A Systematic Approach to Design of Process Displays

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Ph.D. Thesis

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Preface

This thesis is a result of a Ph.D. study which was performed as an industrial Ph.D. project supported by the Danish Academy of Technical Sciences. The overall goal was to bring display design theories closer to industrial practice and to propose new visualisation techniques. Three partners were involved: the Danish software house, Seven Technologies A/S, the Department of Automation from the Technical University of Denmark and the Systems Analysis Department from Risø National Laboratory.

The author was an employee of Seven Technologies A/S and worked full-time on the project, spending approximately 50% of the time at Seven Technologies, 25% at the Department of Automation, and 25% at the Systems Analysis Department. The project was initiated in March 1996.

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Lejre, March 31, 1999

Rud Pedersen

Abstract

The aim of this thesis is to develop methods for display design that can be used by the industry and to create new visualisation techniques. The display design problem is analysed in two situations: 1) when existing display solutions can be reused and 2) when new visualisation techniques must be created. A display design method and new visualisation techniques are proposed and guidelines for creating new visualisation techniques are outlined.

To be used by the industry, a display design method must consist of an analytical approach close to industrial practice and it should be possible to use the method without a comprehensive study of display design theories. Naturally, the more knowledge the display designer has about the problems involved, the better the foundation for making suitable displays. However, industrial display designers seldom use the display design theories in practice. Only in high-risk plants, such as e.g. nuclear power and some chemical plants, specific analysis and design methods are used in the development of process displays. It is believed that one reason is that different aspects of display design are covered in different theories and at an academic level far from the everyday problems faced by the industrial display designers. Therefore, an aim of this work is to bring the display design theory closer to industrial practice.

A framework comprising the aspects of operator tasks, display content and the form of the display is proposed as a means to systematically analyse and structure display design as a process. One advantage of this approach is that design solutions and problems are made explicit.

Within this framework, a design method supporting reuse of design solutions and which is close to industrial practice is developed. Based on the experiences from creating new visualisation techniques for case studies, the problems revealed are positioned in the framework. Information types found in process displays, basic visualisation techniques (graphical modalities), visual dimensions and gestalt principles are brought together in an attempt to give guidelines on how given information can be mapped into a form, i.e. guidelines for creating new visualisation techniques. Existing and new displays are categorised according to the framework.

The case studies have been made on power and water treatment plants. New supervisory displays are developed for both cases and a production optimisation display is made for water treatment plants. Prototypes of a majority of the displays have been made and their functionality have been assessed based on scenarios with process data from the plants. The optimisation display has been set up at a water treatment plant and comments from users are provided. The new visualisation techniques are generic and can be used on different types of process plants.

The possibilities and limitations of display design theories are studied. An attempt is made to bring the theories together, to structure them according to the framework proposed, and to bring them closer to industrial practice of display design.

Resume

Formålet med dette phd-arbejde har været at udvikle metoder til displaydesign, som kan bruges i industrien samt at udvikle nye visualiseringsteknikker. Displaydesign-problemet er analyseret i to tilfælde: 1) når eksisterende displays kan genbruges og 2) når det er påkrævet at udvikle nye visualiseringteknikker. En displaydesign-metode og nye visualiseringstekniker er udviklet og retningsliner for tilblivelse af nye visualiseringteknikker er skitseret.

For at blive brugt i industrien må en displaydesign-metode indeholde en analytisk tilgang som er nær industriens fremgangsmåde og det skal være muligt at bruge designmetoden uden et indgående studie af displaydesign-teorierne. Jo mere viden displaydesigneren har om de involverede problemer desto bedre er baggrunden, naturligvis, for at udvikle brugbare displays. Industrielle displaydesignere benytter sig sjældent af viden fra displaydesign-teorierne. Kun i høj-risiko anlæg, såsom atomkraftværker og dele af den kemiske industri, benyttes deciderede analyse- og designmetoder ved udviklingen af procesdisplays. Grunden til dette skal, sandsynligvis, findes i at forskellige dele af displaydesign-problemet er behandlet i forskellige teorier og som oftest på en måde langt fra de faktiske problemer som de industrielle displaydesignere kender til. Derfor er et af formålene med dette arbjede at bringe displaydesign-teorierne nærmere industriel praksis.

En rammestruktur, der omfatter operatøropgaverne, displayindholdet og visningsformen, er fremsat som et middel til systematisk at analysere og organisere displaydesign som en proces. En af fordelene ved denne tilgang er, at designløsninger og -problemer bliver eksplicit.

Indenfor denne rammestruktur er der udviklet en displaydesign-metode, der understøtter genbrug af designløsninger og som er nær industriel praksis. Baseret på erfaringer fra udvikling af nye visualiseringsteknikker, som er opnået udfra case studies, er problemerne heri tydeliggjort og placeret i rammestrukturen. Informationstyper i procesdisplays, grundlæggende visualiseringsteknikker (grafisk modaliteter), visuelle dimensioner og gestalt-principper er inddraget i et forsøg på at udvikle retningliner for hvordan given information kan præsenteres i bestemte visningsformer, dvs. retningsliner for udvikling af nye visualiseringstekniker. Eksisterende og nye displays er kategoriseret i henhold til rammestrukturen.

Case studies er udført på kraftværker og på rensningsanlæg. Nye overvågningsdisplay er udviklet for begge anlæg og et display til produktionsoptimering er udviklet til rensningsanlægene. For størstedelen af de nye displays er der udviklet prototyper og deres funktionalitet er blevet vurderet udfra fra scenarier med procesdata fra anlægene. Produktionsoptimerings-displayet er installeret på et rensningsanlæg og brugernes kommentarer er givet. De ny udviklede visualiseringsteknikker er generelle og kan anvendes på andre typer procesanlæg.

Mulighederne og begrænsningerne af displaydesign-teorierne er undersøgt. Der er gjort et forsøg på at sammenstille teorierne, at organisere dem i henhold til den fremsatte rammestruktur og at tilpasse dem til industriel praksis for displaydesign.

Acknowledgements

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The Managing Director of Seven Technologies (7T), Jørgen Nielsen took initiative to start this project and has made it possible through continuing interest and financial support. I am also grateful to Jørgen Nielsen for the very liberal limits he put on the scope and the organisation of the project. Bent Nicolaisen, my supervisory from 7T, was helpful with many advices on programming the prototypes. I also thank my colleagues at 7T for their help and support throughout the project.

Professor Morten Lind from the Department of Automation at the Technical University of Denmark has been my main supervisor and has been a great help in organising the design theories. Morten Lind has also provided invaluable assistance through numerous discussions and with his excellent knowledge and overview, he often made me look at things in a broader and different perspective. Moreover, his comments have always been very detailed and precise.

Senior scientist Jette Paulsen from the Systems Analysis Department at Risø National Laboratory has also worked as my supervisor. Her practical sense and experience from control rooms have been useful in transforming the theories into practice. Among the people in the System Analysis Department, Steen Weber helped me in getting started with Visual Basic programming and with comments to the prototypes developed.

Michael May, psychologist at the Danish Maritime Institute, has introduced me to Semiotics and taught me a lot about graphical modalities, cognitive support and how the problems in information mapping can be decomposed and approached.

John Paulin Hansen, the head of the Danish Multimedia School SpaceInvaders, was among the people initiating the project and has provided ideas for how new display and multimedia technologies can be used in control rooms, especially 3D visualisation techniques.

Marinus Nielsen from Krüger A/S, a Danish consultant company specialised in design and commissioning of water treatment plants, has explained the processes in water treatment plants and has been helpful in determining the important process variables that should be displayed. Further, Marinus Nielsen has commented the prototypes and given useful ideas to improvement. I would also like to thank Mogens Jensen, the production manager at Sydkysten's water treatment plant, for letting me set up the display in their control room and for commenting the displays.

I would like to thank Professor Yoshikawa from Kyoto University for his interest in the project and for his hospitality during my journeys to Japan. Also thanks to assistant professor Shimoda and the people I met for inspiring discussions and talks.

The figures 4.5, 4.6, 4.8-11and 4.14-16 have been made available from Kim Vicente and Cathrine Burns, thank you. Moreover Kim Vicente has participated in various discussions.

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Chapter 1. Introduction

Contents[1]

This chapter describes the background for the project, its objectives and the delimitation. The important terms used throughout this thesis are shortly defined. A reader's guide is provided before a resume of the work regarding new display technologies is given.

1.1. Rationale

Industrial systems for automatic control

Today automatic control and supervision systems are used in the industry for all kinds of processes. The plant size varies from small control systems involving only a few components to large, plant-wide automated processes with ten-thousands of components. The control system can either be centralised or de-centralised. In centralised plants almost every task is operated from a control room situated far from the production equipment. In de-centralised plants, the production equipment is controlled from panels near the machinery.

Complexity requires systematic design methods

The larger and more complex the plant is the more effort must be put into the design and specification of the plant. In order to solve these complex design problems systematic methods are required. With regard to design of process displays the problem is a lack of design methods, which are directly applicable to industrial practice. Design frameworks, such as cognitive engineering or task analysis exist but they are very abstract, time-consuming to apply and do not match the industrial practice of plant and display design.

Delimitation

In the larger and more complex plants it becomes a problem for the operators to get a good feeling with the operating plant. What is the automation system doing? How is the relationship between components and process operations? What is the purpose of a specific component? Is it used for production or safety? A part of this problem is related to the construction of the plant including the automation system and is not treated in this work. Another part deals with the construction of the information system (process displays) for the operators and is the scope of this work.

The reason for this delimitation is the industrial practice today. Often the physical constructions, including instrumentation and the task allocation between the automation systems and the operators are determined before the task of designing the process displays is initiated. Several companies work together to build or reconfigure a plant. To make responsibilities clear and to ease co-operation such firm divisions of design tasks are made. Hence the starting point for this work is the design of the process displays. Concurrent engineering might be used but it will not be possible to design suitable process displays before the instrumentation and task allocation including control handles to the automation system are determined.

The focus is on how the needed display content is determined and how it can be presented. The issue of organising several display pages, including navigation between the display pages, is not dealt with in detail. Training of the operators are not considered. Knowledge and experience acquisition and how it can be passed on to other operators are also outside the scope of the work.

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[1] The labels on the left of the page are intended to work either as a minor heading for the paragraph if it is written in **bold** or as a resume of the paragraph if written with normal letters.

The mimic diagram, the most widely used process display

The most common way to present information in process displays today is to use mimic diagrams (see Figure 1.1). The mimic diagram is based on the piping and instrumentation (P&I) diagrams, which represents the topological layout of the plant. Dynamic symbols are used to indicate the status of each component or subsystem and occasionally graphs are also embedded into the diagram. Trend curves (showing historic values of process variables) and alarm lists are usually placed in separate windows on the operator's computer screen.

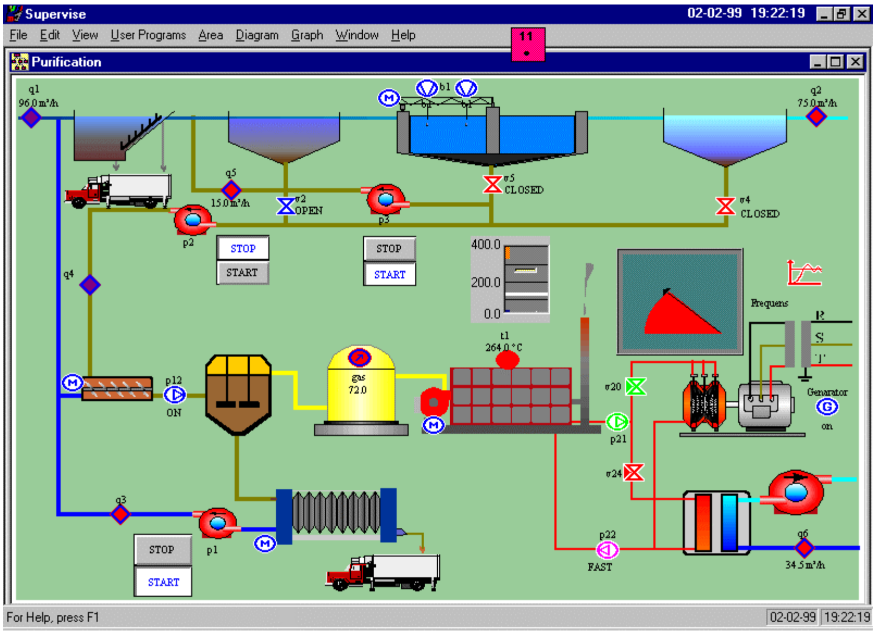

Figure 1.1. A typical mimic diagram (from the IGSS[2] demonstration system).

Display elements

Process display consists of display elements. Display elements are aggregations of several graphical items suitable for a specific display content and a specific operator task. Examples of display elements in the mimic diagram in Figure 1.1 are the pie chart, the buttons for start and stop, the compact trend display (nearly in the middle) and groups of process equipment with instrumentation.

1.2. Core Problems

The mimic diagrams are not enough

There are several problems involved in using the piping and instrumentation diagram as the basis for designing process displays. The main problems are listed below:

- The content of the display is not explicitly considered because the presentation is based on the physical topology of the plant, hence the plant functions and operational goals are not mediated.
- The one-sensor-one-indicator principle is generally used, so the operators have to derive the overall plant state by integrating information from several individual indicators.
- Displays are often designed without explicit consideration of the operator's tasks and information needs.

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[2] IGSS is the SCADA (system control and data acquisition) product developed and marketed by Seven Technologies A/S. IGSS is short for Interactive Graphical Supervision System.

- Only a part of the P&I diagram, which can be fitted into the size of the screen can be shown to the operator.

In order to solve these problems, a systematic approach to display design is necessary. Without such an approach it is impossible to guarantee that all aspects involved are considered.

For the industrial display designer the problem is to build a satisfactory display based on existing display elements without spending too much time on advanced theories for display design. On the other hand the key points from the theories must be known to the industrial display designer in order to make displays, which support the operators in their tasks and match their information needs.

However, the first step is to make the industrial display designers aware of the need for display design methods. Paulsen (1998) have proposed a simple strategy, which helps in illuminating the problems in display design. The strategy consist of the following questions to the display designer: (1) What is the goal of the display? (2) What is the problem in the plant? (3) How does it occur? (4) How is it observed? (5) How to present it? By answering these questions the display designer becomes aware of the problems and is to some extent guided through the display design process. However, the strategy lacks a systematic description of how to tackle the problems encountered when attempting to answer the questions from the strategy.

The overall aim of this work is to make the display design theories more applicable to industrial practice and to provide specific advice on what to do through out the design process. The aspects of display design covered in this work are formulated and specified in the following two sections.

1.3. Objectives

The main objective is to develop methods for systematic design of process displays.

The objective is threefold: a scientific, a development and an application objective as listed below.

Scientific

A scientific objective is to analyse the types of displays developed today with regard to both representation (concepts, content) and presentation (visualisation techniques, form).

Another objective is to reveal which types of representative relations are needed in a display, hence analyse and classify the relations, which are often found in industrial processes.

Development

With regard to development an aim is to develop a design method for process visualisation, i.e. development of visualisation techniques to map the classified representative relations onto the display.

Further guidelines enabling a systematic selection among visualisation techniques should also be developed.

Application

Within the application aspect one of the objectives is to invent new display elements or visualisation techniques and to evaluate which ones are of interest to Seven Technologies to implement in the Interactive Graphical Supervision System (IGSS).

A second application objective is to implement prototypes of promising new visualisation techniques in order to (1) discover the problems involved in a modular design of the software for the display elements and (2) evaluate the display prototypes.

The last application objective is to investigate in which direction the technological development for display systems is moving.

1.4. How the Work Was Organised

Figure A.1 in Appendix A gives an overview

Several topics must be considered to fulfil the objectives above. Appendix A shortly describes the project topics as planned in the beginning of the project together with a comparison between the results expected and the actual results. This is to give an idea of the process and progress of the knowledge acquisition during the project.

Figure A.1 in Appendix A shows the main goals of the project together with the methods used to achieve them. The main methods are theories, especially cognitive engineering, analysis of existing display types, operator interviews, techniques for graphical communication, and new display technologies.

Cases: water treatment and power plants

The process domains analysed in this work are power and water treatment plants. The power plants are complicated with regard to the number of components and subsystems, whereas the chemical and biological process, which is not well-known, complicates the water treatment plants.

1.5. Terminology

Definitions and distinctions between the main terms used in this thesis are given below. Further definitions of some of the terms used in this work to describe the plant entities can be found in Appendix B.

Representation or content ↔ presentation or form

The information on a display can be divided into two aspects, which will be distinguished throughout this thesis: *representation* and *presentation*. Representation is about *what* should be displayed, hence the content and concepts provided by the information on the screen. Presentation deals with *how* the information is shown, in other words the visualisation techniques or the form given to the information on the display. The question of *why* information is shown is answered when it is determined what information the operators needed to perform their tasks.

Building displays ↔ inventing visualisation techniques

A distinction is made between building of a display by using existing display elements and invention of new visualisation techniques or display elements by mapping information types to combinations of graphical modalities, visual dimensions and gestalt principles. The term display design encompasses here both building and inventing displays.

Functions at design time ↔ process operations when plant in operation

The plant is regarded and modelled at design time where the concept of functions is used to describe the plant designer’s intentions. When the plant is in operation, the concept of process operations is used to describe what operations there can made in and on the plant. This distinction has been useful to separate the problems involved in the design of the plant from the problems the operators have to deal with. Further details are provided in Appendix B.

Entities ↔ relations

The informations found in plant descriptions and in process displays are divided into two main categories: entities and relations. Broadly entities are everything found in the description of a process plant except relations. Among the top level entity categories are physical plant items, plant concepts (e.g. states, process operations, functions and goals), magnitudes (numerical values) and events (details are in section 3.3.2.1 Identified Information Types in Process Displays). Relations are the links between the entities, either within a category of entities or between entity categories.

1.6. An Outline of the Thesis, Reader's Guide

This work is aimed at two groups of readers: industrial display builders creating process displays using existing display elements and readers wanting to invent new ways of presenting process information.

Industrial display builder

Section 3.1 resumes the TCF (Task, Content, and Form) design method proposed for industrial design of process displays. More details regarding the TCF design method and the problems involved can be found in Appendix D.

Section 4.20 summarises the analyses of the existing displays and provides an overview of which operator task each display is suitable for.

The interested reader is guided to section 3.3.3. This section describes which of the so-called graphical modalities there can be used to present given information. Graphical modalities are the basic building blocks of process displays. Further it outlines which visual dimensions (means like shape, size, colour, etc.) there can be used to add further information into the graphical modalities. For example, in the graph modality colour can be used to add further information and is often used in trend curves to distinguish several data sets by colour coding.

Chapter 5 describes the development of display elements and visualisation techniques made in this project.

Display inventor

It is believed that a foundation of relevant knowledge and creativity is needed for inventions. The methods available for display design and the problems involved are treated in chapter 2.

The proposed TCF (Task, Content and Form) design method can be used to determine the required display content from analyses of process operations and the operator's task. The TCF method is described in section 3.1 and in details in Appendix D.

Mappings between the display content, i.e. the information types identified in the working domain of process control and the graphical modalities are dealt with in section 3.3. In this section, the visual dimensions and the gestalt principles are also described. In section 3.3.3 the possible combinations between information types, graphical modalities, visual dimensions and gestalt principles are outlined.

