Trends and tasks in control rooms

Citation for published version (APA):
Schaaf, van der, T. W. (1993). *Trends and tasks in control rooms*. (EUT - BDK report. Dept. of Industrial Engineering and Management Science; Vol. 57). Technische Universiteit Eindhoven.

Document status and date:
Published: 01/01/1993

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Download date: 05. Oct. 2023

tu
Research Report

Eindhoven
University of Technology
The Netherlands

GRADUATE SCHOOL OF INDUSTRIAL ENGINEERING AND MANAGEMENT SCIENCE

Trends and Tasks in Control rooms

ed. by T.W. van der Schaaf

Report EUT/BDK/57
ISBN 90-386-0341-X
ISSN 0167-9708
Eindhoven, 1993

INDUSTRIAL ENGINEERING AND
MANAGEMENT SCIENCE

CIP-DATA KONINKLIJKE BIBLIOTHEEK, DEN HAAG

Trends

"Trends and tasks in control rooms" / ed. by Tjerk W. van der Schaaf.
Eindhoven: Eindhoven University of Technology,
Graduate School of Industrial Engineering and Management Science.
(Report EUT/BDK;57)
With index, references.
ISBN 90-386-0341-X
NUGI 689
Subject headings: process control tasks, fault diagnosis tasks,
interface design

Foreword

The five papers in this EUT report were presented in a special session on "Control Rooms" at the Human-Computer Interaction International '93 Conference, held in Orlando, Florida USA from 8-13 August, 1993.

Their topics range from process control and supervision to fault diagnosis tasks; from influencing the interface-design process to validating its results; and from workplace design to decision support.

I hope this collection of "trends" will be just as stimulating to the reader as the preparations for the session were to the author.

Tjerk W. van der Schaaf, session organizer.

Developing process control systems: procedural requirements in design

H.J.G. Zwaga

Utrecht University, Psychological Laboratory - Ergonomics Group, Heidelberglaan 2,
3584 CS Utrecht, The Netherlands

Abstract

The systematic involvement of human factors in the design of human-machine systems is only slowly gaining a foothold in the engineering world. Promoting this involvement is not a skill common among human factors specialists. Management has to be provided with convincing information detailing the knowledge and expertise available in order to justify the resource allocation required. In projects where, for various reasons, human factors specialists cannot be involved, the option should be explored to compile application specific design rules to guide the designers in their decisions. An example is described, demonstrating how general guidelines and standards can be converted into sets of application-specific rules intended for use in the design of the operator interface of production platform control rooms.

1. INTRODUCTION

Human factors engineering activities can be grouped under two headings: 1)the application of human factors knowledge to facilitate the interaction between humans and machines and 2)the evaluation of human-machine systems. In general, it is an easier task to evaluate a human-machine system (whether it is in its final state or in an intermediate state of development) than it is to provide information to engineers to optimize the relationship between people and their work. The methodology to evaluate human-machine systems is much better developed; a wide variety of techniques is available to evaluate almost every conceivable aspect of a system. Human factors experts can often also rely on the research techniques developed in their original discipline (e.g., physiology, medicine, psychology). There are many books and other texts describing evaluation methods and techniques. An early, and still very readable example, is Chapanis' (1959) book on research techniques, while a more recent example, more than four times the size of the book by Chapanis, is "Evaluation of Human Work" by Wilson and Corlett (1992).

There are far less publications describing how to provide useful human factors information to system designers, or how to contribute, as a human factors specialist on the project team, to the development of a system. Acting as a human factors specialist on a project team is (still) a skill that has to be learned in practice. Frameworks have been put forward to guide human factors involvement in the design of human-machine systems.

Typical examples are the "Man-machine System Development scheme" described by Singleton (1974), and Bailey's (1982) "Total System Design" approach, also described in the later editions of Sanders and McCormick (1987, ch. 18; 1992, ch. 22).

2. USING HUMAN FACTORS KNOWLEDGE IN SYSTEM DESIGN

It is significant that in the description of the human factors activities related to the use of the design scheme, Sanders and McCormick (1992, p. 738) hint at the difficulties a human factors specialist might encounter when working with design engineers. They warn that in the competition for influence on design decisions between members of a design team, human factors people occupy a low rank in the pecking order. In the latest edition of their book they elaborate on this point by adding a section called 'How engineers design'. Here they review what little is known about the mechanisms of the cooperation between engineers and human factors specialists. The cardinal issue is that human performance, and the factors determining performance, are outside the engineer's sphere of thought. Information about human behavior is not a decisive factor in their decisions unless it can be easily found and provided it makes sense intuitively. Following Meister (1989, p. 71), Sanders and McCormick conclude that: 'design is at bottom a highly judgmental process in which all the engineer's biases and predilections have the opportunity to influence the final configuration'.

So, the fact has to be faced that human factors specialists will, for a long time to come, not automatically be members of a project design team. Access to a design team is not easily gained. Knowing the 'truth' is not enough. Much depends on the context-specific experience and the skills of the human factors specialist to relate to people, i.e., to know how to convince people, how and when to compromise.

The literature on process control might sometimes give the impression that human factors knowledge already plays a significant role in system design. Most of these publications originate, however, from public companies (nuclear power is very prominent) and from the military sphere. Compared to those areas, there is only a handful of papers describing human factors activities in commercial system design projects. This indicates that there are far less projects in the process industry on the design or redesign of complex human-machine systems where human factors specialists are involved. Although commercial confidentiality certainly plays a role, costs justification is, when considering involvement of human factors specialists, probably a more determining factor here. And, given the low priority engineers attach to human factors engineering, it is probably not only resource allocation, but also the fact that courage is required from management to make a choice for a more user-centered approach.

Attempts to convince management, or the project team, of the advantages of having human factors members on the design team, should explain that human factors knowledge and expertise with regard to the presentation of information cover three aspects of human behavior: sensation, perception, and cognition. Of these three, the importance of the cognitive side of human behavior is the most difficult to convey. Providing for the limits of human sensation and perception already has gained a degree of acceptance in the engineering world. Many engineers know that 'classic' human factors data exist. Supplying useful data to ensure optimal work conditions with regard to the physical and perceptive requirements, often provides an opportunity to explain and demonstrate what else human factors can do. A typical example of this approach is a study described by Van der Schaaf and Kragt (1992). The authors describe how their study started off with straightforward questions about eliminating glare in VDUs in a new control room and finally resulted in the involvement of human factors specialist on a much wider scale. This included not only the redesign of the control room and a new lighting plan, but also the redesign of the VDU-based information presentation. This redesign concentrated on the information content of the displays, which appeared not to be designed with the requirements of the end-user (i.e. the operator) in mind, but was based on the design engineers' view of the process.

So, the approach of human factors with regard to large-scale projects should be to try to become part of the critical path in the development of a system. Be it at an advanced stage in the project with the difficulty that one might have to convince management to reconsider decisions, but preferably at an earlier design stage.

To facilitate the decision of management to involve human factors specialists, a plan showing how to involve human factors should be part of the information provided to management. In addition, at least some indications should be provided about the advantages or the achievements that reasonably might be expected from the involvement of human factors. This is necessary because justification of resource allocation is for management an essential requirement. In the process of getting on a design team, human factors also has to concentrate on its own role. An important purpose of the information provided is also that it should prevent that human factors will, in the perception of the design engineers, remain the field of expertise to turn to just for classic user- interface information. Management and design engineering have to be convinced that the bottom-up approach of classic interface human factors has to be integrated in a top-down approach that starts with a careful analysis of all system performance aspects, including the organizational changes that automation might require.

3. SYSTEM DESIGN AND STANDARDS, GUIDELINES AND RULES

To introduce human factors knowledge on a wider scale and not only in the design of human-machine systems that are unique, complex and large, other ways have to be used than actually having a human factors specialist on the design team. This takes us to the delicate subject of guidelines and standards. International standards for human-computer-related interfaces and tasks are currently widely developed. A good overview of the state of the art and the many problems involved can be obtained from Abernathy (1988) and a special issue of Displays (vol 13, no 3, 1992). From these publications it will immediately be clear, that standards are not the information sources the engineers want for the user-related specifications of their design. Mosier and Smith (1986) have shown that engineers are dissatisfied with guidelines, because they are considered to be too general or do not apply to a particular system; sometimes guidelines even contradict each other. To a large extent, the same objections apply to standards. A persistent problem with guidelines, and a much discussed point in relation to standards, is that there is always a lag between the application of new technologies and pertinent human factors research. A practical problem is that there are delays in the updating of the guidelines or standards. The results of a questionnaire survey conducted by Mosier and Smith (1986) also indicate that design engineers especially feel ill at ease with guidelines that apply to cognitive aspects of human-computer interaction. Those guidelines are often vague whereas guidelines detailing physical or perceptive aspects are usually more specific and do not have to be interpreted. Guidelines covering cognitive aspects use fuzzy terms such as 'quickly' and 'easily'. Comments and examples are mentioned as helpful parts of guidelines. This, however, brings also about the complaint that one often has to spend much time reading irrelevant material, or that information has to be integrated with information from elsewhere in the guidelines to make it relevant to a particular system. Design engineers want guidelines on cognitive subjects to be just as clear and to the point as most guidelines on physical and perceptive aspects of human-machine systems.

