characteristics or task requirements (for a detailed discussion on the psychometric properties of this measure with a number of further references see Nickel and Nachreiner, 2002, 2003).

Fig. 11 shows a section of the heart rate variability (HRV) recording from a session with a sieve failure. HRV has been assessed via the 0.1 Hz component of HRV and inverted for reasons of compatibility (so that high values correspond to high mental strain). Some of the operators’ conversation taken from the think aloud verbal protocols and the audio and video tapes is assigned to the time related recording of this psychophysiological measure. The operators’ experiences while performing the monitoring and control task where assessed via interviews and by discussing the course of events in the control room immediately after finishing the simulation session.

The sieve failure was a creeping soiling, to be detected via a decrease in the digitally displayed P401 (see Fig. 4), the pressure in the feed. None of the participants detected this failure before an alarm from the system occurred. This alarm would usually indicate a problem in the head of the column, not in the feed, since the control units there are more sensitive than the pressure measurement. Fig. 11 shows that the operator is at a modest level of load at the onset of the failure. As a consequence of the (ambiguous) alarm the emotional strain of the operator increases while he was trying to identify the reason for the alarm, but not coming to a correct diagnosis. Only a hint from the experimenter leads to a
correct diagnosis, which then reduces the strain for a short while. It then increases again until about half a minute after the bypass is fixed, since the operator cannot be sure that he solved the problem. Strain then decreases a little bit but remains rather high compared to the initial condition, with the operator still observing the pressure in the feed.

Fig. 12 shows another example of the same system failure. Again the operator does not detect the failure by himself and again immediately after the alarm the level of strain increases while the operator is trying to detect the cause of the problem, until he notices that “nothing is coming” through. He then tries to fix this, with some ups and downs in

![Graph showing mental strain](image1)

**Fig. 11.** Mental strain of operator ‘a’ during a sieve failure.

![Graph showing mental strain](image2)

**Fig. 12.** Mental strain of operator ‘b’ during a sieve failure.
strain, but again does not detect the true cause of the failure. After a hint from the experimenter he calms down and initiates the bypass, but then has to wait, while becoming nervous, to see whether his repair has been successful. Since this is not the case he becomes nervous again, looking for the problem in his bypass, and after fixing the failure obviously calms down again.

Working on the monitoring and control operations while the experimenter implements a valve failure in FC201 (see Fig. 13), which is somewhat more difficult to detect, leads to quite similar results according to the operator’s emotional strain (indicated by the 0.1 Hz component of HRV, along with his conversation). Again an increase in strain shows up right after the alarm, since the operator knows that some alarms occur, when the process had already become instable and therefore there is only short time to find the reason of the disturbance and to get it provisionally fixed. Strain maintains on a high level during isolation of the area in which the disturbance originated, problem diagnosis and solving activities while the process is still out of normal operations and therefore needs to be treated to continue. While the operator erroneously is under the impression that he has solved the problem by laying a bypass in the sieve section he calms down. The hint from the experimenter telling him that the problem still exists increases his strain considerably. During the next (unsuccessful) trial to solve the problem he calms down again until he finally detects the true cause of the problem, the valve failure. An adequately designed interface, facilitating the detection of the valve failure (see above), would have reduced the time to detect the true cause and avoided erroneous and unsuccessful control operations, with their associated increases in work load. Here the detection of the real problem increases the operator’s strain again, followed by some more ups and downs until the problem is in fact solved by repairing the valve and returning to automatic control of FC 201, with an associated decrease in strain.
All these examples (as well as the results from other operators) clearly show that the design flaws discussed above lead to increased mental or emotional strain in the operator which could most probably be avoided or at least reduced if the diagnosis were supported by an adequate display of process parameters. Such a change in the task interface would leave more capacity for tasks for which the operator is in fact better suited. Operators confirmed this in the interviews by pointing to the fact that they were not able to quickly find a correct diagnosis and that instead it took them a lot of time to check a lot of irrelevant parameters instead of being guided towards the really relevant parameters. This might be an appropriate strategy for training diagnostic skills and developing mental models, but definitely not for emergency procedures within hazardous systems.