Chapter 5 describes the development of display elements and visualisation techniques made in this project.

1.7. The Influence of New Display Technologies

Introduction

This section should be regarded as a source of inspiration and a survey of the possibilities that new technologies bring to the design of process displays. Before the analysis and assessment of the new technologies, the influence of technological improvements is discussed.

The influence of technologies on inventions and improvements

Retrospectively it can be seen how the available technologies have influenced the development of process displays. When the personal computer (PC) got the capabilities to manipulate large amounts of graphics, the first PC-based supervision systems were developed in the mid-eighties. The piping and instrumentation diagrams were ported from conventional mimic panels to computer screens, introducing the problem of navigation between computer screens.

Technology-driven ↔ demand-driven

Ideally new types of displays and visualisation techniques can be made without considering the technology available. On the other hand, in practice it is often the invention of new base technologies, which is the driving force behind an invention or improvement. This has been seen with the PC-based supervision systems. The technology-driven improvements often lack a more systematic and encompassing analysis and assessment of the advantages and disadvantages of the technology. The technology is used simply because it is available. In the process industry this was seen when it became possible to place animations and 3D drawings on the process displays. Nearly every mimic diagram should have an animation of the rotating paddle wheels when the pump is running. Moreover, shadows and 3D effects were placed on the components making it even more difficult for the operators the find the relevant information among the sump of pixels, which do not provide any useful information in the context of operating the plant.

Balancing technology and the real problems

Therefore a balance between the available and coming technologies and the actual problems of the process operators must be established. For that reason a survey of the new technologies for process displays was made early in this study. Details of the survey made in 1996 can be found in Appendix C. The conclusions are given in the following.

1.7.1. A Survey of New Display Technologies

A study of multimedia, virtual reality, new interaction methods, and new display devices in the control centres for industrial processes was done in December 1996.

Multimedia

Storage and exchange of larger amounts of data

Tools for data searching and filtering will be needed

From the survey in Appendix C it is concluded that multimedia in the form of video and sound soon will be seen in supervisory systems. Furthermore, the possibility of data distribution on media such as digital videodiscs (DVD) will result in larger and more complex databases. These databases will besides plant data contain component specifications, videos and tutorials for maintenance of components, documentation for hardware and software implementation, production plans, energy plans, etc. Different groups of employees will need to access different parts of the data and to exchange information through these databases. The interface to this huge amount of data will be provided by personal computers and probably as an integrated part of the SCADA system, as it contains the interface to the process data today. This means that new tools for searching and filtering together with tools for building and maintaining the databases will be required.

Virtual reality

Virtual reality (VR) is still in its early phase of development (1996) and is expected to develop from design applications to learning by doing and data exploration in virtual worlds within the coming years. From there on it might be used for remote control where the operators act on the artificial world and eventually virtual reality might be used as complete user interfaces. The most interesting use of VR in process control is for data exploration, which might give better visualisation of the correlation between process variables. Another possibility is training of maintenance staff in virtual environments.

Possibilities for interaction

Gestures and speech recognition

Interactions between human and computer are developed in two main directions: video recordings of gestures (including facial expressions) and speech recognition. Both technologies are far from being applicable in industrial control rooms. However, it should be possible to develop prototype systems for navigation on computer screens or in virtual worlds by use of simple hand movements. The problems with the existing prototype systems for speech recognition are that they can only understand a limited vocabulary spoken very clearly and it seems to take a while before better systems will appear.

Display devices

Large screens, touch screens and flat displays

Display devices comprise large screens, touch screens, and flat displays. Large screens are available on the market today (1996), but are presently so expensive that they will only be affordable in large-scale industries. Moreover, they are only useful if several operators have to work as a team to run the plant.

The response time of touch screens has been reduced making them a viable choice as input device. Evaluation by Toshiba Corporation (Kawano et. al., 1996*)* has shown that operators did not have any problems in using the touch screens.

Flat displays do not give new functions compared to CRTs, but takes up less space and power.

Chapter 2. Theories

Contents

In this chapter the theories from cognitive engineering, semiotics, gestalt psychology, and task analysis are described and assessed with regard to the problem of designing process displays.

Why study cognitive engineering?

The weighting between the theories is indicated by the sequence above. The reason to focus on cognitive engineering is that it is, to the author's knowledge, the only framework for design of process displays that apparently deals with both representation and presentation. In addition, the Ecological Interface Design (EID) approach was developed based on cognitive engineering and within the domain of process control. Therefore, cognitive engineering seemed appropriate to achieve a deeper understanding of the problems described in chapter 1 and EID looked promising for designing new process displays.

Rationale for looking at semiotics, visual dimensions and gestalt principles

Semiotics was brought into the project as a supplement to EID, as it turned out that EID did not provide the required details for structuring and inventing new visualisation techniques. A minor study of semiotics has been made in order to get an overview of possible visual dimensions and to structure the graphics used in existing displays. The gestalt principles were studied as a means to clarify the influence on perception when several visual dimensions are combined.

How task analyses are used

Task analyses were studied to obtain methods to select the information the operators need to perform their tasks. Different methods are surveyed in Kirwan and Ainsworth (1992), but none of them are used explicitly during the design of process displays in the two case studies in the present project, due to the time required to make such task analyses. Instead, they were used as background information to clarify different aspects of the operator's tasks.

2.1. Cognitive Engineering

Content in this section

The background and the different starting points for the development of cognitive engineering is given. The basic problem is illustrated by a simple example. Human behaviour models and the problem of information interpretation are outlined. The decision ladder and the abstraction hierarchy are described before a review of multilevel interfaces, which are interfaces based on the abstraction hierarchy.

2.1.1. Background and Starting Points

Who introduced it and when?

Cognitive engineering came into existence in the 1980s. Donald Norman and the Electronic Department at Risø National Laboratory including Eric Hollnagel and led by Jens Rasmussen introduced and defined the term.

What is it?

Cognitive engineering is the interplay between cognitive psychology and engineering design. Cognitive engineering does not regard technical systems alone, isolated from their environment and users. It includes the human beings interacting with the technical system in the system description.

What can it do?

Cognitive engineering can be used to analyse, design and evaluate complex socio-technical systems.

Starting points

Norman and Rasmussen had different backgrounds and different starting points for developing cognitive engineering. The starting points are important in order to understand the results obtained by Norman and Rasmussen. In this thesis the results are assessed with regard to the problem of designing process displays.

Norman's starting point

Donald Norman worked as a professor at University of California, San Diego (UCSD) doing research about everyday things, their functionality and use. Norman uses among others doors, refrigerators and kitchen ranges as objects for studying their use and how the design can be improved.

Rasmussen's starting point

Rasmussen used two case studies. One where technicians were to locate failed (electrical) components in electrical units. A result from this study was an analysis and identifications of human strategies during diagnosis (Rasmussen, 1986). Moreover, the abstraction hierarchy, as a means of structuring information supporting the human behaviour during problem solving, took shape. Furthermore three different behaviours of cognitive control were identified. The other case study was recordings of verbal protocols of skilled operators during a start-up of a power plant. The decision ladder, describing human information processes during decision making in process control, developed from this work.

2.1.2. Designing for Humans

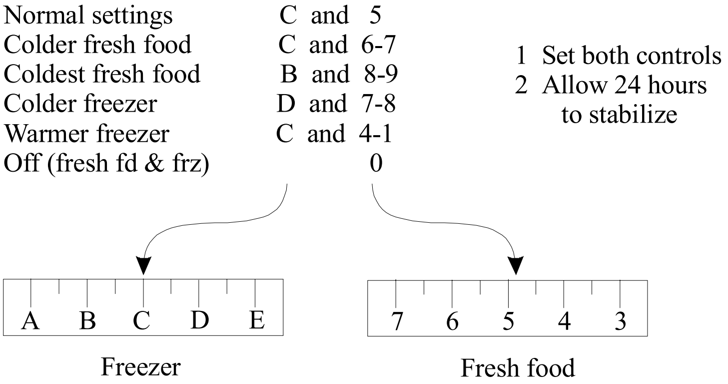
An example is used to illustrate the problems involved in designing for humans. The main problem is explicitly stated together with a rationale for cognitive engineering. Then follows a description of the gulfs of execution and evaluation.

2.1.2.1. What is the Problem?

Norman's refrigerator example

The following example is taken from Norman (1988) and illustrates the problems involved in making an intuitive and understandable user interface.

The user interface for a two-compartment refrigerator is shown in Figure 2.1. It has two controls and a short textual instruction. Suppose the freezer should be warmer and the temperature of the fresh food compartment should be the same. How should the controls be manipulated to achieve this?



Normal settings	C	and	5
Colder fresh food	C	and	6-7
Coldest fresh food	B	and	8-9
Colder freezer	D	and	7-8
Warmer freezer	C	and	4-1
Off (fresh fd & frz)			0

1 Set both controls
2 Allow 24 hours
to stabilize

Figure 2.1. The user interface for a two-compartment refrigerator (from Norman, 1988).

From the form of the user interface one would immediately think that the left control should be adjusted to make the freezer warmer and the right control for the fresh food compartment should be untouched. When looking at the interface, a model of the system is created in the user's mind. The user's mental model as gleaned from the user interface is shown in Figure 2.2.

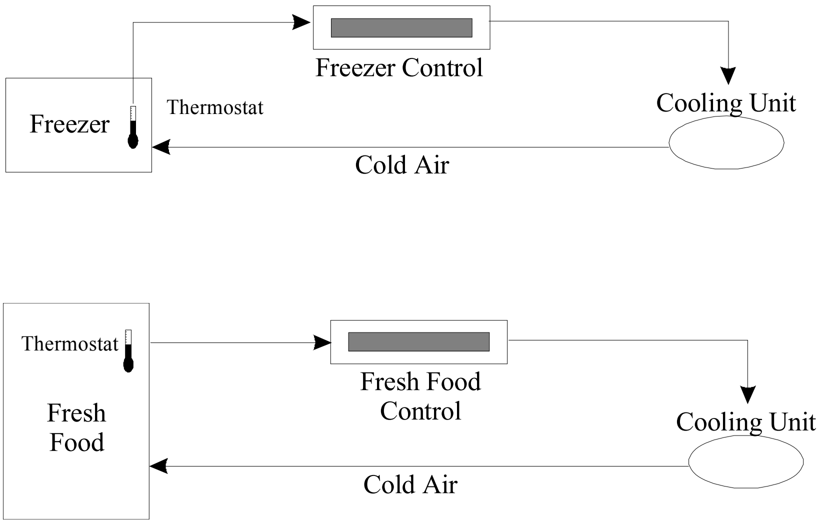


Figure 2.2. The user's mental model of the refrigerator as derived from the interface (from Norman, 1988).

The correct model for the refrigerator is shown in Figure 2.3. From this model it is obvious that the controls for the freezer and fresh food compartment are not independent and both controls must be adjusted to make the freezer warmer and to keep the temperature in the fresh food compartment.

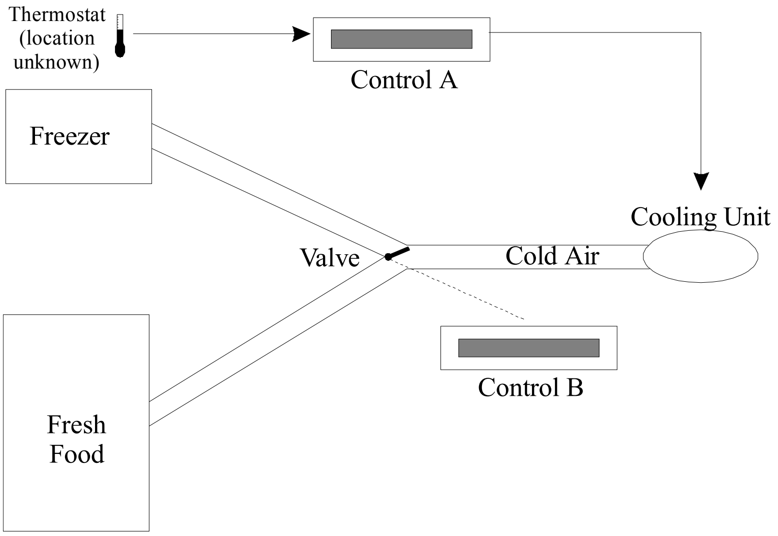


Figure 2.3. Correct mental model of the refrigerator. The freezer and fresh food controls are not independent (from Norman, 1988).

What the example showed

The example illustrated how a user interface can lead the user to a mental model of the system, which is inconsistent with the actual construction. The actual construction is made from the designer's model of the system. When such an inconsistency occurs, due to a badly designed interface, it becomes difficult for the user to get the system to act according to the user's intentions. The interaction with the system becomes difficult and at times frustrating.

Main problem

The main problem is to avoid an inconsistency between the user's mental model of the system and the system image, i.e. the actual physical model of the system. This is outlined in Figure 2.4.

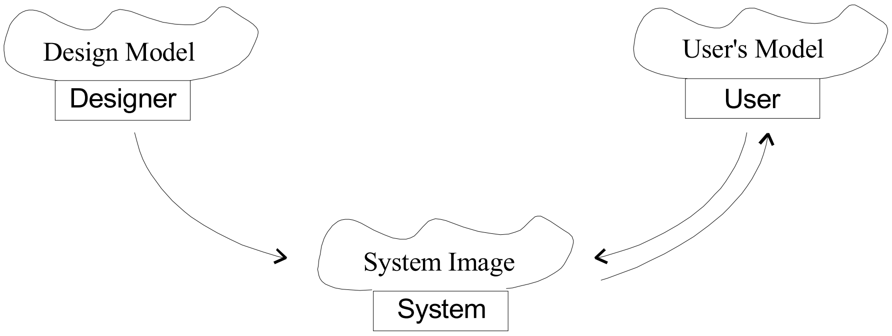


Figure 2.4. Norman's conceptual models. The design model is the designer's conceptual model. The user's model is the mental model of the system developed from the user interface and through interaction with the system. The system image results from the physical structure that has been built (from Norman, 1988).

Rationale for cognitive engineering

When a designer creates a user interface, which leads the user to a wrong model of the system it is because the designer's understanding of the user is insufficient. The rationale behind cognitive engineering is therefore to integrate knowledge about the user's behaviour in the design process. Therefore, an interplay between engineering design and cognitive psychology is required when designing for humans.

2.1.2.2. Gulfs of Execution and Evaluation

Intentions and control handles

Norman (1988) distinguishes between intentions and control handles. The user's intentions are expressed in the mind as wishes and needs. The control handles are intervention points on the physical objects that the user must manipulate in order to achieve the intentions.

The gulfs of execution and evaluation

Having a specific intention in mind the user must act in an attempt to fulfil the intention and then evaluate the outcome of the actions to see if the intention is obtained. This is the gulf of execution and evaluation as shown in Figure 2.5. In order to communicate with the system, the user's intentions must be transformed into a plan of action sequences needed to fulfil the intentions. The action sequences must then be executed using the control handles (intervention points) that the system provides. The system's response to the actions should be visible to the user. The user must perceive the changes in the user interface and interpret what the changes signify before it is possible to evaluate if the intentions are achieved.

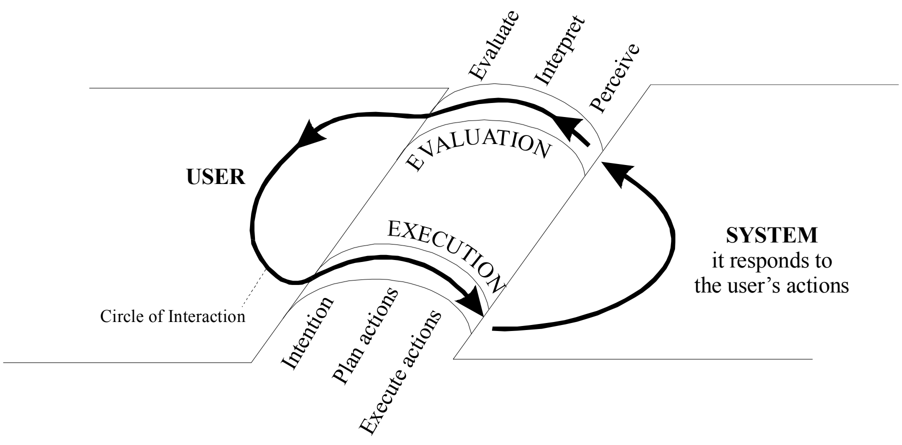


Figure 2.5 The gulfs of execution and evaluation (adapted from Norman, 1988).

It is the user who must cross the gulfs!

Notice it is the user who has to cross the gulfs of execution and evaluation, i.e. usually the user cannot change the control handles or the response from the system. In other words, once the system is made the user have to live with it as it is, because usually the system's control handles and response can not be reconfigured. For execution the user must transform the intentions into actions the system understands and for evaluation the system's response must be interpreted. Well-designed systems narrow the gulfs by proving an interface that matches the user's "language" of intentions and evaluations.

2.1.3. Human Behaviour Models

Models of human behaviour can either be quantitative or qualitative (Rasmussen, 1986, page 61-63).

Quantitative models

Quantitative human behaviour models are based on experimental psychology on individual subjects. When a result can be reproduced on several other individuals, the result is generalised and regarded as valid for all persons belonging to the context of the experiment.

Quantitative models of humans describe the sensori-motor behaviours.

Qualitative models

Qualitative models are based on generic behaviour of people. Humans are studied and the observations of their behaviour are compared and grouped together. In this way, groups or categories of human behaviour appear.

Rasmussen's qualitative model

From the study of the technicians locating failed electrical components Rasmussen identified the following three categories of human behaviour during diagnosis:

- Skill-based behaviour
- Rule-based behaviour
- Knowledge-based behaviour

Below are definitions and explanations of the different categories of behaviour. The definitions are quoted from Rasmussen et. al. (1994, page 107-111).

Skill-based behaviour

"[skill-based behaviour is] control of activities [that] require on-line, real time control based on tacit knowledge that cannot be described by the actor. It depends on interaction with the temporal-spatial configuration of objects that can be real material objects or configural representations of concepts."

That is acts done instinctively. Examples are bicycling or using a mouse for navigation in a software application.

Rule-based behaviour

"[Rule-based behaviour is] generation of proper organisation of patterns of movements (i.e. acts) into plans depending on access to stored rules and to experience from past work scenarios. The planning is done ahead of the action, that is, it is not synchronised with the interaction and is based on recall of past experiences and imagination of future encounters. It depends on the availability of convenient cues to release acts, cues that are only conventional signs with no functional significance."

Rule-based behaviour takes placed when a problem occurs and the solution is well known. For example, an alarm occurs in a process display and the operator knows (from experience or training) that a specific component must be manipulated.

Knowledge-based behaviour

"[Knowledge-based behaviour] is based on a symbolic, mental model representing the deep, internal sources of regularity of the behaviour of the work environment, and information is interpreted symbolically with reference to this model."

Knowledge-based behaviour is performed when a problem arises and a solution is not known. The available information sources together with knowledge of the system dynamics are used to solve the problem. Following the example from rule-based behaviour an alarm occurs and the operator does not know what to do. By investigation e.g. the mimic diagrams and knowing the functionality of the displayed components, the operator might be able to induce the solution and manipulate the right component.