The basic problem is, that guidelines and standards are written for human factors specialists and not for design engineers (Mosier and Smith, 1986). It should therefore not be surprising that they are often of little use to design engineers. The proper use of guidelines and standards requires human factors experience, a fact most texts with guidelines omit to stress. Guidelines and standards can best be seen as attempts to integrate and summarize existing knowledge, experience and expert opinions in generally defined task conditions (e.g. VDU work station). The compilers of the guidelines assume that the user of the guidelines has the knowledge and experience to judge the applicability of the different guidelines in a specific context or application (e.g. a refinery control room console). Guidelines should therefore be stated generally, because in this way they not only can reflect the conclusions from knowledge and experience originating from many different sources, but also better serve the purpose of a guideline, i.e. to be useful for a wide range of applications.

Guidelines can only be made useful to designers by converting them into application-specific design rules, which can be used without the need for further interpretation by designers. Deriving specific design rules from guidelines for a well defined and narrow context is mentioned in the survey from Mosier and Smith (1986). These 'in-house rules' are considered a better way to promote user-oriented design than asking designers to adhere to human factors guidelines they find difficult to use.

4. DESIGN RULES AS TOOLS FOR DESIGNERS

In deriving specific design rules from guidelines, the human factors specialist is in fact developing a tool for designers. By following the rules, designers should be able to apply human factors knowledge without further interpretation or help. For design rules to be useful they should be application-specific, i.e. they should be mapped onto the system and the user of the rules. So, three aspects should be considered: the tasks and task conditions, the equipment, and the designer. For rules to be applicable without further interpretation, the range of systems they apply to has to be narrow. This can imply that for the translation of guidelines into design rules for 'in-house use' more than just one set of rules has to be derived, each one for a specific application of a range of comparable systems.

The feasibility of this approach may be demonstrated here with the development of, up to now, two sets of rules for the design of operator consoles on-board oil and gas production platforms. Production platforms are built using a project type organization with a tightly fixed time schedule and budget. For a few platforms, human factors guidance and information was requested. This followed the usual pattern of specific and detailed questions. Major task-determining decisions had already been made, only minor changes to hardware and software could be implemented. However, based on the experience gained, a proposal could be made to central management, and was accepted, to compile three sets of design rules for the incorporation of human factors requirements into the design specification of the operator console and the central control room of average-sized production platforms. Not only is it expected that a few more of these platforms will be built, but also the control rooms and control systems of existing platforms are scheduled for refurbishment.

One set of rules provides design requirements for the information presentation on VDUs with regard to content, format and the navigation between displays. A second set of rules specifies the requirements for the design of the operator console in the central control room with regard to equipment installed, layout and shape of the console, control facilities, and the requirements for the navigation between VDUs. A third set specifies the requirements for the design of the central control room on a platform. Compilation of the first two sets has been completed. Work on the third set has not yet started.

In both cases the approach for the compilation of the two sets of rules was the same. Each set of rules is based on a supporting document: The VDU-based Information Presentation Guidelines Document and the Console Guidelines Document. The first gives guidelines, background information and comments on the presentation of information on VDUs with the restriction, however, that all information in the document is specifically adapted or selected to apply to the VDU-presentation of information in the operator console of Distributed Control Systems (DCS). The operator interface of the different manufacturers might differ in detail, globally they have the same functionality.

The information in the Guidelines Document is then used to derive rules for the design of the content, format and use of the VDU-presented information for a specific DCS; in this case a Honeywell TDC 3000.

The other Guidelines Document provides guidelines, guidance and comments with regard to multi-VDU operator consoles in a production platform process setting. The set of design rules derived from the Guidelines Document applies specifically to a console based on the Honeywell DCS console module.

Both Guidelines Documents are based on existing (draft)standards, guidelines, other available relevant literature and experience gained in the field. Both guidelines documents are in the first place intended for use by human factors specialists. The information in a Guideline Document can be used to answer questions when, for some reason, the rules do not apply, to adapt a rule if technological changes are introduced, or to compile a new set of rules for a different DCS.

To derive rules from a Guidelines Document, three determining factors should be distinguished: the particular DCS to be used, the general and specific characteristics of the process and the task requirements of the operator. Information with regard to the first two factors can be obtained from existing documentation, although field experience is a necessary prerequisite. The task requirements have been determined using different techniques. The most important ones are: walk-through evaluations on-board platforms, systematic observations of operator activities, structured interviews with operators and operations management.

The two sets of rules have been combined in an Engineering Reference Document(ERD) for the use by project teams. In this way the document has an official status in the company and cannot be considered 'as yet another set of recommendations'. Currently, the ERD is put to test in a project. Up to now only minimal adjustments to some rules are requested, but overall the rules are generally considered to be useful and complete.

5. CONCLUSIONS

This development of design rules demonstrates that it is possible to provide design engineers with human factors information in an effective delivery form, even for a type of system with a high level of complexity. This requires effort from the human factors specialist. Compiling guidelines for a wide context and requiring the user (designer) to interpret the guidelines for a specific application has been shown not to be effective and to generate little credit for human factors in the engineering world. To compile ready- for-use application-specific design rules appears to be a better approach. However, this approach demands from the human factors specialist to design a tool for the design engineer in such a way that it supports and facilitates the task of the designer and at the same time ensures the design of an effective and user-oriented human-machine system. This means that for both the 'designer-rules system' and the production system, the human factors system development procedure has to be followed.

REFERENCES

Abernethy, C. (1988). HCI standards: Origins, organizations and comment. In D. Oborne (ed.), International Review of Ergonomics, 2, 31-54.

Bailey, R.W. (1982). Human Performance Engineering: A guide for System Designers (London: Prentice-Hall).

Chapanis, A. (1959). Research Techniques in Human Engineering (Baltimore: John Hopkins University Press).

Meister, D. (1989). Conceptual aspects of human factors. Baltimore: John Hopkins University Press.

Mosier, J.N. & Smith, S.L. (1986). Application of guidelines for designing user interface software. Behaviour and Information Technology, 5, p. 39-46.

Sanders, M.S. & McCormick, E.J. (1987, 5th; 1992, 7th). Human Factors in Engineering and Design. New York: McGraw-Hill.

Schaaf, van der, T.W. & Kragt, H. (1992). Redesigning a control room from an ergonomic point of view: a case study of user participation in a chemical plant. In: Enhancing Industrial Performance: Experiences of Integrating the Human Factor. Taylor & Francis, London, p. 165-178.

Singleton, W.T. (1974). Man-machine Systems (Harmondsworth: Penguin).

Wilson, J.R. & Corlett, E.N. (Eds) (1992). Evaluation of Human Work. A practical ergonomics methodology. (London, Taylor & Francis).

Operator behavior and supervisory control systems in the chemical process industry

H.C.M. Hoonhout and H.J.G. Zwaga

Utrecht University, Psychological Laboratory - Ergonomics Group, Heidelberglaan 2,
3584 CS Utrecht, The Netherlands

Abstract

The effects of modern process control systems on the operator's supervisory control task are described. Considering the approach that operators adopt to perform their task, the relative advantages and disadvantages of various means of disturbance support facilities are discussed. This development is set against the current practice of operators (if involved in display design) to aim for a small set of general purpose displays.

1. INTRODUCTION

1.1. Technological developments in the control room

Technological advances have drastically changed the appearance of control rooms in the petro-chemical industry ever since the introduction of VDU-based Distributed Control Systems (DCSs). Hardware and software technologies are still evolving, resulting in recent applications in interface design such as increasingly higher resolution color graphics displays and touch screen input devices. New kinds of software technologies are being developed continuously, with the aim to provide the control room operators with additional or even better support in their supervisory control task. In recent years, for example, several manufacturers of control systems have introduced products based upon real-time expert systems, neural networks, and fuzzy logic (Cochran, 1992).

With the introduction of digital control, the man-machine interface has changed fundamentally. Discrete analog instruments and controls have been replaced by VDUs, allowing a much wider range of information presentation modes (e.g. trend displays, graphic displays with updated numeric information, and combinations of these displays). Compared with the traditional instrumentation, the information and control facilities are now available sequentially instead of simultaneously. This means that users have to change their ways of sampling information on the state of the process (i.e. they have to 'page' through displays). Furthermore, digital control has brought a large increase in the amounts of process information that can be made available. The complexity of the interface, when measured by the number of control and measuring points and the number of displays, has grown dramatically since the first introduction of DCSs. An evident example of the increased information load is provided by the proliferation of implemented alarm points. As reported by operators (Zwaga & Hoonhout, 1993) this results, during disturbances, in an avalanche of alarms, which do not provide the operator with relevant information, but merely constitute a high work load, because the alarms have to be acknowledged in an already stressful situation.

1.2. Changes in the operator's task

With the introduction of DCSs, the operator has become responsible for a much larger part of the plant. Added to this, the complexity of the operator's task is even further increased by the fact that the pressure on operational personnel to meet production targets is high, while considerations such as production efficiency, cost reductions, and maintenance planning now also have become part of their task.

Although the man-machine interface has seen major changes since the first introduction of DCSs, the task of the operator has basically remained the same: monitoring and control of the process, and the analysis and mitigation of disturbances. As a result of the increased automation, operators have moved from immediate control to a higher level of supervisory control. This means that the control of the process during normal operation is carried out by the DCS. The operator only intervenes in case of a disturbance. Active control is only required during start-up, shut-down, or a mode change.