One could argue that this cannot be generalized to real world situations, where operators learn and develop strategies where and what to observe (de Terssac et al., 1983). So they would keep an eye on P 401 or FC 201 and increase observational activities for these parameters. This even applies to our operators. After being subjected to certain failures in the feed section they do in fact keep an eye on critical parameters, like P 401 (compensating for the design flaws by increased operator activity)—at the cost of monitoring other parameters (with similar display problems) and the associated breakdown in process control in other sections. This is an example where activity analyses are quite helpful for detecting design flaws, besides or especially in combination with task analyses.

One of the more general problems with VDU based systems is the number of necessary VDUs, and the tendency to reduce it. Reducing the number of available VDUs necessitates sequential monitoring and especially control, since not all necessary information can be presented on these VDUs simultaneously, requiring the operators to sequentially switch between relevant screens. With regard to the dialogue principles (ISO 9241-10) this can be classified as a problem of suitability for the task: whereas the task requires parallel presentation of information and/or control actuators (on the VDU) a restricted number of VDUs allows only for sequential presentation. This should deteriorate performance and increase mental work load, both cognitive and emotional. Comparing Figs. 14 and 15 (Nickel et al., 2004a,b), which show the treatment of the sieve failure problem with different numbers of...
operational VDUs (one reserved for alarms and trends and one for control operation vs. two VDUs with free assignment of display and control interfaces) clearly shows that under the more restricted condition the operator took longer to solve the problem and worked with higher strain during problem solving. She thus was subjected to both an increased and extended level of work strain.

It must be mentioned that the results are not always that straight or clear cut, but in general the tendency becomes quite clear: ergonomic inadequate design of the interaction interface increases control difficulty, both in diagnosis and control actuation, or impedes successful control, which is associated with increased mental work load for the operator and increased strain, thus leading to less effective and less efficient process control. Meyer (in preparation) has been able to show that the number of available VDUs and the allocation of displays to these VDUs interacts with the design of the displays (e.g. digital vs. analogue vs. analogue with trend) and the complexity of the task. Whereas the coding and the number of VDUs is of less importance under normal operating conditions it becomes quite important under abnormal conditions or for complex manoeuvres like controlled shut down. The results also show that there is an interesting relation between the design of the interface and the operators’ mental model of the process control system, arguing for increased research activities in this field.

4. Conclusions

According to our experience human factors do not play the role they deserve in the design of process control systems (exceptions acknowledged), making them less controllable than they could be if human factors were adequately incorporated. It would thus seem that incorporating ergonomics in the design of process control systems offers a lot of opportunities for improvements with regard to system effectiveness, efficiency, reliability and safety. As a consequence it would seem that there is a clear demand for action, e.g.
incorporating human factors in the design of such systems right from the beginning, as already recommended by international ergonomics standards. Process control design is simply not a pure process control engineering problem; at least not as long as human operators remain parts of the system.

In this article, it has been shown that there is already a body of ergonomics knowledge which can readily be applied in the design of process control systems. In addition to ergonomics textbooks a lot of this evidence has already been laid down in ergonomics standards. It would seem that there is a clear demand for applying this knowledge to the design of process control systems with a view to improving operator and system performance with regard to effectiveness, efficiency, reliability and safety of process control systems. ISO 11064-5, dealing with the design of (computer supported) interaction interfaces for process control but still under development, could become a valuable tool in this respect.

Since there are legal obligations to take ergonomics into account for the design and operation of process control systems, such systems, especially if they are systems with high risk potentials for their environment, should be systematically evaluated by human factors experts in order to take proper care of human factors aspects—with the aim of improving system reliability and safety. Such evaluations should include assessments of (actual or to be expected) work stress, work strain and their potential effects on operators, in particular with regard to system safety. Although only a few examples have been presented here, experience shows that there is a clear demand for evaluating process control systems with regard to their adequate incorporation of human factors principles.

Something, we have not touched here upon in detail is, that there is also a quite substantial demand for future research regarding problems of human factors in process control design. We still do not have clear knowledge of how we could improve process control by adequately and fully using the available and emerging technologies. According to our experience this would require cooperative joint research ventures among process control engineers, computer science specialists and human factors specialists, in order to reach a common understanding of the problems and to develop effective research strategies for designing process control systems which make full use of technical and human resources and avoid the pitfalls of single sided solutions.

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