2.1.4. Interpretation of Information

Rasmussen (1986, page 103-108) distinguishes between three different ways in which the same information, having the same form, can be interpreted. Moreover, the way the user interprets the information depends on the user's context. This will be described by an example after the definitions and a discussion of the types of interpretation of information.

2.1.4.1. Signals, Signs and Symbols, Definitions and Discussions

In the following the words sign and symbol will refer to the meaning of the words as derived from Rasmussen's definitions. Later on in section 2.3 it is seen that the theory of semiotics put other meanings into the same words.

Information can be interpreted as signals, signs, or symbols as defined by Rasmussen. The definitions are quoted and commented in the following.

Signals
in skill-based behaviour

"Signals are sensory data representing time-space variables from a dynamic, spatial configuration in the environment, and they can be processed by the organism as continuos variables." (Rasmussen 1986, page 108).

Signals inform about plant performance

Signals in the definition above refer to visual data received by human perception and the following cognitive behaviour (it is not electric signals from plant sensors).

From the definition of signals given here and from the definition of skill-based behaviour (on page 13), it is not obvious what the interrelation between signals and skill-based behaviour is. An interpretation could be that the operator is in the control loop and instinctively adjusts a set point by moving a slider while reading the value of a process variable on the screen.

Intervention points needed in skill-based behaviour

A distinction between intervention points for the operators and the presentation of the plant situation is useful. The reason is that skill-based behaviour according to Rasmussen's definition is related to the operator activities and therefore involves intervention points. The intervention points are adjusted instinctively based in the interpretation of the plant situation, which is made from the visual appearance of the plant situation on the operator's screens.

Signs
in rule-based behaviour

"Signs indicate a state in the environment with reference to certain conventions for acts. Signs are related to certain features in the environment and the connected conditions for actions. Signs cannot be processed directly; they serve to activate stored patterns of behaviour." (Rasmussen 1986, page 108).

Signs are related to response from executed actions or to possibilities for actions

Notice how signs are related to actions of the operator. For example the colour coding of pump and valve symbols as seen in mimic diagrams are signs where the colour of the symbols indicate what actions have been made on the system.

Other signs are related to the possibilities for action. Another example of use of colour coding is when the operator knows that a blue pump symbol indicates that the pump is interlocked from another process operation. In the ecological interface for the Duress system (see section 2.2.2) the seesaw construction is a sign mediating the physical constraints of the system, i.e. the operator can figure out what will happen if e.g. the water level is increased.

Symbols
in knowledge-based behaviour

"Symbols represent other information, variables, relations, and properties, and can be formally processed. Symbols are abstract constructs related to and defined by a formal structure of relations and processes, which by conventions can be related to features of the external world." (Rasmussen 1986, page 108).

Symbols are related to plant entities

Symbols are used to represent the plant entities. The relationship between the entities can be presented by different graphical modalities, for example, diagrams or graphs. The symbols representing the entities are embedded into the graphical modalities mediating relations. (See section 3.2.3 for details on information types and graphical modalities).

The mimic diagram supports skill, rule and knowledge-based behaviour

In a mimic diagram, standard symbols representing the plant components are embedded into the nodes of a conceptual diagram, i.e. a diagram focusing on the relation between the nodes and not the size, orientation or position of the nodes. The conceptual diagram mediates the relations between the components, i.e. the topological layout. In addition colour coding is used to present the state or status of the components. Finally, each component can be controlled directly on the interface, that is the symbols representing the components also work as intervention points for operator actions.

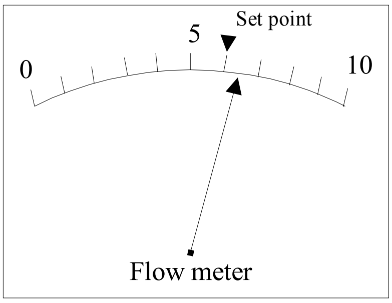
This means that the mimic diagram, according to Rasmussen's definitions, supports skill, rule and knowledge-based behaviour. However, the high level relations between plant goals and process operations have to be derived by the operator, either from experience or by training, because only the low level relations between plant components are visualised.

2.1.4.2. User's Intentions and Interpretation

Interpretation depends on the user's intention, not the form of the information

According to Rasmussen (1986) humans interpret information differently depending on their intentions and expectations. That is, the same information presented in the same form might be interpreted differently depending on the context in which the user operates.

An example from Rasmussen (1986, page 107) shows how the same indicator of a flow can be interpreted as a signal, sign or symbol, see Figure 2.6.

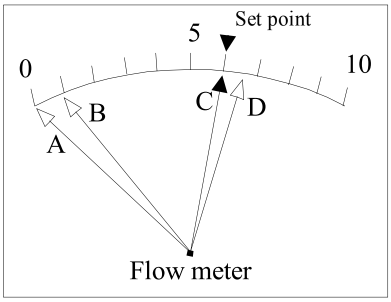


Signal (Skill-based behaviour)

- Keep at set point

- Use deviation as error signal

- Track continuosly

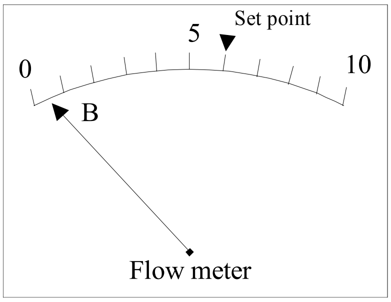


Sign (Rule-based behaviour)

Stereotype acts:

If valve open, and
if indication C: ok
if indication D: adjust flow

if valve closed, and
if indication A: ok
if indication B: calibrate flow meter



Symbol (Knowledge-based behaviour)

If, after calibration, indication is still B, read flow and think functionally (could be a leak)

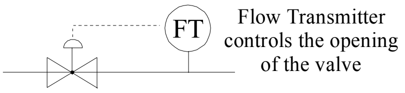


Figure 2.6. The same indicator can be interpreted by a process operator as a signal, a sign or a symbol depending on the circumstances (from Rasmussen, 1986).

Notice that the signal only supports skill-based behaviour if it is possible for the operator to act on the indicator, i.e. to adjust the flow set point. Moreover, the indicator does not provide any means for bringing the measured flow to the set point, i.e. an intervention point to the valve or the automatic controller is missing.

2.1.5. The Decision Ladder

What is it?

A framework for cognitive task analysis in decision making

The decision ladder is a framework for cognitive task analysis. It is a generic model of the human information processes that take place during decision making in process control. The decision ladder does not describe the process of real-time decision making, but describes the logical relationships among states of knowledge involved in a decision making process (Rasmussen, 1986, page 5-12). Moreover, the decision ladder does not describe how to make a decision, but it explicates what process operators might be doing during supervision of a process plant.

It is based on verbal protocols from operators running a power plant during a start-up

The decision ladder consists of information processing activities and states of knowledge. Based on verbal protocols from operators running a power plant during start-up the information processing activities and states of knowledge shown in Figure 2.7 were derived. The activities and knowledge states are defined as genericly as possible to make the decision ladder flexible and thereby applicable to other tasks and working domains than process control.

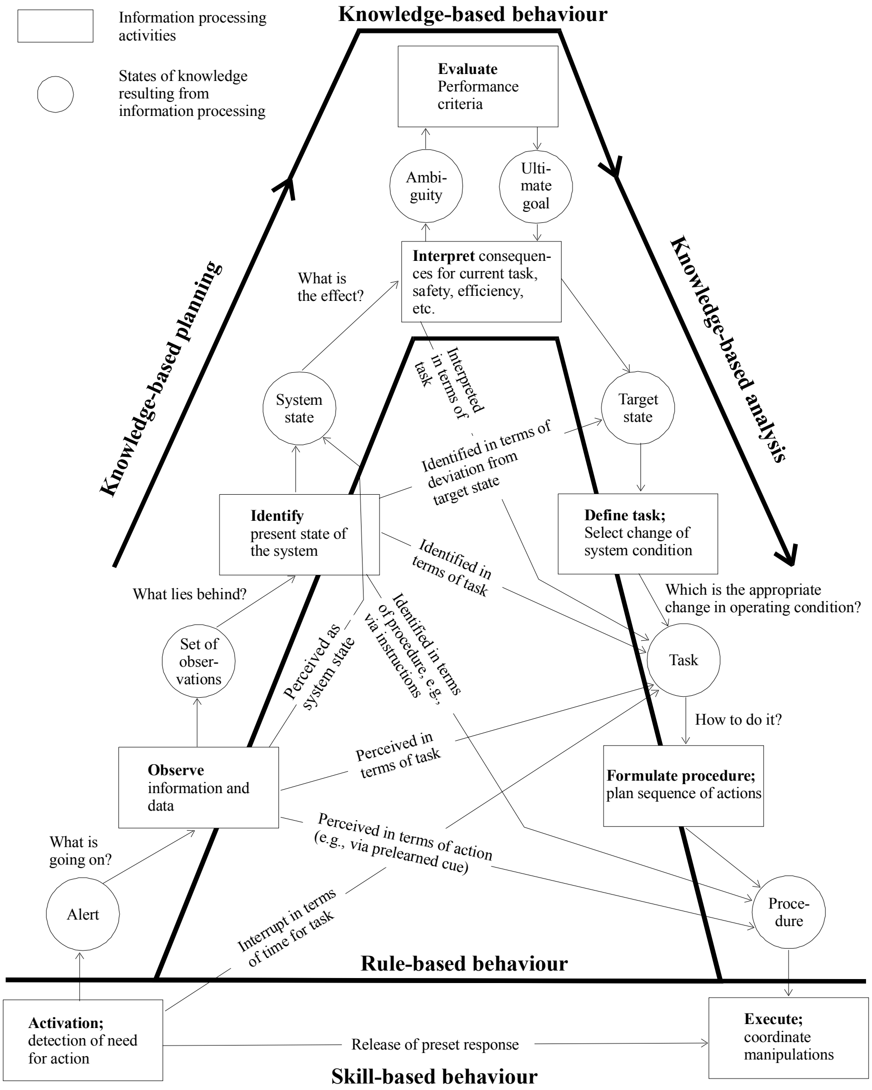


Figure 2.7. The decision ladder derived from verbal protocols of power plant operators during start-up. Shortcuts are shown and related to skill, rule and knowledge-based behaviour of humans (from Rasmussen, 1986).

Shortcuts are often made in decision making

Shortcuts between an information processing activity and a state of knowledge are also shown in Figure 2.7. Often the problem is identified or a solution is known without using all the steps of the ladder. The different paths between activities and knowledge states can be related to the three different modes of human behaviour as indicated in Figure 2.7.

Comparison to the gulfs of execution and evaluation

Notice the similarity between the activities in the decision ladder and the steps across the gulfs of execution and evaluation. The left leg of the decision ladder corresponds to the gulf of evaluation and the right leg to the gulf of execution. The decision ladder is more detailed in the level of activities, but in general the decision ladder and the gulfs of execution and evaluation describe the same, namely the cognitive steps involved in human interaction with technical systems.

The starting point for the decision ladder is that the system alerts the user who then has to decide what to do. In the descriptions of the gulfs of execution and evaluation, the focus is often on the user's intentions and how they can be transformed into system actions and on how the system's responses are interpreted. But the circle of interaction between the user and the system (see Figure 2.5 on page 13) can in principle start anywhere.

2.1.6. The Abstraction Hierarchy

The abstraction hierarchy is also called the means-ends hierarchy, because one of the dimensions in the abstraction hierarchy deals with means and ends.

What is it?

The abstraction hierarchy is a goal-oriented framework for knowledge representation

Rasmussen (1986) proposes the abstraction hierarchy as a framework for representing knowledge of a working domain. The fundamental principle of the abstraction hierarchy is that it is goal-oriented. That is, been at one level of abstraction the next higher level answers the question of why do these entities exist in the system. Moving down one level answers the question of how the entities are realised. That is the causal relations of the system described are represented in the abstraction hierarchy.

Mean-end and part-whole dimensions

Besides the means-ends dimension of different levels of abstractions the abstraction hierarchy also has a part-whole dimension, which is aggregation or decomposition of entities within one level of means-end abstraction. Hence the abstraction hierarchy is two-dimensional as illustrated in Figure 2.8. The five abstraction (means-ends) levels shown are the ones that Rasmussen (1986), Vicente and Rasmussen (1990) and Vicente (1992a, 1992b) find appropriate in the domain of process control.

The information content of the five means-ends levels is listed below (Rasmussen, 1986).

- **Functional purpose**, i.e. production flow models, system objectives, constraints, etc.
- **Abstract function**, i.e. causal structures: mass, energy and information flow, topology, etc.
- **Generalised functions**, i.e. “standard” functions and processes: feedback loop, heat transfer, etc.
- **Physical functions**, i.e. electrical, mechanical, chemical processes of components and equipment
- **Physical form**, i.e. physical appearance and anatomy; material and form; locations, etc.

The division of the part-whole axis into system, subsystem and component is an example used by Bizant and Vicente (1994). Other perhaps more detailed divisions might be appropriate for other modelling tasks. Vicente (1992a) argues that the diagonal structure as illustrated in Figure 2.8 is common.

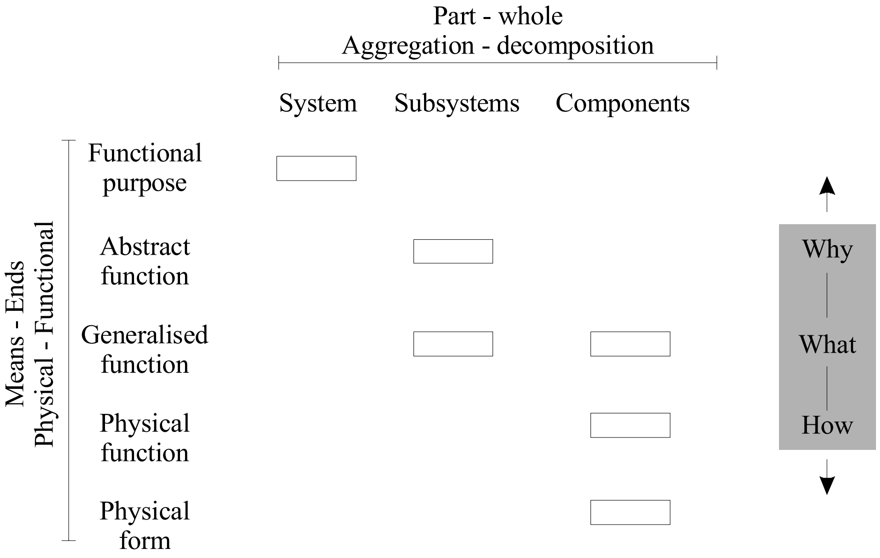


Figure 2.8. The two dimensions of an abstraction hierarchy. The five levels of abstraction often used in process control are shown with three divisions of the part-whole axis. The number of abstraction levels and number of divisions are merely examples, others may be more useful depending on the modelling task (adapted from Bisantz and Vicente (1994) and Rasmussen (1986, page 22)).

The benefits of the abstraction hierarchy

Bisantz and Vicente (1994) mention the following benefits of using the abstraction hierarchy as a knowledge representation framework:

- sufficient representation is provided to allow reasoning about unanticipated faults and control situations,
- reasoning mechanisms that are independent of domain information can be used, and
- it has psychological relevance.

The abstraction hierarchy is for unanticipated events

From the first benefit it can be established that the abstraction hierarchy is relevant for the operator tasks dealing with unanticipated events (disturbance handling). If the purpose of the display is another task, e.g. production optimisation, the abstraction hierarchy might not be relevant.

The second benefit is related to the development of computerised decision-making systems and it can be relevant for the task of designing process displays supporting decision making. However, this has not considered in this work.

The third benefit is based on Rasmussen's case study with the technicians, which indicated that the structure of the abstraction hierarchy is similar to the strategy human beings follow in diagnosis.

Design ↔ production

Notice that the abstraction hierarchy is oriented towards the design goals of the plant as opposed to operational goals. The design goals deal with the needed functionality in order to achieve the overall production and safety goals. The design goals are related to the process equipment including the automation system. Operational goals are the goals that the operators have to achieve, e.g. to produce a specific quantity per day. The operators use the process operations provided by the functionality of the process equipment to achieve the operational goals.

For tasks such as production optimisation and planning and scheduling of production, the operator does not have to know the details about the intended functionality of the equipment as long as it fulfils its design goals. That is the operator can focus on the plant processes rather than on the equipment. In the case of disturbance handling, knowledge about the causal relations between plant goals, functionality and equipment is required. The abstraction hierarchy is a means to structure this information required for the task of disturbance handling.

Difficulties with the abstraction hierarchy

In general, the abstraction hierarchy is useful as a framework for structuring information by use of abstractions. However, a specific design method for creating an abstraction hierarchy for the task at hand is missing. It appears to be difficult to find and extract the information needed to create an abstraction hierarchy from the plant documentation. A central question is whether the information related to plant purpose and functions, in fact, is documented in such detail that it is directly applicable in the abstraction hierarchy. Often the information does not exist and have to be generated from a detailed study, e.g. a system analysis. Lind (1999) deals with various difficulties concerning the abstraction hierarchy in details.

The abstraction hierarchy used in current process display design is discussed in section 2.2.1.1 as a part of the theoretical foundations for ecological interface design.

The considerations made to the use of abstractions in this work are described in section 3.2 dealing with the concept of abstraction in a wider sense and its usability in designing process displays.

2.1.7. Multilevel Interfaces

What is it?

The term covers different approaches to interface design, which are related to the abstraction hierarchy and to the integration of the plant's functionality into the display. Moreover, most of the displays are developed within the tradition of cognitive engineering.

Multilevel interfaces are regarded as a part of cognitive engineering because of their relation to the abstraction hierarchy. Vicente introduces the term multilevel interface in his two companion articles (Vicente, 1992a and 1992b). The first article reviews existing multilevel interfaces and the second proposes a preliminary design space for such interfaces. A resume of the articles follows. Later in section 3.4, the design space will be used as a reference for positioning the framework developed in this work.

2.1.7.1. Existing Multilevel Interfaces

Summary of an integrative review

Broadly MFM[3]-based interfaces (e.g. Goodstein, 1985), the rankine cycle display (Beltracchi, 1994) and the ecological interface for Duress (Vicente and Rasmussen, 1990) are regarded as multilevel interfaces. The interfaces are shown in chapter 4. Vicente (1992a) gives an integrative review of multilevel interfaces and concludes:

- "Multilevel interfaces can provide better support for knowledge-based problem solving than a more traditional interface format" (based on a comparison between a conventional mimic diagram interface and the ecological interface for the Duress system (which is described in section 2.2.2).

---

[3] Multilevel Flow Modelling (Lind 1990, 1994)

- "There is no hard evidence to guide control room designers in developing effective multilevel interfaces based on the abstraction hierarchy".
- "Subjects preferred to think about systems in physical terms at the level of components. Despite this difficulty, however, subjects in both studies [of MFM-based interfaces] tended to use the top-down strategy that the abstraction hierarchy is meant to support."

Only the diagnosis part (disturbance handling) is considered in the studies of multilevel interface. The task of controlling the plant, that is the operator's interaction with the plant through the interface, is not treated in any of the studies. The question from Vicente (1992a): "at what level of abstraction does the operator have to control the system?" remains to be investigated.