Manufacturers commonly see the role of operators in supervising the process as mainly one of a crises-manager. In this view, the main task of the operator is one of process management, fault diagnosis and correction. The design of the interface of most DCSs reflects this view. Overview displays are provided to suit the assumed operator's needs in his supervisory monitoring task. The first indication of a process disturbance is given by the alarm system. Only alarm information and qualitative overview information about the state of the process have to be monitored on an ongoing basis. In this view the operators are only triggered into action in case of an alarm coming up. Analysis of the disturbed process conditions then moves from the use of global to increasingly more detailed levels of information, finally resulting in a diagnosis and in remedial control actions. This view of the operator's role in supervision of the process could be called the 'management-by-exception' approach (Zwaga & Hoonhout, 1993; Swaanenburg et al., 1988).

2. HOW DO OPERATORS WORK

Field studies (Swaanenburg et al., 1988; Kortlandt & Kragt, 1980) in petro-chemical plants reveal that one of the main complaints of operators is that with a DCS it is difficult to maintain an overview of the process at a sufficiently detailed level. Operators prefer to monitor the process quite intensively. They need information about the dynamic state of the process, because their prime concern is to know with an acceptable degree of certainty that the process is not going to confront them with unpleasant surprises. To infer, because there are no alarms, that the process is running smoothly, is not sufficient for them.

Results of field studies also show that they perform this monitoring (updating) task in such a way that it is efficiently tuned to the state of the process. A process with rapidly changing conditions will be closely monitored. If the stability of the process is high, however, the operator will consider it sufficient to rely on the alarm system, and check just a few key variables occasionally. Operators thus adapt their monitoring behavior to the complexity and the condition of the process: the frequency with which the operator updates himself is determined by an estimation of the probability that a section of the plant, or the whole plant, could give reason for concern.

The results of field studies thus indicate that operators as a rule do not perform their task according to the 'management-by-exception' principle, as assumed by manufacturers. Operators consider it their main task to *prevent* alarms, rather than to *react* to alarms. They tend to perform their task according to the 'management-by-awareness' principle, which means that at all times operators are well aware of the state of the process and can predict, to a certain extent, the behavior of the process in the near future, thus achieving a high degree of preparedness for possible changes in the process.

3. INTERFACE REQUIREMENTS AND INTERFACE DEVELOPMENT

As the results of field studies have shown, the operator needs information about the process that enables him to keep an overview of the system's state and to make a confident prediction of the future state of the process. The operator has to make use of information directly related to specific variables (group displays, trend displays, mimic displays), because only this kind of information will allow him to predict future states of the process and, if necessary, to take preventive action.

The persistent demands for changes in the interface of DCSs to meet these requirements, coincided with the introduction of new display techniques and increased computer power. If at first only standard vendor displays were available, now more flexibility in interface design became possible, resulting in customized interface design. The introduction of new display techniques led to increasing use of graphic or mimic displays. Graphic displays were considered to be a useful solution for the inadequacy of the standard vendor displays (overview type of displays and alarm displays) in the operator's monitoring and updating task during normal process conditions.

For the design decisions regarding the interface, the manufacturers increasingly relied on participation of the design-engineering departments of their customers. These developments did not put an end to the complaints of the operators, however. It appears that design engineers often have an opinion on how a plant should be operated, and how the DCS interface should be used, that closer matches the manufacturer's viewpoint of the management-by-exception approach, than it does conform to how operators in fact work (Zwaga, 1993). Thus involving design-engineers does not necessarily result in a much different and better approach toward interface design. If the interface of the DCS were to be accepted by the actual users, i.e. the operators, operational staff would have to be involved in the engineering phase. Only in this way the requirements and needs of operational staff could be incorporated into the design specifications for the displays.

Operators, in the few cases that they have been involved in the design of the graphic displays, usually do not present completely new ideas about display design, but stay close to the familiar P&IDs as a basis for design of the displays. This graphical representation of the plant, or part of the plant, is supplemented with different kinds of detail-information they want to check regularly. In this way, overview information is mixed with detail information in one display, in many cases resulting in displays crammed with information. Operators usually motivate their choice for graphics loaded with information with the excuse that "it is better to be sure than sorry". They use the argument that all displayed information will be needed at some time. Also, operators prefer to have as few displays as possible, because they want to reduce the cumbersome 'paging' back and forth between different types of displays. This results in the design of displays that can be used in normal operation as well as in disturbance control. This practice is in contradiction with the commonly expressed opinion in the human factors literature on DCS-interface design that the information requirements for both (opposite) conditions in the supervisory control task are likely to be completely different, and that this should be reflected in the design of different displays for each condition.

4. GENERAL VERSUS TASK-SPECIFIC INFORMATION

4.1. Normal and fault condition displays

As discussed above, an interface is needed that supports the operator in his management-by-awareness approach. As mentioned earlier, it is often stressed that the two main tasks of the control room operator, i.e. supervisory control and fault management, have quite different requirements with regard to the processing of the information offered by the DCS. In normal conditions, the operator must focus attention upon the forward flow of events: what causes what? In diagnosing a malfunction or a disturbance, the operator must often reverse the entire pattern: what was caused by what? (Wickens, 1984). It can be argued that different ways of information processing may imply highly different information needs, and therefore justify different sets of displays, i.e. a set of displays for normal day-to-day operation, a separate set for fault management, and in addition a number of displays for specific purposes such as a start-up. In this line of reasoning, Wickens (1984) and Van der Schaaf (1990) suggest that the operator should be provided with additional support in his fault management task by information displays that are specifically intended for use in disturbance conditions.

The increased flexibility in display design now enables the design of displays that are adapted to the specific requirements an operator might have for a particular task, e.g., monitoring a particular section of the plant, or a start-up. Thus, separate displays could be designed for the monitoring of a particular section of the plant, and for fault analysis in case of a disturbance in that particular section.

4.2. The feasibility of disturbance-analysis support systems

A logical consequence, derived from the conclusion that separate displays for fault management may be needed, is that (intelligent) disturbance-analysis support systems have to be implemented. The current trend of research on the development of decision support systems can be considered as an example of efforts in this direction. The expectation, however, that these kinds of systems will be widely available in the near future, should not be set too high for two reasons.

First, the range of possible disturbances, abnormal conditions or malfunctions that could occur in a plant is theoretically infinite. The information provided by any kind of disturbance support system will only be useful, if it is directly relevant to the disturbance at hand. The implications for the design of such a system are therefore enormous.

Secondly, the initially high expectations, raised by the new and promising technological advances announced by the domain of artificial intelligence appeared so far difficult to fulfil. The currently more modest aspirations of artificial intelligence in actually realizing advanced decision support systems, in combination with the first point raised, means that it will probably take a long time before such tools will be fully operational.

4.3. The need for disturbance-analysis support systems

Considering the nature of the disturbances, it appears that the large majority of abnormal conditions (fortunately) consists of well-known, relatively frequently occurring disturbances, that will be easily recognized, diagnosed, and corrected by the operator. In fact, the majority of abnormal conditions is 'routine'. Consulting a support system, or specific disturbance displays, for this kind of simple and common disturbances, will never be considered by the operator.

This means that only few disturbances will be caused by some unexpected, unthinkable, bizarre combination of events. In these rare cases, even a highly experienced, well-trained operator will have great difficulties in analyzing and diagnosing the disturbance. It can be argued that in these circumstances *any* kind of support system, be it a specific set of displays with relevant disturbance information, or a more sophisticated support system, will provide the operator with the then much needed support, to interpret the alarm information, and to decide on the appropriate corrective action. In contrast, it can also be argued that in these stressful circumstances, support systems, or specific displays, will be of less help than expected, and may even hinder the operator in performing his task efficiently. The main argument is that, because the support system or specific displays will infrequently be used, these will be unfamiliar, and therefore, the operator will be little inclined to resort to such unfamiliar aids. The operational conditions are stressful, and, as a natural reaction, humans will resort to proven and familiar ways to perform their task, even if it can be shown that these ways are less efficient. Only frequent training, using a well-designed program (preferably implemented on a plant-specific simulator) could overcome this objection. If no training is provided in this way, the interface of the support system should be self-evident, and the presentation of the specific disturbance information should not differ significantly from the usual way the information is presented. Only then can it be expected that operators will use these special information and help facilities.

Even if all these points are taken care of, it will still be difficult for the operator to decide when to switch from the displays normally used, to the support system or to the specific disturbance displays. With the management-by-awareness approach, the operators are in fact continuously on the ball to prevent disturbance conditions from developing at all. They are well aware of current conditions of the process and closely monitor any changes or instabilities that may develop, taking necessary corrective actions in time.

4.4. General purpose versus task specific displays

What supervisory monitoring behavior is about, is using the information presented on the various displays of the DCS in such a way that the operator can develop a correct model of current process conditions and predict with a reasonable degree of certainty the most likely future state of the process. This requires that the operator is able to combine and integrate the displayed information, but also is able to monitor subsystems in parallel in such a way that information about one part is not neglected when information on another part is attended. Finally, the operator should be able to easily 'read' information about a single variable correctly. These information processing requirements presuppose that an operator can easily locate and gather the information items that he needs. These requirements are most easily met when the operator is highly familiar with the interface. Continuing this line of thought, it can be argued that a relatively small set of general purpose displays is to be preferred over a large set of displays, of which each is intended for use in a specific process condition. In the latter case, it is likely that many of the specific displays will in the end not be used, because the operator has forgotten they exist.