Further it is questioned whether the symbols used in MFM to represent abstract functions are the best to show in the interface. Both the original MFM symbols and the symbols based on the hour glass metaphor (Lind, et. al., 1989) seemed difficult to comprehend and remember. Different kinds of symbols are briefly discussed in section 2.3.1.2 on page 32.

2.1.7.2. Vicente's Design Space

Design dimensions

display content, window system, display form, and interaction

From Vicente (1992b) the design space for multilevel interfaces is summarised. The design space has four dimensions as shown in Table 2.1. The first dimension deals with the display content, which is structured by an abstraction hierarchy. The second dimension is also related to the display content, but deals with how the information about the physical plant items and the functional concepts can be organised. The third dimension deals with the presentation of the display content and the fourth dimension takes the operator's interaction with the system into account.

In other words, the design space covers the display content, the organisation of the content (window system), the presentation and the operator's intervention points to the system.

---

1. **Representation content**
   Decomposition network at level of abstract function
   Diagonal along abstraction-decomposition space (see Figure 2.8)
2. **Integration of physical and functional representations**
   Segregated
   Integrated within displays
   Integrated between displays

3. **Formatting of functional representations**
   Icons for normative structure and separate state information
   Integrated state information with normative structure conveyed by nested organisation

4. **Controls**
   Manual control
   Automatic control
   Hierarchical, functionally decoupled automatic controller

Table 2.1. Design space for multilevel interfaces (from Vicente, 1992b).

To be used by researchers, designers and regulators

The design space is intended to be used by researchers to provide a framework for integrating existing and future research, by interface designers to make explicit the dimensions which should be considered, and finally by regulators within the nuclear power industry that can use it for developing evaluation guidelines (Vicente, 1992b).

Again the dimensions in the design space are very general and detailed guidelines on how to proceed for a specific problem are not provided.

2.2. Ecological Interface Design (EID)

Content in this section

This section deals with the Ecological Interface Design method. First the theories behind the design method are given followed by an example of how the display content can be mapped into a visual form. Finally, the ecological interface for the Duress system is described.

EID is based on the abstraction hierarchy and Rasmussen's human behaviour model

EID is NOT only the visual form of the Duress display

EID was developed in the same period (1980s) as cognitive engineering and can be regarded as cognitive engineering applied to the problem of interface design in the work domain of process control.

EID is a generic design principle based on the abstraction hierarchy and Rasmussen's human behaviour model. The visual form of the display invented for the Duress system (described in section 2.2.2) is often regarded as *the* ecological interface, but it is preferred to view this as a special interface fulfilling the generic EID principles. The reason for this view is that it appears to be difficult to apply the specific display form to systems other than energy systems, which can be described by first order differential equations (see discussion in section 2.2.1.4 for details).

2.2.1. Theoretical Foundation

According to Vicente and Rasmussen (1992), the interface design problem can be structured as shown in Figure 2.9.

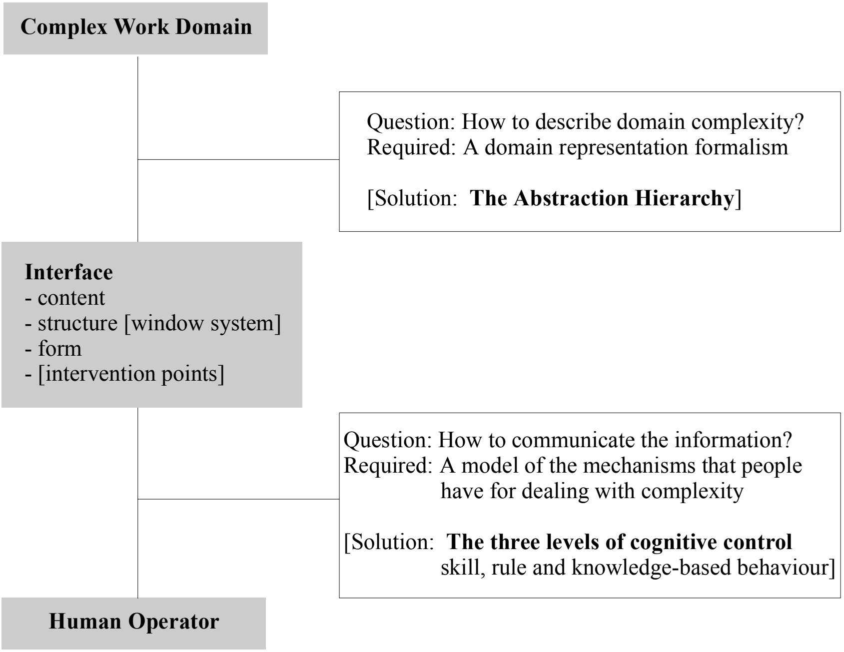


Figure 2.9. The structure of the interface design problem (adapted from Vicente and Rasmussen (1992)).

As indicated in Figure 2.9 the abstraction hierarchy is used as a framework for structuring representations of the process plant. The skill, rule and knowledge-based behaviour model of humans is used as the model to describe how people deal with complexity.

The structure of the interface relates to the layout of the single display page and the window system for handling several display pages. The layout or structure of the interface is not treated in detail in this thesis and, therefore, the focus will be on the parts of EID dealing with the content and form of the interface. Though it should be noted that it has not been possible to find specific design information related to the structure of the interface in EID either.

The intervention points item is added to the interface box in Figure 2.9 for completeness as it regards the fourth dimension in Vicente's design space on page 21.

2.2.1.1. The Abstraction Hierarchy, a Means to Represent Complex Systems

Information structured by the abstraction hierarchy supports problem solving

As mentioned, EID uses the abstraction hierarchy as a framework for structuring representations of the process plant. The exact number of levels in the abstraction hierarchy depends on the working domain but Vicente and Rasmussen (1992) have found five levels useful in the working domain of process control. They further state: "an abstraction hierarchy representation [of a process plant] has two benefits: it provides operators with an information basis for coping with unanticipated events, and it provides a psychologically valid representation for problem solving."

EID focuses on unanticipated events

The aim of EID is to deal with unanticipated events because the abstraction hierarchy is the foundation for representing the plant in EID. The abstraction hierarchy is useful in coping with unanticipated events because of its means-end relations. It is also these goal-oriented relations, which makes the abstraction hierarchy psychologically relevant for problem solving.

Show the goal-relevant constraints

Vicente and Rasmussen (1992) argue that it is the system constraints that the operator need to know of in order to handle unanticipated events. "It is the complete set of goal-relevant constraints governing the system [that] must be represented to permit operators to determine when a constraint has broken, and thereby allow them to directly diagnose the abnormality."

2.2.1.2. How Human Perception Copes with Complexity

Vicente and Rasmussen (1992) see the skill, rule and knowledge-based behaviour as three levels of cognitive control. They divide cognition into perception and thinking and relate it to their model of human behaviour, as shown in Figure 2.10.

Perception is rarely perfect but always close

Thinking can be perfect but sometimes lead to extreme errors

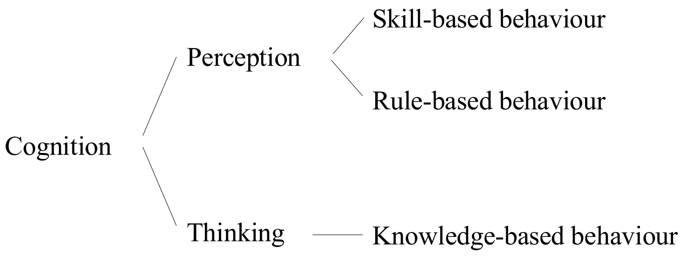


Figure 2.10 Vicente and Rasmussen's (1992) ordering of the concepts cognition, perception and thinking related to their model of human behaviour.

People have a propensity for perceptual processing

Out of sight, out of mind

With reference to Brunswik (1956), they state that perception is rarely perfect but always close. Thinking, on the other hand, can be perfect but sometimes lead to extreme errors. Moreover, people have a propensity for perceptual processing, instead of thinking, that is a propensity for low-level cognitive control. According to Vicente and Rasmussen (1992), this tendency is also recognised by Fishoff, et. al. (1978) and labelled: “out of sight, out of mind”.

To sum up, interface designers should support perceptual processing in the interface to ease the operator’s daily use of the display. But thinking must also be supported in order to be able to deal with unanticipated events (disturbance handling).

2.2.1.3. Design Principles

With the design considerations mentioned above, the principles for ecological interface design, quoted from Vicente and Rasmussen (1992), are listed below.

Support knowledge-based behaviour

”[To support] knowledge-based behaviour represent the work domain in the form of an abstraction hierarchy to serve as an externalised mental model that will support knowledge-based problem solving”.

Support rule-based behaviour

”[To support] rule-based behaviour provide a consistent one-to-one mapping between the work domain constraints and the cues or signs provided by the interface”.

Support skill-based behaviour

”[To support] interaction via time-space signals [needed in skill-based behaviour], the operator should be able to act directly on the display, and the structure of the displayed information should be isomorphic to the part-whole structure of the movements”.

EID is not only for process control

These fundamental design principles for ecological interfaces are very general and are not related to any working domain, that is they can be applied to other domains than process plants. EID has been applied to library systems (Rasmussen et. al., 1994).

Difficulties with EID design principles

How to create an abstraction hierarchy?

The difficulty with such general design principles is that they do not give any explicit advice on how to attack the display design problem at hand. From the ecological interface design principles it is clear that knowledge-based behaviour should be supported in the display if the operators must handle unanticipated events. Knowledge-based behaviour can be supported by representing the work domain in an abstraction hierarchy, but how is the abstraction hierarchy created for the specific work domain?

How to visualise constraints?

Assuming that an abstraction hierarchy is created, another difficulty arises: how are the work domain constraints shown in the interface?

Does the abstraction hierarchy represent the constraints? In that case, the abstraction hierarchy is the basis for both rule and knowledge-based behaviour according to the design principles.

2.2.1.4. One Visual Form of an Ecological Interface

The visual form, which is often regarded as *the* ecological interface is developed for the energy system, Duress. The focus in the following is not on the actual system but on the construction of the visual form, i.e. the method for inventing such a form and the general applicability of the form.

The starting point for the development of a visualisation in EID is that it should support all three cognitive levels of control.

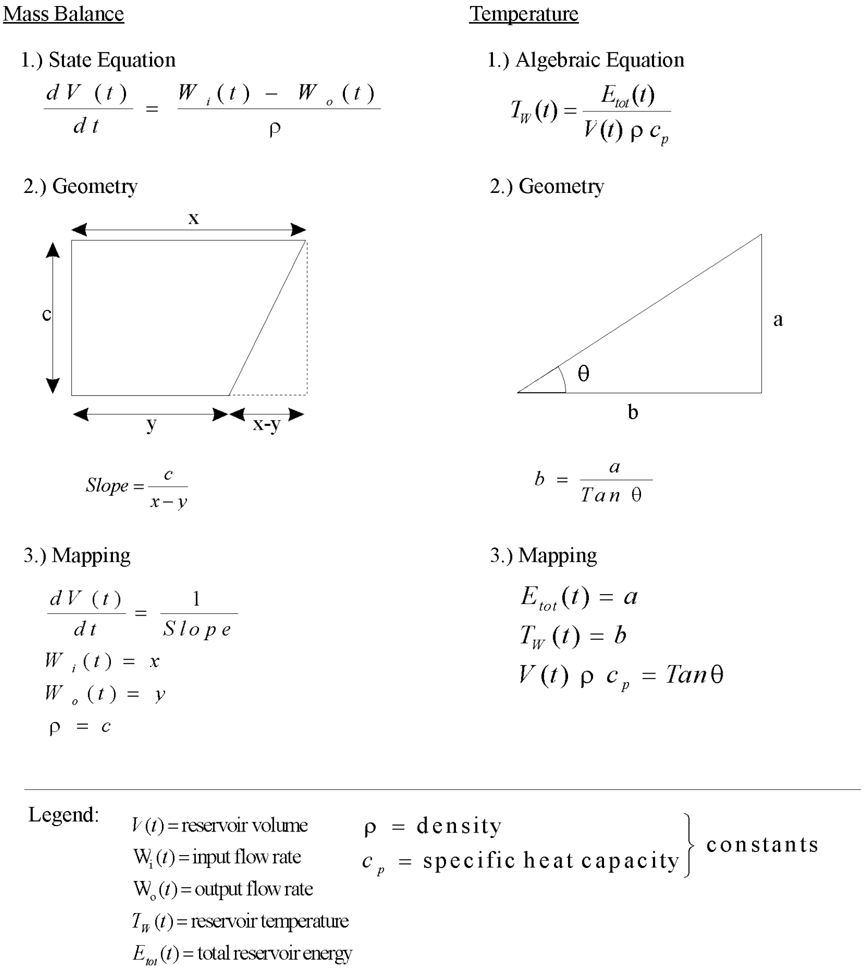
In existing ecological interfaces only the mass and energy separation is visualised to support knowledge-based behaviour

Theoretically, knowledge-based behaviour is supported when the entities and relations from the abstraction hierarchy are be presented (both part-whole relations within each level of abstraction and means-ends relations between the abstraction levels). In practice, here meaning in the ecological interfaces developed for process control, only the separation of mass and energy flows from the level of abstract functions in the abstraction hierarchy is used. The separation of mass and energy flows originates from multilevel flow modelling (Lind, 1990). How the other relations from the abstraction hierarchy re-appear in the visual construction of an ecological interface is not obvious, if they are visualised at all.

Rule-based behaviour is supported by transforming mathematical equations into a visual form

Rule-based behaviour should be supported by a one-to-one mapping between the physical constraints of the work domain and the graphic in the user interface. In the domain of process control, the laws of physics often give the constraints, and therefore the exercise is to transform the dynamics of the system represented by mathematical equations into a visual form.

The fundamental laws of physics for the Duress system are given in Figure 2.11 together with the invented visualisation techniques. Only the mass balance equation is shown because the energy balance has a similar mathematical structure and therefore the same visualisation technique can be used.



$$\frac{dV(t)}{dt} = \frac{W_i(t) - W_o(t)}{\rho}$$

$$T_W(t) = \frac{E_{tot}(t)}{V(t)\,\rho\, c_p}$$

$$Slope = \frac{c}{x-y}$$

$$b = \frac{a}{Tan\,\theta}$$

$$\frac{dV(t)}{dt} = \frac{1}{Slope}$$
$$W_i(t) = x$$
$$W_o(t) = y$$
$$\rho = c$$

$$E_{tot}(t) = a$$
$$T_W(t) = b$$
$$V(t)\,\rho\, c_p = Tan\theta$$

$V(t)$ = reservoir volume
$W_i(t)$ = input flow rate
$W_o(t)$ = output flow rate
$T_W(t)$ = reservoir temperature
$E_{tot}(t)$ = total reservoir energy
ρ = density
c_p = specific heat capacity

Figure 2.11. Transforming the mathematical equations describing the dynamics of Duress into a visual form (from Vicente and Rasmussen, 1990).

These mappings reveal the underlying dynamics of the energy system and when they are combined as shown to the right in Figure 2.13 they provide an understanding of the relations between the involved process variables. The seesaw construction in the middle represents the temperature equation. To the left and right of it, accordingly, are the mass and energy balances.

Finally, skill-based behaviour should be supported by allowing the operators to interact with the system. In Figure 2.13 triangles placed on the bar graphs of the measurements of process variables can be moved to adjust the set points.

Guidance on how to create other visualisation techniques is missing

One problem with these mappings is that no explanation is given on how they were invented, that is a procedure and descriptions of the experiences are missing. This is perhaps understandable as it can be argued that it is absurd to attempt to formalise the process of invention. However, the remaining problem is how to map other laws of physics, e.g. parabolic or exponential expressions into a visual form. A systematic approach to describe such mappings should be considered.

Limitations of the visualisation techniques

It is important to notice that these mappings are limited to equations having the mathematical structure shown in Figure 2.11, therefore these visualisation techniques must be used with care if applied to other types of systems or used in other working domains. If the system dynamics are unknown or not modelled, these visualisation techniques should be used very cautiously.

2.2.2. An Ecological Interface for the Duress System

One of the most widely used examples where an ecological interface has been developed is the Duress system (Dual Reservoir System Simulation), described in Vicente and Rasmussen (1990). Other examples of ecological interfaces can be found in Paassen (1995) and Monta, et. al.,(1993). Other examples than the listed ones exist.

Details regarding the design method are not given here, instead the visual form is presented together with an explanation of the dynamics of the interface. The reason is that it is difficult to understand the mechanism of the visual construction when it cannot be used interactively.

2.2.2.1. System Description and Interfaces

DUal REservoir System Simulation (Duress)

The DUal REservoir System Simulation (Duress) is a thermal-hydraulic process. It consists of two reservoirs (tanks), two heat exchangers, and inlet and outlet piping and instrumentation. The topology of system and the conventional interface (mimic diagram) is shown in Figure 2.12. The ecological interface is evaluated against this mimic diagram interface.

Conventional mimic diagram

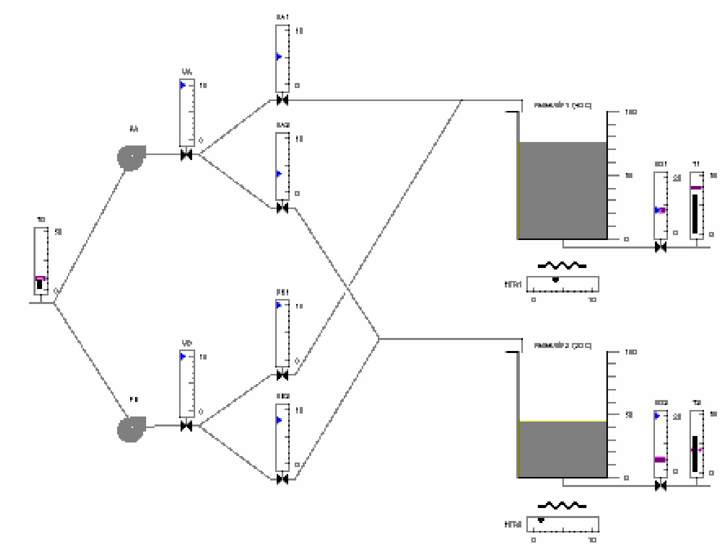


Figure 2.12. The mimic diagram for the Duress system.

The operator task is to keep the water temperatures at prescribed set points and to maintain enough water in each reservoir to satisfy each of the externally determined flow rates. To achieve this the operator must control the plant components shown in Figure 2.12 manually. 16 process variables are presented (Vicente, et. al., 1995).

The ecological interface for the DURESS system is shown in Figure 2.13. Notice how flow sensors are added on the inlet pipes and how the developed visualisation techniques from Figure 2.11 are used together. In total, 34 process variables are presented. The dynamic interrelations between the visualisation techniques are described in the next section.