A relatively small set of general purpose displays is just what operators, when they are involved in the design of the displays, are trying to achieve. This approach, intuitively used by the operators, perhaps allows a way of performing supervisory control, and also disturbance analysis, using the same set of displays that more closely and effectively matches with the management-by-awareness approach. As it is now, it cannot be ignored that operators who create and use these displays, are satisfied with the results. Considering the remarks about the crowded appearance of displays, it has to be realized that an experienced operator, who sees the displays daily, and has been trained in their use, will know 'his' displays inside out. Though for an outsider the displays may look unstructured, cluttered and unorganized, the operator will perfectly know how to use them, where to find a particular information item, etc. If displays are really overloaded with information, this may cause, of course, that an operator, however experienced, will overlook, or misread a particular critical value, especially under stress conditions.

Display design is now to a large extent still a matter of instinctively making choices regarding information content and layout of the information presentation. Apart from some general design rules, usually dealing with the use of color for coding, the use of symbols, and some basic layout rules, the design of displays will not be guided by a systematic approach regarding information requirements in relation to the various tasks. The preference of operators for a small set of general purpose displays is born in experience. Human factors guidance in interface design should seriously consider their arguments.

5. REFERENCES

Cochran, Edward L. (1992) Control room user interface technology in the year 2000: evolution or revolution? In: Proceedings of the Human Factors Society 36th Annual Meeting, Santa Monica, p.460-464.

Kortlandt, D., Kragt, H. (1980) Process alerting systems as a monitoring tool for the operation. In: Loss Prevention and Safety Promotion in the Process Industry, Vol. 3, p. 804-814.

Swaanenburg, H.A.C., Zwaga, H.J. and Duijnhouwer, F. (1988) The evaluation of VDU-based man-machine interfaces in process industry. In: Proceedings of the 3rd IFAC/IFIP/IFORS/IEA symposium on Analysis, Design and Evaluation of Man-Machine Systems, Oulu, Finland. p. 100-106.

Van der Schaaf, T.W. (1990) Interface design for process control tasks. Paper presented at the conference: The Human Factor in Safety: Implications for the Chemical and Process Industries. November 20-21, 1990, Manchester.

Wickens, Christopher D. (1984) Engineering psychology and human performance. Illinois: Scott, Foresman and Company.

Zwaga, H.J.G., Hoonhout, H.C.M. (1993) Supervisory control behaviour and the implementation of alarms in process control. In: Stanton, N. (ed.) The Human Factors of Alarm Design. London: Taylor and Francis. (in press).

Zwaga, H.J.G. (1993) The use of colour in CRT displays for the process industry. In: Lovesey, E.J. (ed.) Contemporary Ergonomics 1993. London: Taylor and Francis. p.278-283.

HOW TO SURVIVE PROCESS CONTROL AUTOMATION:

a case study of integral user participation

Loek A.A. Bollen (Exxon Chemical Holland B.V., Rotterdam)
Tjerk W. van der Schaaf (Eindhoven University of Technology)

Abstract

This paper describes the background, execution and results of two large ergonomics projects in a Centralized Control Room (CCR) of a highly automated chemical process plant in Rotterdam. Special emphasis will be put on the extensive use of **user participation** techniques throughout all phases of these projects.

Introduction:

This paper describes the background, execution and results of two large ergonomics projects in a Centralized Control Room (CCR) of a highly automated chemical process plant in Rotterdam. Special emphasis will be put on the extensive use of **user participation** techniques throughout all phases of these projects:

- deciding on functional requirements
- developing design guidelines
- building and evaluating prototypes
- introduction and training related to the final designs
- maintenance

One of the projects concerned a total redesign of the entire CCR (Central Control Room) **operator-process interface**, involving not only VDU- (or: CRT) based information and control facilities, but also hardwired annunciator panels, trend recorders, and a conventional back-up panel. Obviously, this project mainly involved a **cognitive ergonomics** contribution to the design team.

The other project was primarily concerned with classical ergonomics: the redesign of almost all physical aspects of the existing CCR, both to accommodate the interface changes mentioned earlier, and to bring this 12 year old control room again up to the ergonomic "state-of-the-art" level. The following aspects were included in the CCR "face-lift".

- lay-out of the new VDU consoles, back-up panel, and other workplaces
- new ceiling with special lighting equipment and adapted airconditioning
- new, balanced choice of colours and other measures to ensure optimal concentration when necessary.

The emphasis on user-participation methods will be illustrated by describing one example from each of the two projects:

- designing the VDU-**based schematics** (or: mimics) using the graphical options of the new Honeywell TDC3000 process control system interface.
- designing the **lay-out of the new** VDU **consoles** in the existing CCR.

Finally, a discussion of some of the important **trends in process automation** will show major implications (and great concern!) for issues like task-allocation, simulation, decision support, and selection of future operators.

Aromatics plant overview

The Plant is a typical petrochemical continuous production facility producing aromatic hydrocarbons from Benzene to ortho-xylenes. It is a highly automated, heavily integrated plant with various processes such as destillation; isomerisation a couple of catalitic conversion processes and a cryogenic H2 recovery plant as well as a crystallization process. In 1979 a Honeywell TDC2000/PMX control system was installed which was replaced by a TDC3000/AM control system in 1991. Computer control is applied to around 50% of the control loops and currently Dynamic Matrix Control is widely deployed.

Why new control equipment?

The TDC2000/PMX system had a very satisfactory performance during the 12 years in service. At the end of the '80's however several reasons emerged to convert the system:

- The "one window" configuration would allow the operator to get better access to the unit operation. A conservative guess predicted a yield improvement of 0.25%.
- The library of the TDC2000 was full.
- The TDC2000 system hardware had to be renewed (CRT's mainly).
- Possibility to introduce RTO (Real Time Optimization) and Dynamic Matrix Control.

You may conclude that mainly vision rather than real solid figures drove this investment.

Project schedule

Preparation such as writing the Design Basis, cost estimating and preparation for project execution including scope control and gate reviews by approving management took 6 months. Project execution took another 18 months and included console design; schematic design, development of help displays; annunciator design/installation and transfer (on-line) from TDC2000 to TDC3000.

Adaption of the infrastructure of the central control room lasted 6 months (lighting; AC; ceiling offices; floor; furniture etc.). Installation and migration of computer application is still ongoing. It means installation of VAX and application modules (hardware); migration of computer applications (software); clean-up software; installation of simulator; adapting documentation and design of new applications.

User participation

Key to this project was the involvement of the users (operators) as **experts** throughout the entire project (Van der Schaaf, 1990). In fact the operators were participating as of day 1 in a multi-disciplinary team (Zwaga, this volume) of design engineers, industrial hygienist, ergonomic specialist, vendor and process control engineers. Operators played a major role in designing or developing:

- the operating philosophy (task analysis),
- design of basic control strategies and displays,
- lay-out ergonomics of the control room,
- initial training,
- transfer of control loops,
- alarm philosophy and tagging strategies.

Engineers focused more on developing and designing;

- economic modules,
- integration of systems
- systems to comply with internal and external safety requirements,
- computer control strategies,
- spare capacity strategies,
- simulator applications.

Example 1: Operators as "experts"

A comprehensive task analysis was performed with the help of a checklist of the University of Eindhoven (Van der Schaaf & Kragt, 1985) and with the involvement of leading console operators. A prediction of "the operator of the future" delivered the operating philosophy and formed the basis for control strategies and display design. Guidelines of Exxon Research and Engineering company; documentation of Honeywell; own developed guidelines for schematics together with TU Eindhoven "state of the art" operator interface design consideration (Van der Schaaf, 1989) were the building stones for a schematic design team. An example unit (isoformer) was used because all major equipment components are part of such an unit like towers, compressors, furnace, reactor etc. etc.

Fundamentals for building schematics were agreed and schematics were designed by operators and discussed within shifts and engineering.As soon as the demo system became available the paper schematics were transferred to the system and adapted according the remarks of the operators. All options were discussed and based on consensus agreed. This method had two major advantages:

1. the users were forced to think and develop and thus grow gradually with the system.
2. anticipated problems with a switch from numeric to graphical info profiles to schematics were dramatically reduced and the buy-in for a different operating interface was almost complete.

A representative from Honeywell did the actual "building" of schematics and help displays in the TDC3000 system on site so that the results could be reviewed immediately during night and afternoon shifts. Finally the building techniques for displays and maintenance of the process interface were thought and assigned to some operators.

Example 2: console lay-out

For the console lay-out a similar method of user participation was followed. Based on a initial package of requirements from operators a wooden mock-up assembly on scale (1:10) was provided to play with and to compose the final "ideal" lay-out (Van der Schaaf & Kragt, 1992). Major considerations were:

- Optimum communication between console operators during up-sets. Eye contact possible.
- Annunciators in front of operator.
- Panel operators have a somewhat shielded territory from the rest of the control room (no meeting room behind the screens).
- Optimum use of writing space and communications apparatus.
- Designed for future expansion without touching the present "ideal" lay-out.
- Build in possibilities to reduce manpower without compromising operations integrity.
- Simulator inside the control room but outside the real control area.

Training

A temporary demo console was installed with two screens in the control room and the operators had during 6 months a "view only" option to train and to get used to the schematics.
During 3 months one of the new consoles was put in parallel to the old system and finally the TDC2000 system was dismantled.

The same sequence was followed with the other two "old" consoles and the transfer went very smoothly without any cut back in production or dissonant with the operators.
No expensive out of house training was followed; only a one day in-house system training given by one of our own shiftsupervisors.

Conclusions:

Pro's and con's of digital controlrooms

Pro
- Computer control possible
- more units per console; manpower reduction possible
- less upsets; better maintenance possible
- unit integration easier
- lower operating costs; increased yields; better quality performance etc. etc.

Con
- less process-status overview by operators (Hoonhout & Zwaga, this volume).
- less "feel" for process dynamics
- loss of ability to handle upsets
- expensive simulation systems "must"
- more "experts" needed
- more expensive CCR's (airco etc.)
- adaption of the whole infrastructure and the culture of the organisation necessary.

Priorities to survive process control automation

User participation is key in every element of process control automation. That means that the classic type of operator and the classic use of operator capabilities is not longer suitable in highly automated processes.
To breed and select the new generation of operators we have to start in school and a high degree of industry participation in the technical school programs is mandatory.
Selection of operators can be enhanced by use of selection tools like work-samples (simulation tools) (Ridderbos, 1992).
The knowledge transfer from engineers to operators and vice versa has to be intensified. Unit performance teams (engineers/operators/maintenance) play a major role in knowledge transfer and optimum use of industrial capabilities (Van der Schaaf, 1992). Requalification and "education permanente" is a must.
Use of real time simulators is increasingly needed, but does not solve all skill-reduction problems!
Decision support systems (not: "expert" systems!) to help operators judge are needed in controlling complex integrated units (Brinkman & Van der Schaaf, this volume). Intelligent alarmsystems are a must.

A constant evaluation of men/machine interface based on cognitive ergonomics (Hollywell & Hickling, this volume) will prevent the future operators from 99% deadly vigilance and 1% deadly fear.

REFERENCES

Ridderbos, A. (1992). Selection by simulation.
Ph. D. Thesis, Eindhoven University of Technology, The Netherlands

Van der Schaaf, T.W. (1989).
Redesigning and evaluating graphics for process control.
In: G. Salvendy and M.J. Smith (Eds), Designing and Using Human Computer interfaces and Knowledge Based Systems. Amsterdam, Elsevier Science.

Van der Schaaf, T.W. (1990).
User participation in designing process control interfaces.
In: L. Bambridge and S. Reinartz (Eds), Proceedings of the First Workshop on Cognitive Processes in Complex Tasks. Wilgersdorf, TUV Rheinland Report.

Van der Schaaf, T.W. (1992).
Near Miss Reporting in the Chemical Process Industry.
Ph. D. Thesis, Eindhoven University of Technology, The Netherlands

Van der Schaaf, T.W. & Kragt, A. (1985).
Control Room Evaluation Questionnaire. Eindhoven University of Technology Report (in Dutch).

Van der Schaaf, T.W. & Kragt, H. (1992).
Redesigning a control room.
In: H. Kragt (Ed.), Enhancing industrial Performance, London, Taylor & Francis.

A Tool Set for the Verification and Early Validation of a Control Room Computer-Based Display System for Sizewell 'B' Nuclear Power Station

P.D. Hollywell[a] and E.M. Hickling[b]

[a]Electrowatt Engineering Services (UK) Ltd, Electrowatt House, North Street,
Horsham, West Sussex RH12 1RF, United Kingdom. Tel +44(0)403 250131

[b]Nuclear Electric plc, PWR Project Group, Booths Hall, Knutsford, Cheshire WA16
8QG, United Kingdom. Tel +44(0)565 682698

Abstract

This paper describes a new set of tools for the evaluation of prospective HCI-based control room operator interfaces. Each tool is summarised and its application to an extensive control room interface is reported. It is concluded from this study that the new tool set is powerful in application and reduces much of the complexity associated with such evaluations hitherto, and has the potential in other HCI systems to minimise abortive systems design in advance of prototypes or simulation becoming available. The structured and systematic approach to HCI system evaluation, together with the scrutability and auditability of subjective judgements made and the human factors guidance given the analyst in making those judgements, ensures a very thorough and unbiased analysis.

1. INTRODUCTION

In the Main Control Room of Sizewell 'B', a PWR nuclear power station currently being built in the UK, a networked computer system will display process information together with embedded alarms to operators on 34 VDUs. A hierarchy of 450 process mimic formats, plus associated trends, bar charts, data tables, alarm lists, etc, will constitute the principal operator interface for monitoring purposes. The human factors evaluation of such an interface can be daunting due to its complexity, which arises from: (i) the large number of system features needing to be considered, (ii) relevant ergonomics guidelines often being an artefact of the originating technology rather than relating to human performance, and (iii) long lead times between specifying the system software and its availability for evaluation. Suitable evaluation tools for such an application therefore need to be able to cope with the above challenges. In addition, appropriate evaluation tools need to be able to support the design process and to assess proposed changes whilst satisfying the requirements of the regulatory authorities for highly auditable methods.

A new set of tools was developed to overcome the problems associated with the evaluation of prospective HCI-based control room operator interfaces. The tool set was used for the Verification and Early Validation (V&EV) of an early candidate system for the Sizewell 'B' Main Control Room as well as the final implemented system. The V&EV was just one task within a comprehensive VDU format design process. The new tools are a substantial refinement of the HUFIT Tool Set [1] for use with process control industry applications and closely resemble Quality Function Deployment (QFD) matrices [2]. In describing the V&EV methods, each tool is summarised and its application to the control room operator interface is reported.

2. VERIFICATION METHOD

In verification, the human factors specialist must establish that all system features, as specified on paper, will meet human factors criteria, thus ensuring that any human performance problems can be eliminated at an early stage in the design process.

2.1. System Features & Human Performance Characteristics Interactions

In this method, the system features are compared against Human Performance Characteristics (HPCs) and a performance score is derived independently of any user task for which the system feature is used. These system features are the elemental building blocks from which the entire operator interface will be built, e.g. text types, symbols, keyboard elements. In order to identify all the system features, a systematic review was made of vendor and client documentation and system feature attributes recorded. For example, a VDU-based symbol is recorded in terms of shape, size, colour, dynamic properties, etc. System features are grouped into families of similar types, to minimise repetitious judgements and to ease global changes of scoring. The certainty/quality of the information obtained is also recorded in terms of the degree of firmness in the design. In order to evaluate each system feature thoroughly, the relevant HPCs need to be identified. A taxonomy of HPCs has been developed, which includes 23 relevant characteristics, such as visual acuity, contrast sensitivity, accommodation, auditory discrimination, reach envelope. This taxonomy is relevant to all types of operator interface, as it refers to human characteristics which are generic and universally relevant (i.e. task independent).

2.2. Verification Matrix & Evaluation Guidelines

Following the definition of system features and HPCs, a matrix is created showing the system features' links with HPCs (Figure 1(b)). Where an HPC interacts with a system feature, so affecting human performance, then a link is declared within the matrix. Each link is scored on the quality of the human factors design of the feature and its expected effect on human performance. The six point unipolar scoring is supported by extensive evaluation guidelines to ensure consistency. A summary score for a system feature across all relevant HPCs is then derived by taking the worst score for that feature. This approach is inherently conservative but is appropriate as the lowest quality accommodation of an HPC by a feature is the one that would cause the feature to fail to achieve the desired human performance. For example, a symbol may be of sufficient size, adequate contrast and discriminable colour, but it may fail entirely if the symbol shape itself is easily confusable with another. Thus, the resulting matrix is able to verify in a structured form the quality of the human factors engineering of the interface features and their expected effect on human performance. Therefore, human performance problems can be identified at an early stage and the appropriate remedial measures taken.

2.3. Application of Method

In the verification of the early candidate system, over 200 features of a computer-based display and alarm system were identified and a verification matrix with 9,330 cells was created. Of these, 5,000 links, representing interactions between system features and HPCs, were identified and were assigned performance scores.

3. EARLY VALIDATION METHOD

In early validation, the objective for the human factors specialist is to ensure early in the design process that the operator interface adequately supports the user task requirements.

3.1. PAGODA

In order to identify all the task elements associated with system use, an evolutionary task analysis method was developed called PAGODA (Purpose And Goal Orientated Diagrammatic Analysis) [4]. PAGODA combines elements of Hierarchical Task Analysis (HTA), Success Tree Logic (STL) and Function Analysis System Technique (FAST) in order to fully capture HCI-based tasks (Figure 1(a)). This tool enables a human factors specialist to identify all the task elements associated with a particular system design, e.g. detect an alarm, identify a parameter, read a parameter, predict a parameter rate-of-change value.