An ecological interface

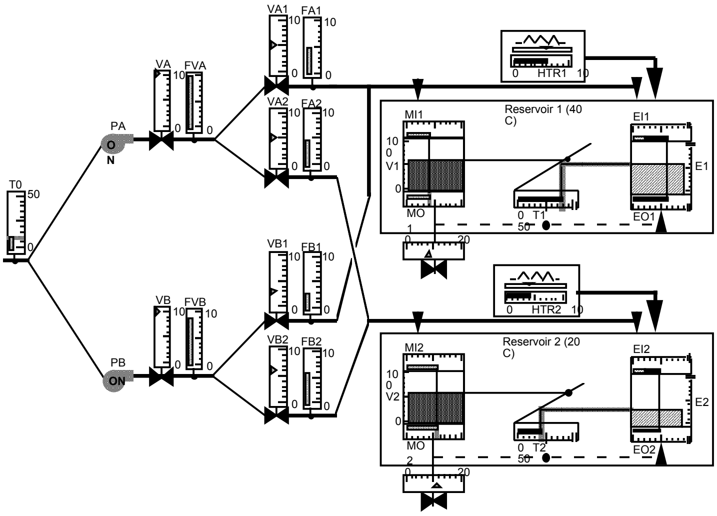
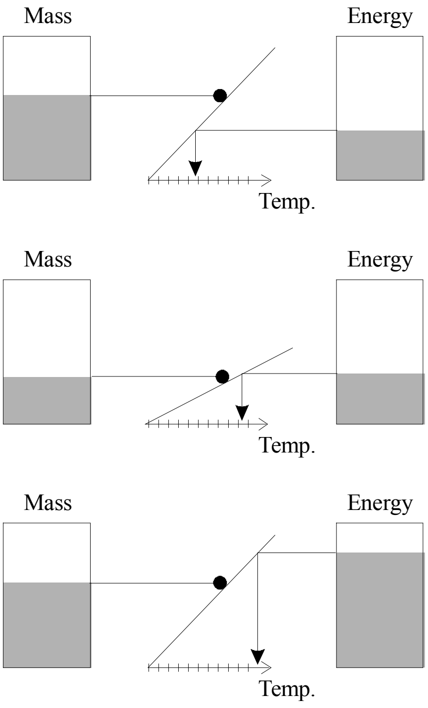


Figure 2.13. An ecological interface for the Duress system (received from Burns and Vicente).

2.2.2.2. A Static Description of the Dynamics of an Ecological Interface

The strength of the ecological interface for the DURESS system is its capability of mediating the thermal-hydraulic physical laws (constraints). However it is difficult to see the dynamic behaviour of the system from the static picture of the interface in Figure 2.13, therefore the illustration in Figure 2.14. It is an attempt to visualise the dynamic behaviour of the ecological interface (which corresponds with the behaviour of the process). The behaviour is described with words in Vicente and Rasmussen (1990).

How a change is seen in the ecological interface



Initial state

A decrease in volume (mass)
and same amount of heat (energy)
increases the temperature

An increase in amount of heat (energy)
and same volume (mass)
increases the temperature

Figure 2.14. Different views of the ecological interface for the Duress system. An attempt to visualise the dynamics in the interface, which corresponds to the dynamics of the process

2.3. Semiotics

Content in this section

This section describes the very basics of semiotics. Only the parts, of the limited amount of literature studied, which have been found relevant to design and analysis of process displays are mentioned here. Arguments for applying semiotics to process displays are given before a short explanation of the concepts of semiotics will be listed and their relevance to process displays are discussed. A comparison to Rasmussen's use of the words sign and symbol is given. Finally, Bertin's semiology of graphics is outlined including a taxonomy of possible content in graphs and a description of visual dimensions.

The usefulness of semiotics in process displays

As discussed in the previous sections, cognitive engineering and ecological interface design do not treat the visualisation part of the design process of displays in detail. By looking at the existing displays it was clear that different visual forms are used. Further, some graphical forms are more appropriate for certain information types and for certain operator tasks than other forms. It appeared that semiotics as a general theory, encompassing the visual form, provided a deeper insight into the mechanisms involved in interpreting the visual appearance of process displays. Therefore, the basic principles of semiotics are studied.

2.3.1. The Basics of Semiotics

Chandler (1994) gives an overview of semiotics and its different traditions. The aim is to get an insight into semiotics and to use it on process displays. The objective is not to perform comprehensive analyses and therefore the more fundamental sources, such as Saussure, Peirce, Morris and Eco have not been considered in this project.

The study of signs

Semiotics is the study of signs. It is concerned with the structured whole of information communication with no limitations to medium. The focus is on the appearance and interpretation of signs, not so much on the usefulness of the content, i.e. why the content is mediated.

Signs is anything from which meaning may be generated

In semiotics the central concept is signs, which are anything from which meaning may be generated. Examples of signs are words, images, sounds, gestures and objects. Notice how these signs are from different media, that is different communication channel such as the visual, acoustic or haptic medium.

From the tradition of Saussure, every sign is composed of *a signifier*, i.e. the form of sign and *the signified*, that is the concept it represents. Saussure refers to concepts only and not to objects, according to Chandler (1994).

Pierce uses a slightly different model and adds an interpretant to the model. Due to the interpretant, Pierce's model seems more suitable for process display because the operators interpret the signs (items, figures) on the displays. Moreover, a sign in process displays often refers to objects (physical items) in the plant, which, according to Chandler (1994), is not included in Saussure's model.

The semiotics triangle

The semiotics triangle is shown in Figure 2.15 where the concepts from process control are integrated.

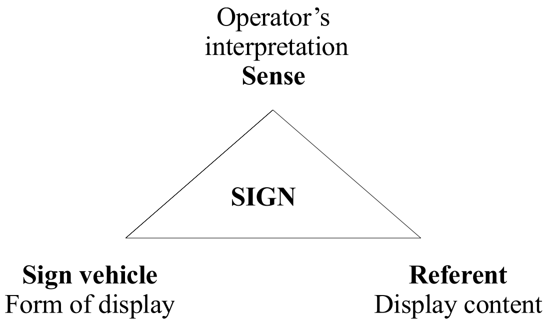


Figure 2.15. The semiotics triangle made by Pierce. Adapted from Chandler (1994) and supplemented with concepts from process control.

The sign vehicle is the form of the sign. This corresponds to the form of the display or to the form of individual display elements depending on the viewpoint.

The sense is the understanding made of the sign. In process control this is the interpretation of the display made by the plant operator based on the actual situation and their perception of the graphical items presented to the operator.

The referent is what the sign stands for i.e. the display content. It is the entities (magnitudes, events, physical items, or the concepts) and relations used in process control.

The next section describes the semiotic relations between a sign and the entity (referent or signified).

2.3.1.1. Information Mapping, the Semiotics Way

Information mapping in general deals with how given information can be visualised. Later in section 3.2.3 the problems and some of the possibilities for information mapping in process displays are discussed in detail. Here the semiotics contribution to information mapping is discussed together with some general considerations related to process displays.

Inverse information mapping

Information mapping as part of the display design process deals with the mapping between content and form (content → form), that is how should the information be visualised. Semiotics considers the categorisation of signs, having the focus on the form. In other words, semiotics focus on the relation between form and content (form → content), which here is regarded as inverse information mapping.

Semiotic relations between form and content

Three modes of relationships between sign vehicles (the form) and their referent (the content) are commonly referred to (Chandler, 1994).

"**Symbolic**, i.e. a sign which does not resemble the signified [content] but which is 'arbitrary' or purely conventional (e.g. the word 'stop', a red traffic light, a national flag, a number)".

"**Iconic**, i.e. a sign which resembles the signified [content] (e.g. a portrait, a cinematic image, an x-ray, a scale model, 'realistic sound' in music, sound effects in radio drama, a dubbed film soundtrack, imitative gestures)."

"**Indexical**, i.e. a sign which is directly connected in some way (existentially or causally) to the signified [content] (e.g. smoke, weathercock, thermometer, clock, spirit-level, footprint, fingerprint, knock on door, pulse rate rashes, pain)."

Further, Chandler (1994) notices that “it is easy to slip into referring to these three forms as types of signs, but they are not necessarily mutually exclusive: a sign can be an icon, a symbol and an index, or any combination”

Symbols, icons and indexes are distinguished as different types of relations between form and content. The words symbol and icon referring to actual graphical items are in principle distinct from the symbolic and iconic relations between form and content.

2.3.1.2. The Semiotic Way of Information Mapping Related to Process Control

Mapping plant entities to a display form

Plant entities include physical items, concepts used in the plant (e.g. states, process operations, functions and goals), process variables, etc. That is everything, which might be found in a process display except relations.

From a semiotic point of view, the information about plant entities can be mapped to the display by use of symbols or icons or both.

The standard signs for plant components used in mimic diagrams are symbols. Icons are seldom seen in process displays, though recently more or less realistic pictures of plant components have been integrated in the mimic diagrams and can be regarded as icons.

Some symbols are well-known, others are not

Notice how the well-known symbols for the plant components are easily recognised and understood, even though there is no resemblance between the form and the content, only a symbolic relation. Less common symbols to the process operator, such as the MFM symbols are more difficult to remember and comprehend (see Figure 2.16). From a semiotic point of view, the symbolic relation between the sign and the signified in MFM symbols is identical to the symbolic relation between standard symbols and components. One explanation of the difficulties with the MFM symbols could be that they represent abstract concepts such as functions and goals, whereas the standard component symbols represent well-known physical items.

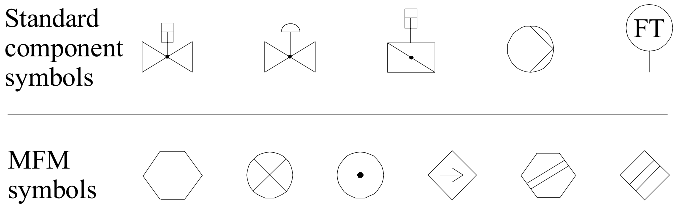


Figure 2.16. To the process operator standard component symbols are well-known and the MFM symbols less known (there is no relations between the shown component symbols and the MFM symbols).

With regard to cognition, the difficulty of remembering what a symbol represents implies that the focus must be on understanding the symbols before the actual problem can be dealt with. If the symbols are well-known, the operator’s mind is not deviated from the problem at hand. Training can solve the problem of recognising what a symbol represents.

Mapping plant relations to a display form

Some of the relations between plant entities are indexical, e.g. temperature sensor to temperature measurement or the start button to the pump and further to the flow in the pipe. The indexical relations are all well-known and learnt through life. The problem is the relations, which are not known to the operator, e.g. the relationship between volume and temperature in the ecological interface for Duress. If the relationships are known instinctively a visual construction mediating the relation is unnecessary. **It is the relationships unknown to the operator that must be mediated in process displays.**

It is difficult to state exactly how relations are best visualised, c.f. the discussion of the construction of the ecological interface for Duress. Some of the means (graphical modalities) available for mediating relations are mentioned and discussed in sections 3.3.2.2 and 3.3.2.3, examples are in section 3.3.3.1.

2.3.2. Comparison to Rasmussen's Signs and Symbols

It appears that Rasmussen (1986) uses the same terms (signs and symbols) as used in semiotics. A comparision is made to clarify whether there is a correspondence between the way Rasmussen uses the words and the semiotic definitions.

The meaning of signs

Rasmussen's meaning with the word sign is (from the definition on page 15) "Signs indicate a state in the environment with reference to certain conventions for acts. Signs are related to certain features in the environment and the connected conditions for actions."

This is different from the semiotic definition of signs as anything from which meaning may be generated. Further the sign is the central, umbrella concept in semiotics, whereas Rasmussen uses the word to describe specific information needed to support rule-based behaviour.

The meaning of symbols

Rasmussen argues that symbols should be used to support knowledge-based behaviour and defines symbols (see page 15) as "symbols represent other information, variables, relations, and properties, and can be formally processed. Symbols are abstract constructs related to and defined by a formal structure of relations and processes, which by conventions can be related to features of the external world."

The semiotic meaning of symbols is a sign which does not resemble the signified but which is 'arbitrary' or purely conventional.

Some identical meaning between Rasmussen's and the semiotics' definitions of symbols can be found as they both refer to something defined by conventions. But Rasmussen also refers to conventions in his definition of signs.

Rasmussen's definitions are related to the content

The semiotic definitions are related to the form

It seems that Rasmussen's definitions of signals, signs and symbols are closely related to the content of the displays, that is the information types. Moreover, signs (used in rule-based behaviour) in Rasmussen's terminology appear to be the intervention points on which the operators can act and the visual response from these actions, though it is argued that intervention points are required for skill-based behaviour. Finally, Rasmussen places the remaining physical items and concepts, which can be a part of the display content, in the category that can be presented by symbols.

The semiotic definitions are related to the presentations themselves, that is the visual appearance and its interpretation.

Rasmussen's use of signs and symbols differs from semiotic definitions

Therefore, it is important to distinguish between the two meanings of the words symbols and signs in Rasmussen's meaning and in the semiotic meaning, because as can be seen a clear correspondence between them does not exist. The conclusion is that it is not possible to compare the meanings of the terms signs and symbols from semiotics with the words signs and symbols used by Rasmussen.

2.3.2.1. Display Content to Support Skill, Rule and Knowledge-based Behaviour

A free interpretation of Rasmussen's use of signal, signs and symbols are made in order to specify the display content for each of the three cognitive behaviours. The focus is on the content and therefore the semiotic terms are not used.

Skill-based behaviour

To support skill-based behaviour the operators must be able to act directly on the display and the result of the actions must be shown immediately on the screen.

Rule-based behaviour

Rule-based behaviour is supported by action-response cues. Ideally, the consequences of an action should be visible to the operator. The action-response cues originate from the physical constraint of the system. A good example is the ecological seesaw construction for the Duress system. It can be argued that knowledge-based behaviour is supported if the response of an action can be figured out from the form of the display. This is not the case in most process displays.

In most of the process displays, rule-based behaviour is supported by the visual pattern the graphical items for action and response exhibit. For example, the operator knows that when a certain component is manipulated, the curve in the trend window shifts.

Knowledge-based behaviour

Knowledge-based behaviour is supported when the relations between plant entities can be seen. Those are relations between process variables (volume and temperature in the Duress system), relations between components, relations between process operations, relations between goals, process operations and components, etc. The different types of relations in process plants are treated in further detail in section 3.3.2.1.

2.3.3. Semiology of Graphics

Introduction

Bertin (1981 and 1983) covers this topic. What has been found useful in relation to the design of process displays is described below and the connection to the terminology of process control has been pointed out.

Bertin separate content and form. First Bertin's taxonomy of content is described, followed by the visual dimensions and the possible combinations of these. It should be noted that Bertin's focus is on visualisation of data, that is information that is often visualised in graphs or graphs embedded in maps. Bertin does not consider the real-time dynamics of the information; it is assumed that all information is available when the visualisation is designed. Further, physical items are not considered as part of the visualisation, only the data values (magnitudes) of the properties of the physical items are in focus. Therefore, relations between objects are not dealt with either.

2.3.3.1. Bertin's Content Taxonomy

Data refers to magnitudes (process variables)

Bertin is mainly concentrated on describing relationships in and between data variables. Later in this thesis such data variables will be referred to as magnitudes. Bertin analyses all kinds of data variables, but they are all magnitudes. Bertin uses the term component to refer to data variables, but the word component is dedicated to plant components in this thesis. Consequently, data or data variable will be used instead.

All levels of information should be mediated from data

Bertin's focus on the mediation or extraction of information from the data without excluding any data. "A graphic should not show only the leaves, it should show the branches as well as the entire tree. The eye can then go from detail to totality and discover at once the general structure and any exceptions to it" (Bertin, 1983).

Bertin (1983) defines three levels to which all data variables belong. The definitions are quoted below.

Qualitative variables (discrete)

"The qualitative or nominal level includes all the concepts of simple differentiation (trades, products, religions, colours, …). It always involves two perceptual approaches: This is similar to that and I can combine them into a single group (association). This is different from that and belongs to another group (differential)"

"What is qualitative is neither quantitative nor ordered, but is arbitrarily reorderable" (see below).

Ordered variables

"The ordered level involves all the concepts that permit a ranking of the elements in a universally acknowledged manner (e.g. a temporal order; an order of sensory valuations: cold-warm-hot, black-grey-white, small-medium-large; an order of moral valuations: good-mediocre-bad, …). This level includes all the concepts, which allow one to say: this is more than that and less than the other."

"What is ordered is also qualitative."

Quantitative variables (continuous)

"The quantitative level or interval-ratio level is attained when one makes use of a countable unit (this is quarter, triple or four times that)."

"What is quantitative is likewise ordered and qualitative."

Notice that there is no direct correspondence between Bertin's use of the word concept in the definitions above and the use of the word in the classification of information types in section 3.3.2.1. In the classification, concepts are introduced as the "opposite" of physical items, that is concepts are used to describe untouchable "things" in process plants.

2.3.3.2. Bertin's Visual Dimensions

The visual dimensions are shape, position, size, orientation, colour, brightness, and texture

The visual variables of Bertin, here called visual dimensions (not to be confused with data variables), are separated into planar and retinal variables. The planar variables are the x and y coordinates in the plane. In this thesis, they will be referred to as the position enabling the possibility for 3-dimensional visualisation spaces. The retinal variables are the ones, which can be used to indicate a position and they are in the following referred to as markers. Bertin uses the following retinal variables: size, value, texture, colour, orientation and shape.

Examples of Bertin's visual dimensions are shown in Figure 2.17.

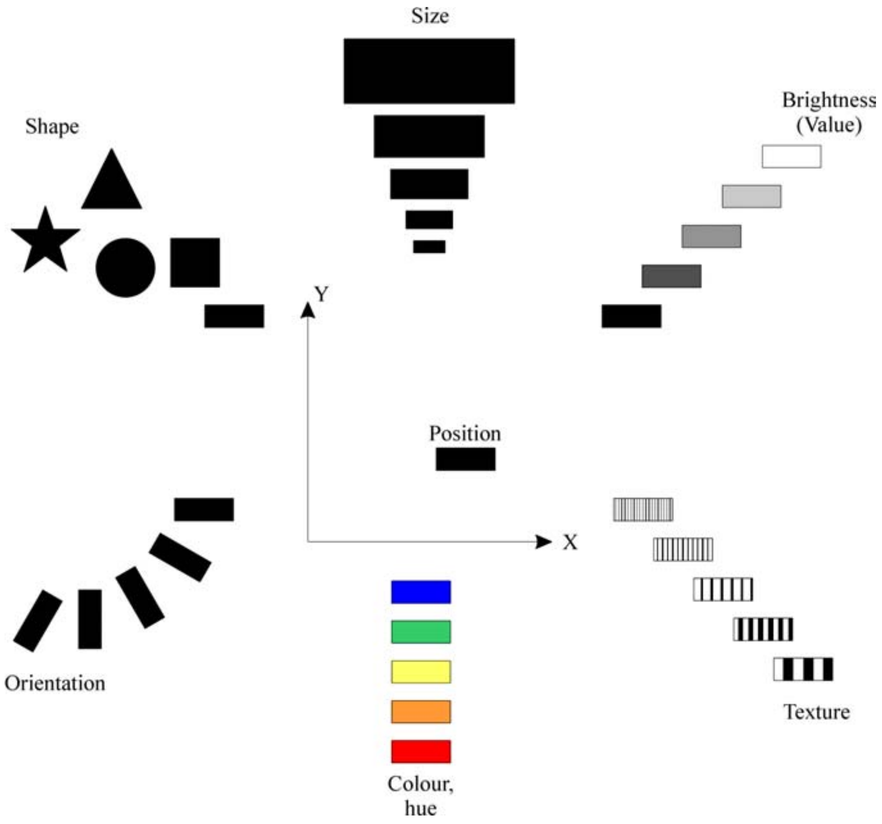


Figure 2.17 Visual dimensions (from Bertin, 1983).