3.2. Early Validation Matrix & Evaluation Guidelines

Following the definition of task elements, another matrix is created (Figure 1(c)). Where a task element is identified as being supported, in part or in whole, by system features, links are declared within the matrix. Since system features are generally used in groups, sets of features are linked together in the matrix forming super-features. Alternative sets of features which can support a task element are often identified. Also, system features can appear in more than one super-feature. Each link between a super-feature and a task element is scored on the quality of the task support that super-feature provides and its expected effect on human performance, independent of the performance scores already obtained. The task support scoring is achieved using a six point unipolar rating scale and is supported by extensive evaluation guidelines to ensure consistency. As an example of this scoring, both a trend graph and the visual observation of the rate of change of a numeric display would enable an operator to predict a future value for a process parameter. However, a trend graph gives an operator much better support for this particular task element. Thus, the resulting early validation matrix is able to capture in a structured form the effectiveness of the task support given by the interface super-features and their expected effect on human performance. Problems with supporting user tasks can therefore be clearly identified at an early stage and the appropriate remedial measures taken.

3.3. Application of Method

In the early validation of the early candidate system, 52 user task elements associated with the use of a computer-based display and alarm system were identified and an early validation matrix with 9,830 cells was created. Of these, 330 cells required links and involved task support scores.

4. COMBINED VERIFICATION & EARLY VALIDATION METHOD

The combination of the results from the verification and the early validation enables a human factors specialist to make accurate design judgements concerning the quality of the human factors design of the system features and the effectiveness of the super-features in supporting user task elements.

In the method, each system feature summary score from the verification matrix is entered into the early validation matrix (Figure 1(c)). A user performance score for each super-feature is obtained from the mean value of the set of system feature performance scores associated with it. This is appropriate as poor features in the super-feature would not necessarily cause the execution of the task element to fail. Continuing with the previous example, both a trend graph and a numeric display would enable an operator to predict the future value of a process parameter. As already stated, a trend graph gives an operator much better support for this particular task element. However, design judgements may have to be made concerning the quality of the human factors design and the effectiveness of the support for that task element and for other associated task elements. Judgements about re-design may depend on the importance of the task element under consideration and its impact on the total system performance. The V&EV matrix is able to support the human factors specialist and system designers in making such complex design judgements (Figure 1(d)).

5. CONCLUSIONS

The new tool set, incorporating a Human Performance Characteristics description tool, a Task Elements definition tool (PAGODA), Evaluation Guidelines, Verification and Early Validation (V&EV) Matrices and a V&EV Matrix, have shown themselves to be useful both in supporting the design process and in satisfying the regulatory authorities. The application of the methods during the early design stage offers threefold benefits. First, its systematic and structured approach enables all judgements to be easily scrutinized and discussed by others. Secondly, it offers the human factors specialist the ability to break down large and potentially convoluted judgements, sometimes based on uncertain design information, into small, tractable chunks which can be successively built up into more global judgements. Thirdly, proposed changes to the system can be rapidly re-assessed. The combination of system features into higher level sets also enables broader human factors considerations to be fully expressed and explored if necessary.

The methods described cannot purport to reflect the appropriateness of the operator interface for the user tasks in the fullest sense; it cannot be as precise as using potential users in prototype trials or in a simulation. It does offer the ability to scrutinise all the features thoroughly, which simulator trials may not. However, it is the authors' opinion that in its current state of development the tool set could be readily used on other similar HCI and non-HCI based systems within the process industries, both at the early design stage, when system modifications can be more readily made and in advance of a system prototype becoming available. This would provide identification of operator interface difficulties. As the method also records the quality of available design information, it can be successively re-applied and human factors judgements refined as design and design modification progresses.

The authors believe that the new tool set's provision of systematic and well defined stages, together with the scrutability of subjective judgements made and the guidance for a human factors specialist or another analyst in making these judgements, ensures a very thorough, complete and unbiased evaluation.

6. REFERENCES

1 M. Galer, S. Harker and J. Ziegler (eds.), Methods and Tools in User-Centred Design for Information Technology, North-Holland, 1992.

2 S. Pugh, Total Design, Addison-Wesley, 1991.

3 E.M. Hickling, M.R. Herbert, E.C. Marshall and P.D. Hollywell, The Verification and Early Validation of a Plant Status and Alarm Display System. In, Contemporary Ergonomics 1992, Proceedings of the Ergonomics Society's 1992 Annual Conference, Taylor & Francis, pp. 485-492.

4 E.M. Hickling, J.G. Harvey and P.D. Hollywell, The Consistent and Structured Definition of Process Plant HCI-Based Tasks. In, Contemporary Ergonomics 1992, Proceedings of the Ergonomics Society's 1992 Annual Conference, Taylor & Francis, pp. 275-283.

ACKNOWLEDGEMENTS

Acknowledgements are due to Nuclear Electric plc, for providing the opportunity to enhance and apply the HUFIT Tool Set to an HCI-based control room operator interface. Thanks are also due to Bernie Catterall who provided early insights into the practical application of the HUFIT Functionality Matrix. All views expressed in the paper are those of the authors and may not represent those of their respective organisations.

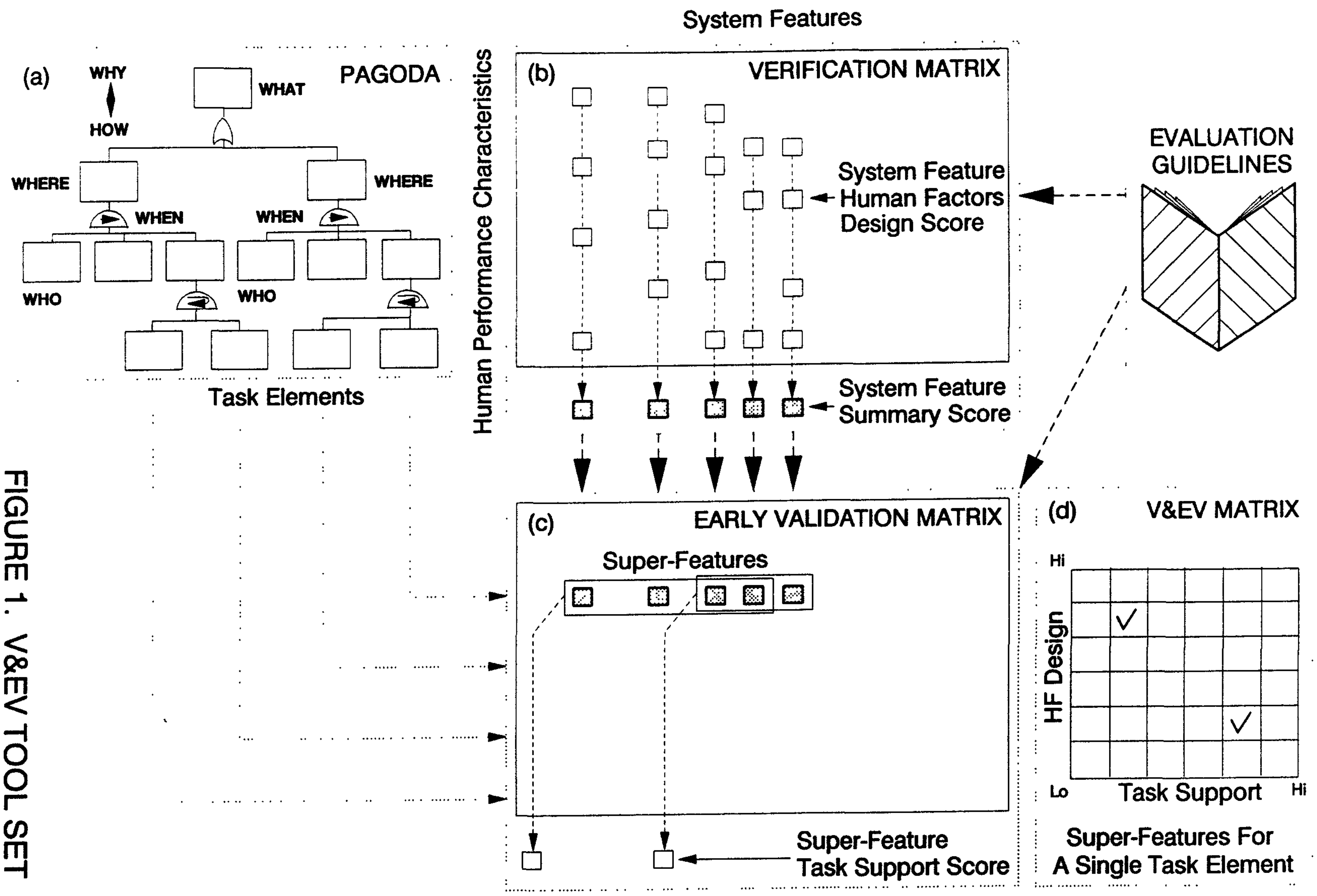


FIGURE 1. V&EV TOOL SET

Analysis and support of fault diagnosis strategies

J.A. Brinkman and T.W. van der Schaaf

Eindhoven University of Technology, Graduate School of Industrial Engineering and Management Science, P.O. Box 513, 5600 MB Eindhoven, The Netherlands

Abstract

It was examined whether an operator, when confronted with a variety of strategy-specific information aids during fault diagnosis, would have the ability to select the aid that matches his/her current strategy best. To answer this question, 18 process operators performed a simulated topographic search task to which several strategy-specific help functions had been added. The results indicated that the operators selected the help functions in accordance with the strategy they actually adopted. It is argued that for the task of fault diagnosis different types of information aids should be designed for different strategies and that the operator should be free to select the aid that suits his/her needs best.