Bertin (1983, page 73) defines the value variation as "the continuous progression which the eye perceives as a series of greys ranging from black to white". Experiments have shown that is possible to distinguish between the colour (hue) and the brightness i.e. the eye sees bright objects before the darker (c.f. the gestalt principle of lightness or contrast, page 39). Therefore Bertin's concept of value will in the following be named brightness. Colour is implicitly referring to the hue.

2.3.3.3. Classes of the Visual Dimensions

Bertin (1983, page 48) classifies each of the visual dimensions as selective, associative, ordered or quantitative according to how any individual immediately will classify a series of data values.

Selective

"A visual dimension is selective when it enables us to immediately isolate all the correspondences belonging to the same category [of this data variable]". The question: where is a given data variable (a set of samples) among other data variables can be answered by using a selective visual dimension. An example is colour coding used in trend curves to distinguish different data variables.

Associative

"A visual dimension is associative when it permits the immediate grouping of all the correspondences differentiated by this [data] variable". Markers are perceived as a group across several data variables. Associative visual dimensions are used when one is trying to equalise a variation in a data variable and to group correspondences with other data variables, i.e. to mediate correlation between data variables.

Ordered

"A visual dimension is ordered when the visual classing of its categories, of its steps, is immediate and universal".

Quantitative

"A visual dimension is quantitative when the visual distance between two categories of an ordered component [data variable] can be immediately expressed by a numerical ratio".

When to use a given visual dimension?

These classes of the visual dimensions correspond to the classes of Bertin's content taxonomy, though the qualitative content class is divided into the associative and selective visual class. This means that having a given data content, it is possible to reduce the number of visual possibilities, because not all the visual dimensions support all the visual classes. In Table 2.2, the possible combinations between the visual dimensions and the visual classes are shown as given by Bertin.

	Selective (identification of a data set from others)	**Associative** (groupings across data sets, correlation)	**Ordered**	**Quantitative**
Shape		✓		
Position	✓	✓	✓	✓
Size	✓		✓	✓
Orientation	✓	✓		
Colour	✓	✓		
Brightness	✓		✓	
Texture	✓	✓	✓	

Table 2.2. When to use the visual dimensions (adapted from Bertin, 1983).

Table 2.2 is, to the author's knowledge, the only analysis available in the literature to determine which visual dimension to use for visualising a given display content. However, it should be mentioned that is not complete. An example is that shapes of markers connected by lines are used in a graph as a selective visual dimension to distinguish different data variables (see Figure 2.18). An explanation for why this works might be found in the gestalt principles of good continuation, see the next section.

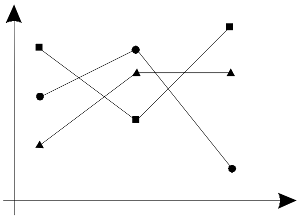


Figure 2.18 An example of how shapes and connecting lines can be selective

2.4. Gestalt Principles

What is it?

The word gestalt can be translated into pattern. In Germany in the 1920s psychologists, including Wolfgang Kohler, Kurt Koffka and Max Wertheimer, were concerned about how humans view and organise visual cues. The essence of the gestalt theory is often cited as "the whole is greater than the sum of the individual parts".

Rationale

The example of using shapes to identify (select) different data sets in graphs indicates that the possible combinations of single visual dimensions given by Bertin are not sufficient. Knowledge about how humans may perceive combinations of the visual dimensions is desirable. This can be obtained from the gestalt principles.

Grouping effect and figure-ground separation

The gestalt principles can be divided into two: principles regarding grouping effects and principles for figure-ground separation.

The gestalt principle of proximity, similarity, good continuation, closure and common fate are related to the grouping effect.

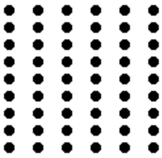
The gestalt principles of symmetry, smallness, surroundedness, convexity, orientation and lightness regards figure-ground separation.

A description of the main principles together with an illustration is given below and is taken mainly from Chandler (1997).

Proximity

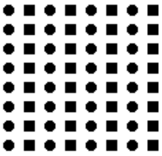
The principle of proximity is that features, which are close together, are associated.

Not just a square pattern of dots is perceived but rather a series of columns of dots.



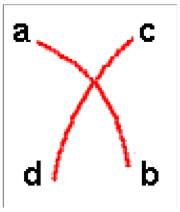
Similarity

The circles and squares are evenly spaced both horizontally and vertically so proximity does not come into play. However, alternating columns of circles and squares tend to been seen. This is the principle of similarity - features that look similar are associated.



Good continuity

This principle is that contours based on smooth continuity are preferred to abrupt changes of direction. For example, it is more likely to identify the lines a-b and c-d crossing than to identify a-d and c-b or a-c and d-b as lines.

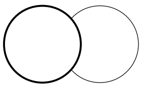


Closure

Interpretations that produce 'closed' rather than 'open' figures are favoured.

Three broken rectangles (and a lonely shape on the far left) are observed rather than three 'girder' profiles (and a lonely shape on the right). In this case the principle of closure cuts across the principle of proximity, since if the bracket shapes are removed, an image used earlier to illustrate proximity is seen.

Notice how the principle of good continuation and closure combined with experience makes it possible to perceive the circle to the right.

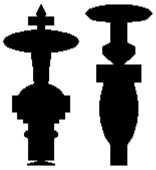


Common fate

For moving figures, elements with common velocity and direction tend to be seen as a group.

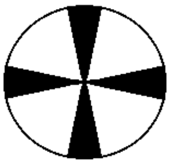
Symmetry

The principle of symmetry is that symmetrical areas tend to be seen as figures against asymmetrical backgrounds.



Smallness

Smaller areas tend to be seen as figures against a larger background. In the figure to the right it is more likely to see a black cross rather than a white cross within the circle because of this.



Surroundedness

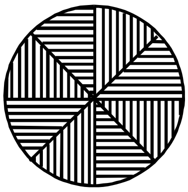
Areas that can be seen as surrounded by others tend to be perceived as figures.

Convexity

Convex contours are seen as figures in preference to concave contours (Boff and Lincoln, 1988).

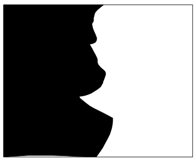
Orientation

A region oriented horizontally or vertically is seen as a figure in the preference to one that is not.



Lightness or contrast

A region that contrasts more with the overall surroundings is preferred as figure to one that does not.



Pragnänz

All of these principles of perceptual organisation serve the overarching principle of pragnänz, which is that the simplest and most stable interpretations are favoured. Proximity is stronger than similarity and closure overrules proximity. Similar statements regarding other gestalt principles are desirable, but unknown to the author.

2.5. Task Analysis

What is it?

Task analysis is developed in order to be able to formally describe what humans do or should do when a certain job is performed. A task analysis includes both the human interaction with the system and the interaction between other humans.

Task analyses can be applied both to optimise and assess existing work procedures or to develop and assess new procedures.

Rationale for task analysis in design of process displays

Task analysis is relevant for interface design because it must be known what the operators should do in order to select the proper information to present to them. Therefore, in this project the different methods for task analyses is seen as a tool for determining and describing the operator's work in a formal and standardised manner. A part of some of the task analyses is to ensure or check that there is consistency between the user's tasks and the display content. Further, some methods check the consistency of the visual form between several computer screens or dialogs.

The relevance of task analysis in this project

A specific task analysis is not made for the case studies in this project, because it has been regarded as too time consuming. However, it could have been done and it might be useful to considered task analysis in other projects. Instead, it was decided to keep the basic principles in mind when a display design method was proposed (see chapter 3). Moreover methods and applications should be separated.

Another argument is that only the last three aims of task analysis (mentioned below) are relevant for this project because the allocation of functions, person specification and staffing, and job organisation often is determined when the interface design is initiated in industrial process plants.

2.5.1. Aims and Techniques for Task Analyses

Here the aims and generic techniques for task analyses are listed to give an idea about the content of such analyses. Detailed information about how to make a task analysis is not given. Kirwan and Ainsworth (1992) provide a survey of different methods and the procedures needed to make a specific task analysis.

Aims of task analysis

The aims of a task analysis are briefly listed. Not all the aims might be relevant in every task analysis. The aims quoted below are from Kirwan and Ainsworth (1992).

- Allocation of function

  Analyses the allocating of functions between personnel and machines, and defines the extent of operator involvement in the control of the system.

- Person specification

  Defines the characteristics and capability requirements of personnel to enable them to carry out the tasks effectively.

- Staffing and job organisation

  Defines the number of staff required, the organisation of team members, communication requirements, and the allocation of responsibility.

- Task and interface design

  Ensures adequate availability and design of information displays, controls and tools to enable the operator(s) to carry out the tasks adequately, whether in normal or abnormal operations.

- Skills and knowledge acquisition

  Analyses the training and procedures design

- Performance assurance

  Deals with assessment of performance predictively via human assessment, retrospectively via incident investigation or analysis, or concurrently via problem investigations.

Task analyses techniques

In order to be able to make analyses within these aims, Kirwan and Ainsworth (1992) have identified the following generic techniques. Notice that there is not a one-to-one correspondence between the aims of the analysis and the techniques listed below.

- Task data collection techniques
- Task description techniques
- Task simulation methods
- Task behaviour assessment methods
- Task requirement evaluation methods

2.6. Summary

Cognitive engineering is a framework for designing for people. It is generic and involves both engineering design principles (proposed as the abstraction hierarchy) and human behaviour models (skill, rule and knowledge-based behaviour).

Ecological interface design is cognitive engineering specifically applied to process control, though it has been used in other domains, too. Design principles are described and an example is given on how the physical constraints can be mapped into a form. The ecological interface for the Duress system has been tested against a conventional mimic diagram (Vicente, et. al. 1995). The operators made better diagnosis (disturbance handling) using the ecological interface than with the mimic diagram display. The lack of formalism describing how to create the display form mediating the domain constraints is pointed out.

Semiotics shed light on the problem of visualising given information. The similarities and difference between a semiotic study of a visualisation and the information mapping involved in the design problem of process displays are discussed. The visual dimensions of Bertin are included in this study.

The gestalt principles from perception psychology are mentioned in order to be able to make statements on how different combinations of graphical items (especially the visual dimensions) are perceived by humans.

The availability of task analysis is briefly mentioned.

Chapter 3. Designing Process Displays

Contents

This chapter deals with the problems involved in designing process displays, that is both the process of building displays by use of existing display elements and the process of inventing new display elements or visualisation techniques.

Building displays

A framework for systematically building and to some extent inventing process displays is proposed and the main aspects involved are outlined. A systematic method for building displays is given together with a classification of the main items found in each of the design aspects.

The use of abstraction

The use of abstraction as a means of problem solving both in design and during plant operation is discussed, focusing on the design of process displays.

Inventing displays

Use background knowledge and be creative!

This part of the chapter is an attempt to describe some of the design steps involved in invention of a new visualisation technique. Naturally, if the invention process could be described in detail, it would no longer be invention, but development. Therefore, creativeness is an important part of the invention process. Here a systematic approach to bring the different theories together is outlined in the hope that new ideas might grow or jump out of this foundation of background knowledge.

The principles for designing can also be used to categorise existing displays

The focus in this chapter is on designing (building or inventing) process displays, because that is the main objective of this work. The framework proposed is also suitable for analysing and categorising the existing displays. The reason to develop categories of existing displays is that such categories will reduce the number of possible display elements that the display builder can select between early in the design process. The categorisation of display types is given in chapter 4.

Foundation for the framework

The proposed framework is partly based on the available theories and partly on today's practice in designing process displays combined with common sense. This is based on the hope that the framework might be useful for the industrial display designer and therefore must be evolutionary rather the revolutionary. Moreover, it is hoped that the organisation of the theories and the separation of the design problem into three aspects will help in the invention of new visualisation techniques.

3.1. Building Process Displays

The process of designing process displays, especially building process displays, including the problems, the aspects and the proposed framework is described in Pedersen and Lind (1999). Here some of the main points from the article are briefly mentioned. The entire article is in appendix D.

Besides the main issues mentioned below, the article treats reusability and modular construction of display aggregates. A distinction between functions at plant design time and process operations when the plant is in operation is made. The proposed design method is used on a simple batch process as an illustrative example. Later it is applied to the condenser and ejector system of a nuclear power plant and the problems involved in shifting from batch to continuous processes are discussed.

Moreover, it is argued that the structure of the framework, i.e. the three aspects, is useful for analysing and classifying existing process displays.

3.1.1. The TCF Framework

Operator tasks, display content and the form of the display

The three aspects: the operator tasks, the display content and the display form, are found useful in describing both the building and to some extent the invention process. TCF stands for Task, Content and Form. In Figure 3.1 the three aspects are shown together with a common design path between the aspects.

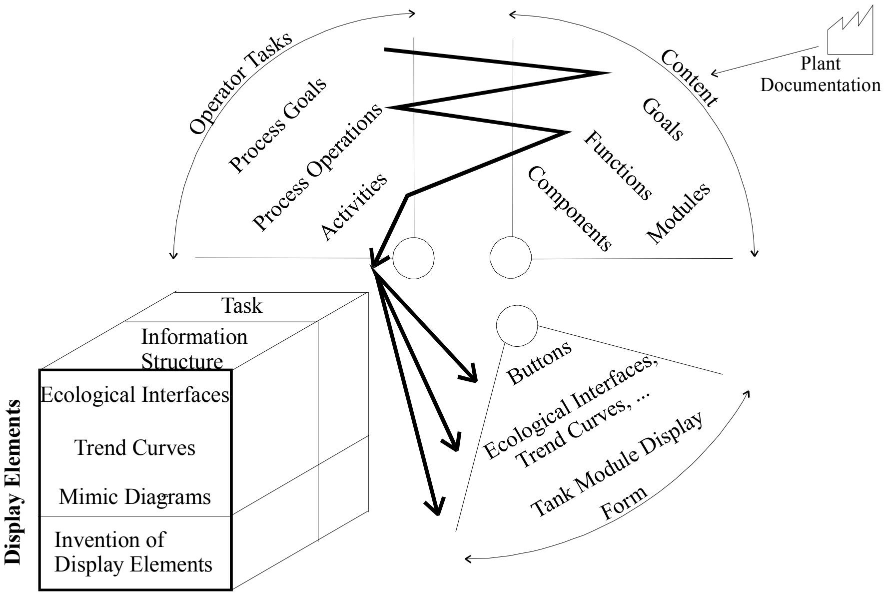


Figure 3.1 The TCF framework separates the design process into the three aspects: operator tasks, the display content and the display form. Different levels of abstractions and aggregations are shown together with a typical design sequence, where the form of the display is chosen among available display elements.

The process of determining the display content based on the operator's task can be said to be analytic as opposed to the process of determining the form based on the content, which is synthetic.

3.1.2. The TCF Design Method

TCF =Task, Content and Form

The method is named TCF for Task, Content and Form, encompassing the three aspects of the framework.

The design method proposed in the example by Pedersen and Lind (1999) is outlined below. For definition of process operations, process modules, and operator activity see Appendix B or Pedersen and Lind (1999) for details.

The procedure

1. Identify process operations
2. Determine process modules from P&I diagrams
3. Associate process modules with process operations
4. Decide the display content for each process operation

5. Determine the operator's activities
6. Select existing display elements suitable for the operator's activities.

A template

Using a template as the one in Table 3.1 has been found useful to support the design method. Here a filling operation is used as an example.

Process operation	Module	Display content Primary	 Secondary.	Operator activity	Display element
Filling	Inlet, tank	WT01	PUM01 AV01 AV02	1. Choose tank number 2. Start filling program 3. Monitor filling process	Combo box or input box Command button Bar graph or trend curve

Table 3.1. Template supporting the TCF design method. The filling process is an example from Pedersen and Lind (1999).

3.1.3. Classification Within the Design Aspects

Categories reduces the number of choices

As discussed in Pedersen and Lind (1999) it has been appropriate to define some generic categories of operator tasks and associated display content and form. The reason for doing this is to reduce the number of choices as early as possible in the design process.

Batch and continuous domains

Moreover, the differences between continuous and batch processes are explicate by such a classification. Batch processes are here regarded as the planning and scheduling of several continuous processes.

In Table 3.2 a generic classification of the design aspects is shown.

Operator task	Content	Form
Disturbance handling	State of and relations between goals, process operations, functions and components	Overview displays and hierarchies
Production optimisation	Correlation between process variables	Configural[4] displays
Production planning and scheduling	Relations and interlocks between process operations	Hierarchies and networks
Activation of process operations	Intervention points to automation system or components	Means for parameter input and manipulation of processes and equipment

Table 3.2. Generic classification of operator tasks, display content, and form.

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[4] Configural means dimensions that arise from combinations of perceptual distinct dimensions, e.g., symmetry (Boff and Lincoln, 1988).

3.2. The Use of Abstraction

Content in this section

This section defines abstraction and explains how abstraction can be regarded as a means for problem solving. Problem solving is considered both in the context of design and in the context of plant operation. The focus is on the use of abstraction in the design of process displays. The usefulness of abstraction in each of the aspects operator's tasks, display content and form is considered.

3.2.1. What is Abstraction?

Definition of abstraction

Abstraction is the act of considering something as a general quality or characteristic, apart from concrete realities, specific objects or actual instances (Webster, 1994).

Levels of abstraction

Using the definition above different levels of abstraction exists. For example a person can be classified as either male or female, which again at the third abstraction level can be classified as boy/man and girl/woman accordingly.

Notice how the levels of abstractions can be ordered into hierarchies.

Hierarchy types

Class hierarchies and the abstraction hierarchy

The types of hierarchies used in this thesis are class hierarchies and the abstraction hierarchy. The decomposition of a person into male and female, etc. is an example of a class hierarchy, where categories are defined at different abstraction levels. There are no causal relations between the classes in a class hierarchy.

As described in section 2.1.6, the abstraction hierarchy is goal-oriented and there are causal relations between the abstraction levels, i.e. the next higher level answers the question of why the entities exist and the level below answers how the entities are realised.

Determining the number of abstraction levels

Levels of abstraction are used to decompose problems. The number of abstraction levels depends on the context in which the problems occur. For a given problem it is a kind of art to define to appropriate levels of abstractions. As a rule of thumb no further abstraction levels should be added downwards when the specified details are good enough for the problem at hand. Making the delimitation upward is more difficult because the more abstract and thereby the more general things are made the bigger are the chances that the derived solution for the problem might be reused. A trade off must be made between the extra time needed to make the abstract solution and the possibility that the solution will be reused.

Use of abstractions in problem solving

Levels of abstraction are useful in problem solving, making it possible only to focus on the items of interest with regard to the problem at hand. In that case, abstraction levels can be regarded as a filtering mechanism.

Figure 3.2 illustrates how the span of attention narrows moving downward in the levels of abstractions in an abstraction hierarchy.

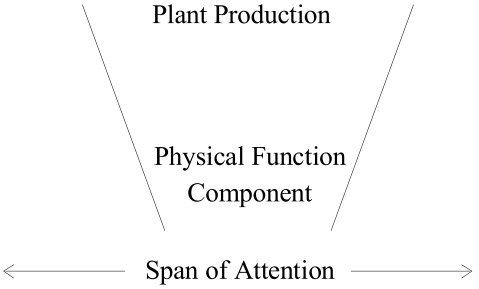


Figure 3.2. The span of attention narrows moving downward in the abstraction hierarchy (from Rasmussen and Lind, 1981).

3.2.2. Abstractions Used for Problem Solving

Within the domain of process control, it is useful to distinguish between problem solving during design (of plant and process displays) and problem solving when the plant is in operation.

Problem solving in design

When a top-down approach to design is taken the following three steps, i.e. levels of abstraction, are considered.

1. The purpose of the artefact to be developed are defined, i.e. definition of goals.
2. The functions or means required to achieve the goals are identified.
3. Implementation of the required functions.

The terminology commonly used in plant design, design of process displays and in software development is shown in Table 3.3 .

	Plant Design	Process Display Design	Software Design
1.	Design goals (derived from operational goals of the plant)	Display purpose (with regard to operator task)	Specification
2.	Functions	Required display content	Required function or objects
3.	Assembling of components	Aggregation of the display form	Implementation (coding)

Table 3.3. The terminology used at three levels of abstraction with different design tasks.

If a bottom-up approach is used, the three steps are applied in reverse order. This is rarely the case in design of process plants, probably due to the economical cost of reconstruction, but in the development of software and process displays step two is often omitted. Code and process displays are then developed directly from vague ideas of what must be achieved. In the design of process displays, mimic diagrams are usually made from the piping and instrumentation diagrams, implying that the purpose of the display is not considered in detail.

Problem solving when then plant is in operation

When the plant is in operation, most of the problem solving is performed by the operators. The generic categories of operator tasks considered in the following are disturbance handling, production optimisation, and production planning and scheduling.

Activation of process operations is the fourth operator task in Table 3.2, but it may be regarded as the operator's activities when it is decided what to do, that is some action must be performed before any of the tasks are completed.

Each of these tasks can be classified into more details, thereby increasing the understanding and helping in determining the display content needed by the operators.

3.2.3. Abstractions in the Design of Process Displays

Introduction

The TCF design method spans the aspects of operator tasks, display content and form. The design questions (problems) corresponding to these aspects of display design are:

- What must the operator do to perform a given task?
- What information is required?
- How should this information be presented?

In this section, levels of abstractions are used to decompose the problems, i.e. a specification is made within each of the three aspects of the TCF design method.

3.2.3.1. Abstractions in Operator Tasks

Disturbance handling

Rasmussen (1986, page 21) identifies three subtasks which the operator must perform during disturbance handling:

1. "Judge the overall consequence of the disturbance for the system function and safety in order to see whether the mode of operation should be shifted to a safer state (e.g. standby or emergency shutdown [for nuclear power plants])".

The operator needs information about the functional purpose of the part of the system influenced by the disturbance, that is information about the design goals (intended function) of the system

2. "Consider whether the situation can be counteracted by reconfiguration, that is to use other functions or resources."

Here the operator must have information about the process operations and about the functions and equipment that each process operation use.

3. "Find the root cause of the disturbance and determine how it can be corrected."

Information about components, their connections and locations are required.

In Pedersen and Lind (1999) the task of disturbance handling is further decomposed using Rasmussen's decision ladder. Each of the seven steps in the decision ladder might be further specified as shown in Table 3.4.

Detection	be aware of the number of alarms in the alarm list check that process variable A is below xx when the status of B is on, etc.
Observe	if a disturbance is detected check the following process variables and states: Process variable B, state of C, state of H, etc.
Identify	if process variable B is within range and state of C is on, then disturbance in process operation X if status of H is off and process variable B is out of range, then disturbance in process operation Y
Interpret	disturbance in process operation X threatens personal safety disturbance in process operation Y means that production is not optimal
Evaluate	Personal safety have higher priority than production optimisation, therefore solve problem regarding safety
Define Task	Get people out of area ZZ shut down plant section ZZ, that is: disable process operations X, Z and start process operation “fast shut down”
Formulate procedure	Plan which parameters and set points must be changed and which digital components must change status
Execute	enter needed parameters, adjust set points, manipulate digital components

Table 3.4. An attempt to decompose the steps in Rasmussen’s decision ladder.

It is observed that it is difficult to specify the operator’s tasks in detail without a specific plant at hand. The main reason for this is that the functional allocation between the automatic control system and operator determines the details in the operator’s activities.

Further notice that unanticipated events are not covered in this approach. According to the ecological design principles, the physical constraints of the plant must be mediated if the operators shall be capable of handling unanticipated events.

Production optimisation

When knowledge about the optimal production for each subsystem is available, production optimisation can be dealt with in the same manner as disturbance handling, because deviations from the optimal production can be interpreted as a disturbance and can be treated as such.

More often though detailed knowledge about the optimal production is not available and it is the task of the operator to “get the most out of the plant”. In that case, it is not possible to state or predict a sequence of operator tasks. The important issues are 1) that the operators get the information needed from the entire plant because optimisation must be made globally and 2) that the information is visualised in a manner so that the operator can see the correlation and relations between presented information and can see what can be done to optimise the production.

Regarding problem 1) experts of the actual plant will be able to explicitly state the primary process variables. Notice that it is the process variable that is of interest and the digital components are the means to manipulate the process variable. For example, it is the temperature or flow, which influence the overall process and, accordingly, it is the status of a heat exchanger and pump which control the temperature and flow.

Problem 2) of visualisation is therefore the main problem for the display designer regarding production optimisation, because even though the right information is presented to the operators, they may not be able to see the relations between the process variables.

Notice that the operator's span of attention should not be narrowed and therefore a hierarchy is not needed for this task. Actually the opposite is the case, nothing must be let out of consideration, that is everything must be visualised (out of sight – out of mind). The reason is that when a process operation is regarded as a whole, all components are equally important for the optimisation task – "the chain is not stronger than the weakest link".

In fact, the operator's task in production optimisation can be regarded as: analysing and exploring relations, especially correlation, between process variables.

With the restriction to visualisation of magnitudes (i.e. the quantitative level using Bertin's vocabulary, see section 2.3.3) the subtasks identified by Keller and Keller (1993) may be used. The subtasks are identify, locate, distinguish, categorise, cluster, rank, compare, associate, and correlate.

These subtasks for data visualisation in general have not been studied in further details. It is therefore unknown whether they are suitable for decomposition of the optimisation task. They are mentioned here because they are, to the author's knowledge, the only starting point available for such a decomposition.

Production planning and scheduling

During production planning the operators have to look at the production goals and figure out how they can be achieved by applying the process operations available. Therefore, the relations between the production goals and the process operations are the important information (display content). Another obstacle to the task is that process operations may be dependent on each other (interlocks), involving the dimension of time. The task of production planning and scheduling found in batch processes have not been dealt with in further detail in this project due to the fact that both cases (water treatment plant and power plants) are continuous processes.

3.2.3.2. Abstractions in Display Content

There is a close relationship between the operator tasks and the display content as indicated in the TCF framework. Therefore the display content is discussed for each of three main categories of operator tasks.

Disturbance handling

For disturbance handling, the possible static contents are operational goals, process operations, functions, components, states and intervention points. The dynamic content is state of static display entities. Further, the relations (static or dynamic) between and within the display entities must be mediated.

The shift between different levels of abstractions (operational goals, process operations and plant functions and components) is central in the task of disturbance handling. Remember how the levels in the abstraction hierarchy correspond with human strategies for diagnosis. Rasmussen (1986, page 23) mentions that the operators might not be conscious about a shift between abstraction levels. This is interesting with regard to display design, because if the operator is not conscious about the shift needed in abstraction, all the information, i.e. operational goals, process operations, functions and components, must be available at the same time. With the limited size of a computer screen, this is almost impossible for a real industrial process plant. If the operator has to navigate through individual displays for operational goals, process operations, functions and components, they will have to be aware of the shift between levels of abstraction. This problem is concerned with the integration of physical and functional representations, which is the second dimension, regarding the windows system, in Vincete's design space for process displays (see section 2.1.7.2). Recent work by Burns (1999) has shown that operators prefer the physical and functional representation integrated on one display. The scientific experiment was based on an objective evaluation of the interface however, the experiment was made using the interface for the Duress system, which is a small system compared to real process plants.

Production optimisation

For production optimisation, it is mentioned that the operator's task is to explore the process data and find correlation between process variables. It is argued that in this case a hierarchy between process variables does not exist, thereby abstraction becomes irrelevant.

The main display content is the numerical values of process variables (magnitudes) and the correlation between the process variables. Further, it is desirable that the relations between process variables and components (which influence the process variables) are visible. Moreover, the relations between components and intervention points should be shown.

Production planning and scheduling

This is a task which involves decision making and evaluation similar to what is seen in disturbance handling. The operator must decide what to do regarding operational goals, process operations and components and therefore abstractions become useful and the information can be structured in a hierarchy.

3.2.3.3. Abstractions in the Display Form

Visualisation cannot be abstracted, the content can

From the definitions of abstraction given on page 46, it is not possible to regard visualisation techniques as different levels of abstraction. Abstraction deals with notions or general qualities, whereas visualisation techniques include concrete graphical items, such as lines, text, co-ordinate systems, etc. It is not the visualisation techniques that can be abstracted but the content behind the visualisation.

In useful displays several graphical items are aggregated, e.g. a co-ordinate system consists of lines, labels (text), markers (points), etc. That is visualisation means are combinations of basic graphical types (modalities). This means that if the different graphical modalities can be identified, new visualisation can be created as combinations of the modalities. Some modalities are more capable of presenting (visualising) certain types of information than others. Therefore, if the fundamental information types can also be identified, it will be possible to make guidelines for the mapping from information types (display content) to graphical items (the display form). This is the subject for next section.

3.3. Inventing Display Elements and Visualisation

Introduction
Supporting creativeness by background knowledge

When it comes to invention of display elements and visualisation, it is not just a matter of selecting a suitable display element for the given content. As already mentioned creativity is important for inventions. To support creativity, it is believed that background knowledge is needed. Besides the design theories mentioned in chapter 2, the following topics are regarded as background knowledge for inventing process displays: information mapping including information types and graphical modalities, visual dimensions, gestalt principles and principles for cognitive support. These topics will be treated in detail after the theories from chapter 2 are related to the TCF aspects and the problems involved in inventing visualisation techniques for process displays are outlined.

Relating the theories to the TCF aspects

An attempt to provide an overview of how the theories from chapter 2 are related to the task, content, and form aspects is made in Figure 3.3. The position and extent of the theories are only meant as a rough indication of what each theory covers.

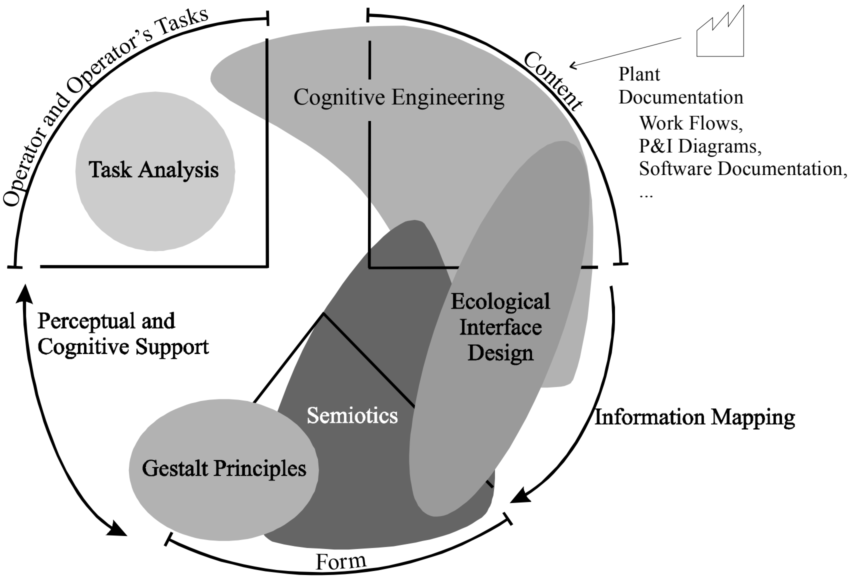


Figure 3.3. An attempt to position the theories from chapter 2 into the task, content and form aspects from the TCF framework.

3.3.1. The Problems Involved

In Pedersen and May (1998) (see appendix E), the problems involved in analytical assessment of visualisation is treated. This knowledge can also be used as the backbone for inventing new visualisation and display elements. The involved problems related to the TCF aspects are shown in Figure 3.4.

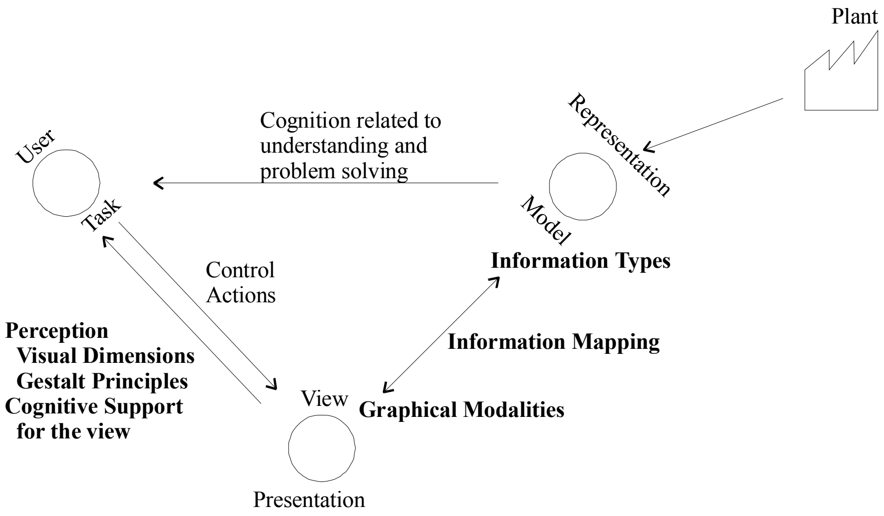


Figure 3.4. The main problems in the relations between the user's task, the plant representations (the display content) and the presentation (the form of the display).

Understanding and problem solving

The problem of selecting a representation of the plant that supports the operator's capabilities of understanding the plant processes and problem solving is shown for completeness, but not treated here. It is partly dealt with in the TCF design method (step 1 to 5) and in detail, at a more theoretical level, in cognitive engineering stating that skill, rule and knowledge-based behaviour must be supported and that the information can be structured in an abstraction hierarchy.

Control actions

Likewise, the operator's control actions are mentioned but not treated here. The theories described in chapter 2 do not provide much help for the display inventor in this matter, so the best advice for the moment is to carefully consider the use of already existing display elements for interaction, as briefly illustrated in the example in Pedersen and Lind (1999). Moreover, an eye should be kept out for upcoming interaction technologies, see e.g. appendix C, A Survey of New Display Technologies.

The other problems outlined in Figure 3.4 will be treated in the following sections.

3.3.2. Information Mapping

What is it?

As illustrated in Figure 3.4, information mapping deals with how different types of information can be presented by the use of graphical modalities.

In Pedersen and May (1998) it is argues that the types of information existing in a work domain and the visualisation techniques available must be identified. This is the subject for the next sections.

3.3.2.1. Identified Information Types in Process Displays

Within the domain of process control, the common information types are identified.

Displays analysed

Six existing displays have provided the backbone in identifying the information types. The displays were mimic diagrams, trend curves, Paulsen's dynamic overview display (Paulsen, 1996), the mass data display (Beuthel et. al., 1995), the ecological interface for Duress (Vicente and Rasmussen, 1990) and Goodstein's functional display (Goodstein, 1985). A view of the displays can be seen in chapter 4.

How the information types were identified

The method to identify the different information types has been a combination of bottom-up and top-down approaches. Bottom-up by analysing existing process displays, which gave information types such as component status, numerical values of process variables, alarm states, set points, deviation from normal condition and connections between components. Top-down by leaving the specific displays and considering abstract categories of information. The information types derived from the displays analysed were then reorganised into these abstract information categories. Notice that the information is organised in a class hierarchy, not an abstraction hierarchy, because causal relations between the classes do not exist.

The result is shown in Table 3.5. Definition for some of the terms used in the classification can be found in Appendix B.

Information types in process displays

- Magnitudes (numeric values)
  - Process variables
    - Actual value
    - Time series

    - Absolute value
    - Relative value
      - to admissible range
      - to typical range
      - to normal value

    - Division into classes/intervals
  - Status indicators
    - Actual value
    - Time series

    - Deviation from normal
- Physical Items
  - Components
    - Properties
  - Intervention points
    - Activation of process operation
    - Activation of component
    - Parameter adjustment
- Concepts
  - States
    - Actual value
    - Time series

    - Deviation from normal
  - Process Operations
    - Operator controlled
    - Automated
  - Functions
    - Design constraints
    - Constraints from laws of physics
  - Plant goals
    - Set point

    - Production
    - Safety
- Relations
  - Process variable – process variable

  - Status indicator – status indicator
  - Status indicator – process variable

  - State – process variable
  - State – status indicator
  - State – process operation
  - State – plant goal

  - Component – process variable
  - Component – status indicator
  - Component – component
  - Component – function
  - Component – process operation
  - Component – plant goal

  - Process operation – process variable
  - Process operation – status indicator
  - Process operation – function
  - Process operation – process operation
  - Process operation – plant goal

  - Plant goal – plant goal

  - Intervention point – process variable
  - Intervention point – status indicator
  - Intervention point – component
  - Intervention point – process operation
- Events
  - Progress
  - Sequence
- Location
- Language

Table 3.5. Identified information types placed in categories.

How to read Table 3.5

An example of how to read Table 3.5 follows. Process variables are placed in the category of magnitudes. The display content can either be the actual value or a time series of values. The values (actual or time series) can either be absolute or relative to either the admissible or the typical range of the process variable or relative to the normal value. Finally, both the absolute and relative value can be divided into classes, e.g. high alarm, normal value and low alarm.

Comment

It can be argued that a location is a property of a physical item (e.g. a plant component). Here location is placed in a separate class because another graphical modality is used to visualise a location which is different from the graphical modality used to visualise a physical item.

What can the information types be used for?

These information types might be useful for the display inventor in order to get an idea of what should be visualised. Further, the abstract categories can be mapped to different graphical modalities and the possible combinations between information types and modalities can be explicitly stated. This will make the design options clear to the display designer who has to visualise specific information types.

The identified information types might not be complete

It should be noted that other types of information might be found, though it is believed that these types of information cover most of the information found in process displays. Moreover, different classifications of the information types can be argued for. This classification was chosen because it was found useful for the purpose of mapping information types to graphical modalities.

3.3.2.2. A Preliminary Classification of Graphical Modalities

What is a modality?
It is the invariant semantic types across media

A modality is the invariant semantic types that can be used to express information across different media. For example, natural language is a modality, which can be expressed in the acoustic media as speech, in the graphical media as text and in the haptic media as Braille text for blind people.

Graphical modalities and invariant properties

The modalities identified by May in Pedersen and May (1998) are listed in Table 3.6 together with a description of the invariant properties of the modalities. It should be noted that this classification might be developed in further detail by specifying subtypes of the mentioned modalities; therefore the heading preliminary classification.