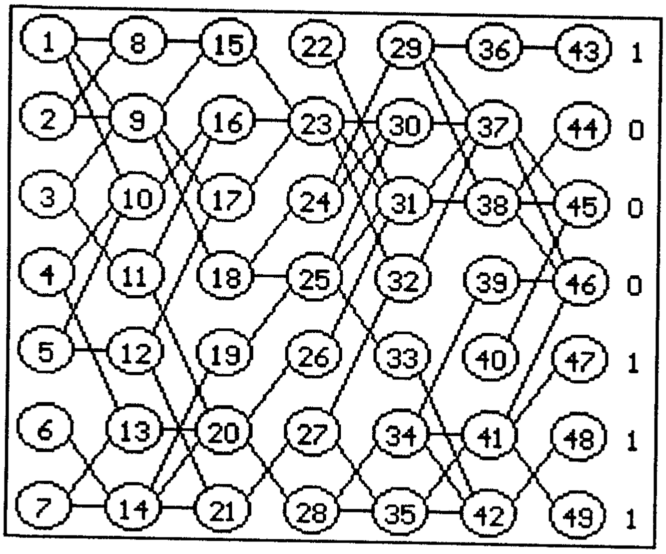
1. INTRODUCTION

One of the main tasks the human operator has to fulfil when supervising a highly automated production process consists of diagnosing faults. Fault diagnosis is commonly conceived of as determining the cause of a malfunctioning process from a set of observable symptoms. Of the various approaches being followed to assist the operator in overcoming the difficulties of this task, providing information aids is probably the most straightforward in keeping the operator an integral part of the man-machine system [1], [2]. Designing information aids for fault diagnosis requires consideration of the following two related points. First, even within relatively homogeneous groups of subjects, like university students [3] and maintenance technicians [4], there are large inter- and intra-individual differences in the use of diagnostic strategy. Secondly, the particular strategy a subject adopts determines to a large extent the kind of difficulties encountered during task performance [4]. Thus, it might make sense to design different types of information aids for different strategies and to have the operator select the information aid that is most helpful for his/her own strategy [5]. This, however, raises the question whether the operator will be able to do so. That is to say, when facing various strategy-specific information aids, is the operator capable of selecting the aid that supports the strategy he/she actually uses best? To answer this question, an experiment was set up in which a group of process operators had to perform a simulated fault diagnosis task to which several relatively simple strategy-specific information aids had been added in the form of computerized help functions. During the task, the operators were left completely free in strategy use and choice of help function. It was examined whether they selected the available help functions in accordance with their actual strategy.

2. METHOD

Subjects. A group of 18 male process operators of a chemical plant served as subjects. The operators differed in the amount of operating experience and they possessed varying degrees of process control skills. With respect to these variables they were fairly representative of the whole pool of operators of the plant involved.

Task. The task used was adapted from the topographic search problem TASK, originally developed by Rouse [6]. TASK requires fault finding in graphically displayed networks which consist of N rows and N columns of interconnected logical AND-gate components (Figure 1). In each network, signals flow through the connections from left to right. There is, however, one randomly selected component which does not work and which therefore does not transfer its input signals. It is the task of the subject to locate this faulty component. He can achieve this by interpreting the values of the output units at the right-hand side of the network (1 is working and 0 is not) and by testing connections (with a cost of 1 point) and components (with a cost of 3 points) within the network. Having made a test, the subject receives its value until he tests the faulty component in which case the problem has been solved. During task performance, a chronological list of the test results obtained so far is kept at the right-hand side of the network.



trial 1: 23 31 status 0
trial 2: 8 15 status 1
trial 3: 10 16 status 0
trial 4: 10 correct

Figure 1. An example of a network and an illustration of the way a subject solved it. The tests made by the subject have been underlined.

Strategies. Two basically distinct strategies, referred to as *tracing-back* (TB) and *hypothesis-and-test* (HT), have been identified for the task [3], [7], [8]. In short, TB involves testing the inputs of a component the output of which has just been found to be 0. This is continued until the faulty component is encountered the characteristic feature of which is that none of its inputs is 0. HT involves testing the input or the output of a component belonging to the feasible fault set. This set consists of all the components that could have failed, given the information acquired so far. The feasible fault set can be derived by determining what components connect directly or indirectly to all components with a known value of 0 and do not connect to any component with a known value of 1. For example, in Figure 1 the complete feasible fault set prior to testing consists of 8, 10, 15, 16, 17, 22, 23, 26, 31 and 38. As will be evident, the amount and the complexity of the information being processed during task performance is considerably larger when adopting the HT strategy than the TB strategy. It thus seems appropriate to qualify HT as more cognitively demanding than TB. TB and HT should be regarded as idealized ways of performing the task. It is very well possible that a strategy is adopted which differs in one or more respects from these two strategies. Such a strategy is referred to as *indefinite* (IN). Furthermore, during task performance one strategy may be changed for another.

Help functions. Seven help functions (in the following referred to as h1, h2, ..., h7) were added to the fault diagnosis task each of which could be activated to obtain one of the following pieces of information:

1. the *input tree* of a particular component (i.e., all the components which can send signals to it),
2. the *output tree* of a particular component (i.e., all the components which can receive signals from it),
3. the *test results* obtained so far,
4. all the components reaching *all the 0-output* units,
5. all the components reaching *all the 1-output* units,
6. all the components reaching *at least one of the 0-output* units,
7. all the components reaching *at least one of the 1-output* units.

As can be seen, a help function gave only information the subject could also have derived by himself. Upon activation of a particular help function, the corresponding piece of information would be visually presented within the network itself. That is to say, with h1 and h2, the components involved, together with their interconnections, were coloured in red. With h3, the tested connections and components with a value of 0 were coloured in red and those with a value of 1 were coloured in green. With h4 and h6, the components involved were coloured in red, and with h5 and h7 they were coloured in green. It should be noted that an operative help function had to be deactivated when using another function or when performing a test. The help functions were developed with the purpose of supporting one or both strategies or neither strategy. More specifically, h1 was designed for the support of the TB strategy. This function was supposed to help in finding a path of interconnected components having a value of 0 and eventually leading to the faulty component. H4 and h7 were designed for the support of the HT strategy. It was supposed that these functions, especially when used in combination, would help in identifying the possibly faulty components. H3 was meant to support both TB and HT by assisting in mapping the list of test results at the right-hand side of the network onto the network itself. H2, h5 and h6 were actually meant as decoys in the sense that they seemed to be informative but were in fact useless for whatever strategy.

Procedure. A subject was tested individually in a separate room in which he sat in front of a PC which had been programmed to control the fault diagnosis task. First, the subject studied an extensive written task instruction in which accuracy rather than speed was stressed. However, he was left free to follow the strategy he preferred. Hereupon, the subject had to solve 8 practice problems. Following this, the subject studied a written instruction on the nature and the use of the help functions. He was told to be completely free in selecting any help function at any time during task performance. The subject was then given another set of 4 practice problems and he thereby got the opportunity to make use of the help functions. Finally, the subject had to solve 12 experimental problems. Here, the help functions were again available. On these problems, the subject was not allowed to make use of paper and pencil and he received no feedback. For each practice and experimental problem being presented, a different network was generated. A network could either be small (i.e., 5 rows and 5 columns) or large (i.e., 7 rows and 7 columns). Network size was balanced across the practice problems as well as the experimental problems.

Performance measures. Two sets of measures were used to describe the subject's performance in each experimental problem he solved. The first set was meant to capture the adopted diagnostic strategy according to an algorithm described fully in [7], [8]. In previous experiments, evidence has been gathered indicating that the algorithm is valid. The following three measures were constructed from the strategy classifications the algorithm produced: the proportion of TB, the proportion of HT, and the proportion of IN. Each proportion was expressed as a percentage of the total number of tests performed on a problem, with the exception of the test on the faulty component and the tests which the algorithm failed to classify into one of the strategies specified beforehand. The second set of measures related to the selection of the help functions. For each help function, the number of times it had been selected was counted. To control for variability in the length of problem solution, this frequency was divided by the number of tests needed to solve the problem.

3. RESULTS

Before being analyzed further, the subjects' scores were averaged across all the experimental problems being solved. To determine whether the subjects selected the help functions in accordance with their actual strategy, each strategy measure was correlated with each help function measure. Given the considerations underlying the design of the help functions, the following relationships were expected to emerge from this correlation analysis: the higher the proportion of TB, the larger the number of h1 and h3 requests, and the higher the proportion of HT, the larger the number of h3, h4 and h7 requests. Allowing for non-linearity of the relationships, Spearman's rank correlation coefficient r_s was applied (i.e., 1-tailed for the relationships being expected and 2-tailed for those not expected). Of all the 21 correlation coefficients computed, only two had a moderate size and reached significance at the 0.05 level. First, the proportion of HT correlated positively with the number of h4 requests ($r_s = 0.59$, $p = 0.006$, 1-tailed). Secondly, the proportion of IN correlated negatively with the number of h4 requests ($r_s = -0.47$, $p = 0.048$, 2-tailed).

To get a better insight into the working-style of the subjects having a preference for an IN strategy, the test behavior of these subjects was considered more closely. This inspection revealed that these subjects first worked in accordance with the HT strategy in that they tried to locate a possibly faulty component within the network. Subsequently, however, they differed from this strategy as they performed a relatively large number of redundant tests in an attempt to establish the real status of the component under consideration.

4. DISCUSSION AND CONCLUSION

Based upon the assumption that the operators would select the help functions in accordance with their task strategies, a highly specific pattern of relationships between type of strategy and type of help function was expected. The results show that this pattern of relationships is partly confirmed. First, use of the cognitively demanding HT strategy was accompanied with selecting h4, the help function displaying in the network to be diagnosed all the components reaching all the 0-output units. This finding indicates that, as expected, h4 is indeed utilized to help in identifying the components that possibly fail. Secondly, where no relationship between strategy usage and selection of help function was expected, it in general is not found so. For example, application of the HT strategy was not accompanied with selecting h5, the help function showing all the components reaching all the 1-output units. This finding should come as no surprise since h5 had been designed so as to be of no help for whatever strategy. Thus, the results point out that, in general, a particular help function is not utilized for supporting the actual strategy, whenever that help function has not been specifically designed for it.

In addition to this supporting evidence, there are, however, also a number of deviations from the pattern of relationships specified beforehand. First, use of the TB strategy was not associated with selecting h1, the help function displaying the input tree of a particular component in the network. As described above, h1 had been meant to help in tracing a path of zeros backwards into the network. One might argue that this relationship could not emerge because the TB strategy was hardly employed by the operators. As a matter of fact, the proportional use of TB was less than 15% on the average. It should be noted, however, that even the 2 operators preferring this strategy also (almost) never requested h1. A likely explanation for this finding is that the processing requirements of TB are so low that during this strategy no support is needed whatsoever. Secondly, application of the HT strategy was not accompanied with selecting h7, the help function showing all the components reaching at least one of the 1-output units. Like h4, h7 had also been designed with the purpose of helping in the identification of possibly faulty components. Actually, of the 12 operators favoring the HT strategy, only 5 requested h7 a reasonably number of times, i.e. more than 0.01 per test made. This finding indicates that several operators made insufficient use of the information provided by the acceptable outputs in order to assist in eliminating infeasible components. This tendency to underutilize disconfirming evidence has been observed repeatedly in the research literature [6]. Third, neither TB nor HT was associated with selecting h3, the help function presenting the test results obtained so far within the network itself. The failure to find these relationships may be attributed to the infrequent use of h3. Only 3 operators requested this help function more than 0.01 per test made. Obviously, the operators did not need support to map the always available list of test results at the right-hand side of the network onto the network itself. Fourth, application of an IN strategy was negatively related to selecting h4. This relationship, however, may simply have its origin in the positive relationship between selecting the same help function and employing the HT strategy. That is to say, one might argue that requesting h4 increased the use of HT at the expense of following an IN working-style. This explanation is supported by a more detailed analysis of the individual tests made during the task. More specifically, this analysis revealed that making an h4 request on a particular test, in comparison with selecting not any help function, increased the chance of an HT classification of that test from 0.23 to 0.66 and decreased the chance of an IN test classification from 0.45 to 0.25. Fifth, there were several operators making considerable use of h2, the help function showing the output tree of a particular component in the network. To these operators belonged 3 having a preference for the HT strategy and also 3 preferring an IN working-style. This finding is somewhat surprising since h2 was not supposed to be of any help for whatever strategy. Note, however, that the output tree of a given component may very well be used to establish whether that component reaches all the 0-output units but none of the 1-output units. Selecting h2 repeatedly can therefore be very helpful in identifying the components that possibly fail. Thus utilized, h2 gives the same information as the combination of the two help functions designed for the HT strategy, i.e. h4 and h7. This might explain why a number of the operators favoring the HT strategy selected h2 so frequently. That a number of the operators favoring an IN strategy did as well may then be attributed to the fact that these operators also followed a working-style of which the identification of possibly faulty components comprised an important phase.

The general picture emerging from the foregoing discussion is that the operators selected the help functions in accordance with their actual strategy. Thus, there is evidence to conclude that an operator, when facing a variety of strategy-specific information aids during fault diagnosis, is capable of selecting the aid that matches his/her actual strategy very well. Therefore, the most important message conveyed by the present study is that for the task of fault diagnosis every effort should be made to design different types of information aids for different strategies and to leave the operator completely free in choosing the aid that suits his/her needs best.

5. REFERENCES

[1] S.-L. Hwang and H.-W. Cheng, "The effects of information aids on fault diagnosis performance in process control systems", *Human Factors in Manufacturing*, 2, pp. 339-355, 1992.

[2] M. Toms and J. Patrick, "Components of fault-finding: Symptom interpretation", *Human Factors*, 31, pp. 465-483, 1989.

[3] D.L. Morrison and K.D. Duncan, "Strategies and tactics in fault diagnosis", *Ergonomics*, 31, pp. 761-784, 1988.

[4] J. Rasmussen, *Information Processing and Human-Machine Interaction: An Approach to Cognitive Engineering*, Amsterdam, The Netherlands: Elsevier Science Publishing Company, 1986.

[5] T.W. van der Schaaf, "User participation in designing process control interfaces", in: *Proceedings of the First Workshop on Cognitive Processes in Complex Tasks*, L. Bainbridge and S. Reinartz , Eds., Wilgersdorf, TÜV Rheinland, Germany, 1990.

[6] W.B. Rouse, "Human problem solving performance in a fault diagnosis task", *IEEE Transactions on Systems, Man, and Cybernetics*, SMC-8, pp. 258-271, 1978.

[7] J.A. Brinkman, *The Analysis of Fault Diagnosis Tasks: Do Verbal Reports Speak for Themselves?* Ph.D. Thesis, Eindhoven University of Technology, The Netherlands, 1990.

[8] J.A. Brinkman, "Verbal protocol accuracy in fault diagnosis", *Ergonomics*, in press.

Eindhoven University of Technology
Department of Industrial Engineering and Management Science
Research Reports (EUT-Reports)

The following EUT-Reports can be obtained by writing to:
Eindhoven University of Technology, Library of Industrial Engineering and Management Science, Postbox 513, 5600 MB Eindhoven, Netherlands.
The costs are HFL 5.00 per delivery plus HFL 15.00 per EUT-Report, to be prepaid by a Eurocheque, or a giro-payment-card, or a transfer to bank account number 52.82.11.781 of Eindhoven University of Technology with reference to "Bibl.Bdk", or in cash at the counter in the Faculty Library.

20 LATEST EUT-REPORTS

EUT/BDK/56	The system of manufacturing: A prospective study **J.C. Wortmann, J. Browne, P.J. Sackett**
EUT/BDK/55	Rekenmodellen voor de grootschalige mestverwerking; gebaseerd op het MEMON-mestverwerkingsprocédé **Mat L.M. Stoop**
EUT/BDK/54	Computer, manager, organisatie (deel I en II) **R. Cullen, H. Grünwald, J.C. Wortmann**
EUT/BDK/53	Risico diagnose methode voor produktinnovatieprojecten; Een uitwerking toegesneden op de Industriegroep TV van Philips Glas te Eindhoven/Aken **J.I.M. Halman, J.A. Keizer**
EUT/BDK/52	Methodological problems when determining verbal protocol accuracy empirically **J.A. Brinkman**
EUT/BDK/51	Verbal protocol accuracy in fault diagnosis **J.A. Brinkman**
EUT/BDK/50	Techniek en marketing **H.W.C. van der Hart**
EUT/BDK/49	Een methoden voor kosten-batenanalyse voor automatiseringsprojecten bij de overheid **M. van Genuchten, F. Heemstra, R. Kusters**
EUT/BDK/48	Innoveren in technologie-gedreven ondernemingen, bedrijfskundige aspekten van de voorontwikkelfunktie **W.H. Boersma**
EUT/BDK/47	The creation of a research model for estimation **M. Howard**
EUT/BDK/46	Het 80 flat square project; Een case studie als aangrijpingspunt voor lerend innoveren **J.I.M. Halman, J.A. Keizer**
EUT/BDK/45	Interface design for process control tasks **T.W. van der Schaaf**
EUT/BDK/44	Afzetfinanciering **S.G. Santema**
EUT/BDK/43	Het gebruik van natte (industriële) bijproducten in de varkenshouderij; Een verkenning van de Nederlandse situatie **Mat. L.M. Stoop**
EUT/BDK/42	An integral approach to safety management **T.W. van der Schaaf**
EUT/BDK/41	De produktie van varkensvlees; Een integrale ketenbenadering Deelrapport 1: Enkele modellen voor de varkenshouderij **A.J.D. Lambert**
EUT/BDK/40	Informatievoorziening ten behoeve van klantenorder-acceptatie; een eerste verkenning **F.J. Faszbender**
EUT/BDK/39	A bibliography of the classical sociotechnical systems paradigm **F.M. van Eijnatten**
EUT/BDK/38	Meten van kwaliteit van Nederlandse instrumentatie op basis van ontwerpgerichte toepassingsaspekten **F.M. van Eijnatten**
EUT/BDK/37	De toepassing van vaardigheden bij de specificatie van het bewerkingsvoorschrift **D.R. Muntslag**

Eindhoven University of Technology
Graduate School of Industrial Engineering and Management Science

P.O. Box 513
5600 MB Eindhoven, The Netherlands
Telephone 31-40-472873