Modality	Invariant properties
Image	Resemblance to a physical item.
Map	Size, location, shape, and orientation maintained relative to a background, often earth.
Graph	Magnitudes mapped into space. E.g. Trend curves or bar graphs.
Structural Diagram	Size, location, shape, and orientation maintained. E.g. engineer's construction drawings.
Conceptual Diagram	Relations between items, instead of size, location and orientation. E.g. flow charts or networks.
Symbol	Simplification and recognition of entities by conventions. Examples of entities are physical items, concepts, and events.
Text	Alphabetic characters (symbols)

Table 3.6. Graphical modalities and invariant properties.

In the example explaining the difference between modality and media (in the start of this heading), it is argued that text is the graphical instance of the natural language modality. With the restriction to the graphical media it is more convenient and natural to refer to this modality as text instead of language.

An iconic relation (in the semiotic meaning) exists between the image and signified (content). An image can be anything from a photo to a sketch drawing.

Useful graphics consist of several modalities

Notice that almost every useful graphic is a combination of several graphical modalities. For example, a map is annotated with labels (text).

3.3.2.3. Possible Mappings Between Information Types and Graphical Modalities

Some modalities are better than others to present specific information

Observing the invariant properties of the modalities in Table 3.6, it is obvious that some modalities are more suitable to present given information than others. For example, a map is very good at presenting a location, whereas a symbol cannot be used to inform about a location.

In Table 3.7, the abstract categories of information types are mapped and assessed to the graphical modalities.

	Image	Map	Graph	Structural Diagram	Conceptual Diagram	Symbol	Text
Magnitude			●			⭘	●
Physical Items	●					●	○
Concepts						●	⭘
Relations		●	⭘	●	●		○
Events			⭘		⭘		○
Location	○	●		⭘			○
Language						○	●

Reader's guide.

This information type can be presented with …

this graphical modality

Legend: ● =good, ⭘=acceptable, ○=bad, = not possible

Table 3.7. Analysis and assessment of mappings between identified abstract information types and graphical modalities.

Conclusion

A conclusion is that the image, symbol and text modalities are suitable to present items and concepts as opposed to maps, graphs, structural and conceptual diagrams which mediate relations.

Text is the only graphical modality able to communicate all the information types, though it is not always the best choice (e.g. relations between several plant components are not easily described with text only). Further, text and image are the only graphical modalities that can be used individually. The other graphical modalities need to be combined with other modalities, often as a minimum with text.

All the information except events is communicated in a good (reasonable) way by one or more of the identified graphical modalities. The problem with events is that time is involved. The dimension of time can either be mapped into space using the graph modality or it can be animated. Sequences in time can be visualised by use of conceptual diagrams or described with text.

3.3.2.4. How to Use Visual Dimensions in Graphical Modalities

What is the problem?

Mapping information types to graphical modalities is the first step in determining the final view of a given content. Though more options exist than to decide how to visualise the relation between two magnitudes (e.g. process variables) in a graph (e.g. xy-plot). Questions like how can different data sets be distinguished when plotted in the same graph remain to be answered. Often such questions are not explicitly stated because it is common practice and experience has shown that, for example, colour coding can be used to separate data sets. But to give some guidelines to the display inventor on which combinations of graphical modalities and visual dimensions are possible, such questions must be considered systematically. This is the subject for this section.

Some visual dimensions are locked by the invariant properties of the modality, others are free channels

For each graphical modality, it is considered which of the visual dimensions it is able to use. Some of the visual dimensions are the backbone of the graphical modality and cannot be changed without changing the meaning of the modality. These visual dimensions are the ones used to mediate the invariant semantic properties of the modality. For example, in a xy-graph the position of the markers is locked by the invariant properties of the graph modality that is, in a xy-plot the position of the markers is given by the data and cannot be changed. But the colour or shape of the markers can, for example, be changed independently of the data. Such visual dimensions are called free channels.

During the investigation of which visual dimensions represent free channels, it was useful to distinguish between graphical items in the modality and the visual form of the modality itself. Some modalities are considered to be an aggregation of graphical items (dots, lines, areas) and other modalities are considered as a whole, even though they also consist of dots, lines and areas. For example, a map is regarded as an aggregation of areas (countries) and contour lines. A graph is an aggregation of markers and structural diagrams are aggregations of the physical items shown in the structural diagram. The symbol and text modalities are regarded as a whole, i.e. the stop sign used in traffic control is regarded as one symbol and not as a circle and a rectangle shape. This is based on the fact that it is the combination of the shapes (and colours) which signifies the meaning of a symbol, not the individual items used in the symbol (c.f. the semiotics definition of a symbolic relation as something defined by convention).

How to use Table 3.8

In Table 3.8, the result of the investigation is shown. The table should be read as follows: this graphical modality uses these visual dimensions for its invariant properties and these visual dimensions are free channels, meaning that they can be used to add further information into the modality. (The rationale for the backward reading from right to left is that the tables will be combined to a whole in Table 3.10).

	Image	Map	Graph	Structural Diagram	Conceptual Diagram	Symbol	Text
Shape	x	x	fc	x	fc	x	fc
Position	x	x	x	x	fc		fc
Size	x	x	x	x	fc	fc	fc
Orientation	x	x		x	fc		fc
Colour (hue)	x	fc	fc	fc	fc	x	fc
Brightness	fc	fc	fc	fc	fc		fc
Texture	x	fc	fc	fc	fc		fc

Reader's guide.

Free channels (fc) of the graphical modality are ...

these visual dimensions ◄

Legend: x=invariant property, fc=free channel.

Table 3.8. Relations between graphical modalities and visual dimensions.

Comments

From Table 3.8 it is seen that text have all the visual dimensions as free channels. The reason is that the signified is expressed the text not the in the form of the text. The same can be said for the conceptual diagram, because it is the relations between the entities in the diagrams which matter, not their form. Images, symbols or text can be used to represent the entities in conceptual diagrams. The relations between the entities can be expressed by any of the visual dimensions.

For graphs, either the position of the markers or the size of a shape, or both are the invariant properties used in mapping a magnitude into space. The well-known xy-plots is an example of a graph where the position of markers is the invariant property and the size of the markers can be used as a free channel. An example where the size is the invariant property is the bar graph.

It is noticed that the map and the structural diagram have the same invariant properties and it can therefore be argued that they belong to the same modality. This is done in recent (unpublished) work by May (1999b), who places maps as a special instance of structural diagrams.

3.3.2.5. Visual Dimensions and Perception

Problems and method used

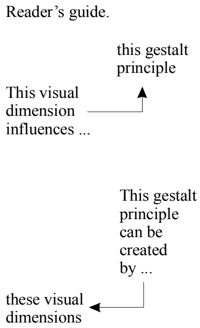
An attempt to analyse what happens when several visual dimensions are used together is treated here. For example, how does it influence the perceptional view of a modality when information is added by use of the free channels? The theory of the gestalt principles is used as an attempt to answer such questions.

What else could be done?

To the author's knowledge, more appropriate theories do not exists. Naturally, tests with human beings looking at and commenting all possible combinations of graphical modalities and visual dimensions will give better answers. But this was not considered as an option due to the resources available.

The relations between the visual dimensions and the gestalt principles are investigated and a result is shown in Table 3.9.

	Proximity	Similarity	Good Continuation	Closure	Symmetry	Smallness	Surroundness	Convexity	Orientation	Lightness
Shape		●		●	●		●	●		
Position	●	○	○	○	●		●			
Size		○			●	●	●			
Orientation		●			●				●	
Colour (hue)		●								
Brightness		●								●
Texture		●							●	



Legend: ● =good, ○=bad, = not possible

Table 3.9. Relations between visual dimensions and gestalt principles. A line between visual dimensions indicates that all visual dimension must be used simultaneously to support the gestalt principle.

Comments

Table 3.9 shows which visual dimensions can influence which gestalt principles. For example, it is seen that all visual dimensions can be used to create a perception of similarity, though position and size are not as good as the other visual dimensions.

Position is the only visual dimension that supports proximity and to some extent good continuation. Good continuation mainly deals with the perception of lines and a precondition to create good continuation is the position of the lines (they must be relatively close to or cross each other).

Similarities and differences between visual dimensions and gestalt principles

It is noticed that there is some correspondence between the gestalt principle orientation and the visual dimension, orientation, though the gestalt principle is concerned with how a view is perceived, i.e. how the vertical and horizontal orientation clearly can be distinguished. The visual dimension of orientation is concerned with the physical form of a view, e.g. this is rotated *n* degrees. Similar argumentation can be made for the relation between the gestalt principle of lightness or contrast and the visual dimension of brightness.

Visual dimensions supporting similarity can be used to distinguish groups of entities

The visual dimensions that support similarity can be used to distinguish between groups of entities when applied to different entities including data sets (magnitudes). Using Bertin's terminology (see section 2.3.3.3), the visual dimensions supporting similarity are selective, i.e. correspondence between the visual dimensions supporting similarity (Table 3.9) and the visual dimensions being selective (Table 2.2) exists. As already mentioned, Bertin does not regard shape as being selective, though shapes are used in graphs to distinguish data sets where the markers are connected by lines using the gestalt principle of good continuation.

3.3.2.6. Cognitive Support

Besides the visual perception of the combination of visual dimensions, our general perception of entities and relations in the world must be considered. May, in Pedersen and May (1998), has brought the following five principles together.

Principles for cognitive support

Natural association (e.g. high temperature → red colour).

Metonymic association (whole → part, e.g. start process operation → push button).

Metaphor (whole → whole, e.g. desktop metaphor: office desk → workspace of screen).

"Image schematic association" (e.g. vertical schema: up is more, down is less in mapping of magnitudes).

Symbolic convention (e.g. pictographic symbols in flow charts).

3.3.3. Guidelines for Creating Visualisation Techniques

The design steps and tables from the last sections are summarised in the following. The attempt is to provide some guidelines for how new visualisation techniques can be created.

The design steps in Figure 3.5 should be considered when a given information is mapped into a visual form. The design steps are inspired by May (1999a), where the content selects the modality, which specifies the presentation that displays the object. Note that May considers all media types, whereas only the graphical medium is treated here.

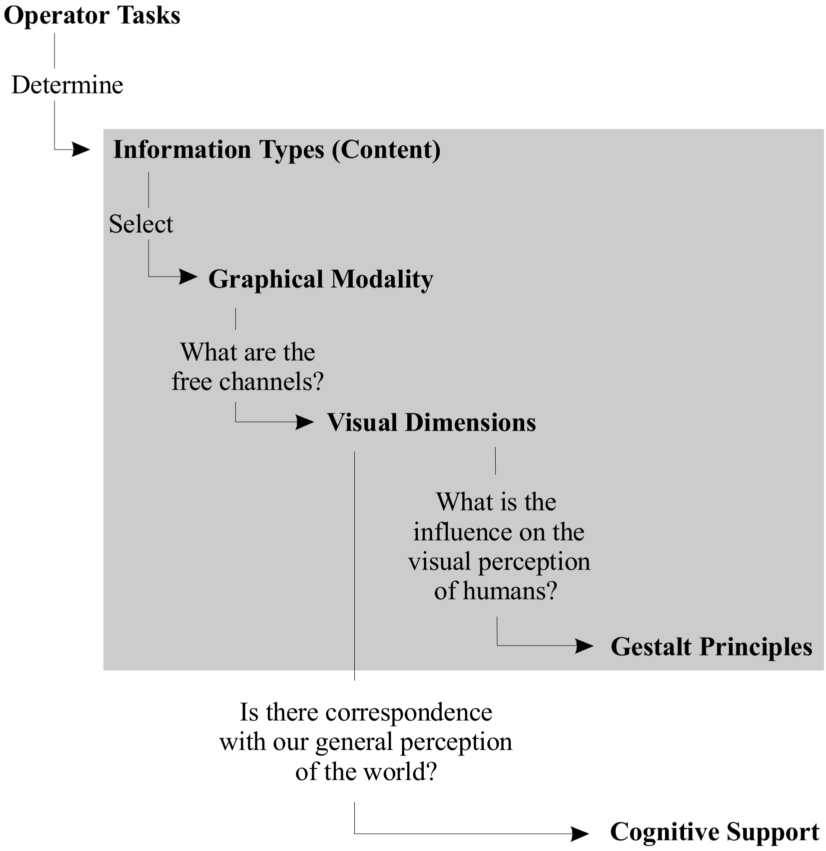


Figure 3.5. Design steps in mapping information into a view. The operator tasks and the principles for cognitive support are shown for completeness.

As an overview for the display designer Table 3.7, Table 3.8 and Table 3.9 are brought together in Table 3.10.

	Image	Map	Graph	Structural Diagram	Conceptual Diagram	Symbol	Text	Proximity	Similarity	Good Continuation	Closur	Symmetry	Smallness	Surroundness	Convexity	Orientation	Lightness
Magnitude			●			⭘	●										
Physical Items	●					●	○										
Concepts						●	⭘										
Relations		●	⭘	●	●		○										
Events			⭘		⭘		○										
Location	○	●		⭘			○										
Language						○	●										
Shape	x	x	fc	x	fc	x	fc		●		●	●		●	●		
Position	x	x	x	x	fc		fc	●	⭘	⭘	⭘	●		●			
Size	x	x	x	x	fc	fc	fc		⭘			●	●	●			
Orientation	x	x		x	fc		fc		●			●				●	
Colour (hue)	x	fc	fc	fc	fc	x	fc		●								
Brightness	fc	fc	fc	fc	fc		fc		●								●
Texture	x	fc	fc	fc	fc		fc		●							●	

Legend:● =good, ⭘=acceptable, ○=bad,   = not possible
x=invariant property, fc=free channel
connecting line indicates that all visual dimensions must be used to support the gestalt principle

Table 3.10. Possible mapping between information types, graphical modalities, visual dimensions and gestalt principles. A guide to reduce the display designer's possibilities as early as possible in the design phases.

3.3.3.1. Examples of Visualisation Design

Time history of magnitudes (process variables) known as trend curves

The time history of process variables (magnitudes) can be visualised by a 2-dimensional graph, which has the position as the invariant property and the size as free channel. The other visual dimensions are also free channels. The free channels can be used to distinguish between other magnitudes (data sets) visualised in the same graph. A visual dimension supporting the gestalt principle of similarity should be used for each data set in order to make it possible to distinguish the data sets.

Size is not very good at supporting similarity, which means that shape, orientation, colour, brightness and texture can be used. In Figure 3.6, texture and brightness are used two separate to data sets.

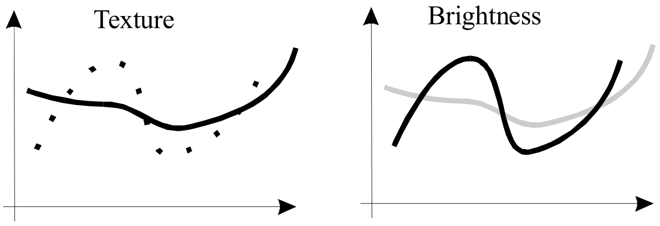


Figure 3.6. An example of how texture and brightness can be used to separate data sets.

Relations between physical items (components) and concepts (process operations)

Suppose that the relations between physical items (components) and concepts (process operations) should be mediated. Maps, structural and conceptual diagrams are the graphical modalities that are good at expressing relations. A map or structural diagram is not appropriate here because a concept is involved and concepts do not have a location (a map or structural diagram would be relevant if relations between physical items should be mediated). Therefore, a conceptual diagram is chosen.

The physical items and the concepts themselves must be visualised. A symbol is chosen for the physical items and text is chosen for the concepts.

The invariant or special feature of conceptual diagrams is that all the visual dimensions can be used to express the relations. The most obvious way to visualise the relation is by a connection line or by colour coding.

The example of a storage tank (see Pedersen and Lind, 1999) is suitable for illustrating some of the possible ways to visualise the components, the process operations and the relations between these physical items and concepts.

Static and dynamic relations

The term dynamic relation is used to emphase the dynamic behaviour of the plant in operation as opposed to the static relation between the components. Of course, the plant can be reconfigured and the relations between the components change, but this is not of interest for the scope of operating the plant.

In Figure 3.7 colours are used to mediate the dynamic relations between components and process operations. For each process operation, the components involved are shown on an individual mimic diagram.

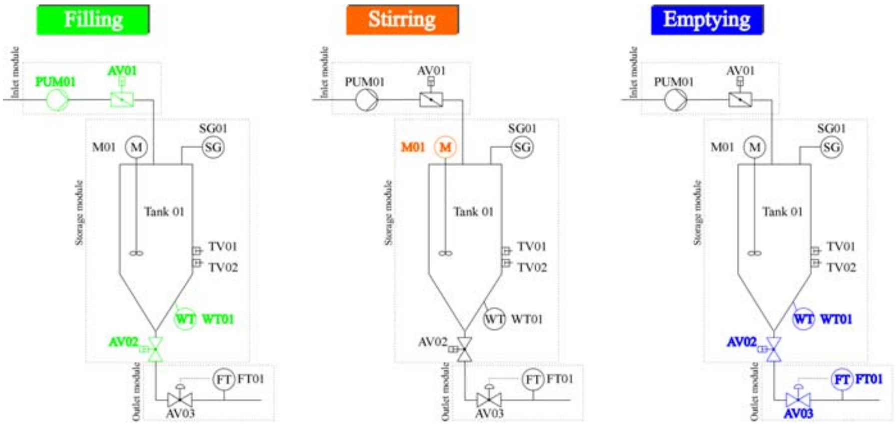


Figure 3.7. The dynamic relations between process operations and components are shown on the mimic diagrams, which mediate the static relation between components.

In Figure 3.8 connecting lines are used to mediate the dynamic relations only, meaning that the static relation in form of the mimic diagram is omitted.

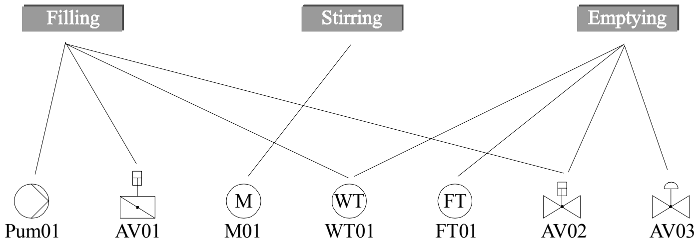


Figure 3.8. Mediating only the dynamic relations between components and process operations by use of connecting lines.

In a real plant such a view becomes very confusing because of the one-to-many relations and because of the number of components and process operations.

The one-to-many relation is the main problem, which also makes colour coding difficult. How should several colours be applied to one graphical item? An attempt to use transparent colours is shown in Figure 3.9.

Figure 3.9. Showing one-to-many relations by use of colour coding.

The one-to-many relation also makes it impossible to use the position to mediate relationships using the gestalt principles of proximity. One graphical item cannot be placed near several others without copying it.

The static relation between the components, shown by the piping and instrumentation diagram, is very useful as a background for the dynamic relations such as e.g. relations between components and process operations. It is also seen that the display easily becomes very crowded when more relations are added. This can be handled by letting the operator or the automation system control when the dynamic relations shall be shown.

Finally, the colour coding of the one-to-many relations is used in the mimic diagram making it possible to view both dynamic and static relations simultaneously. To make this simple example a bit more realistic, it is assumed that the bottom valve AV02 must be closed during stirring. This is to get an idea of how the transparent colour coding might work when three process operations use the same components. The result is shown in Figure 3.10.

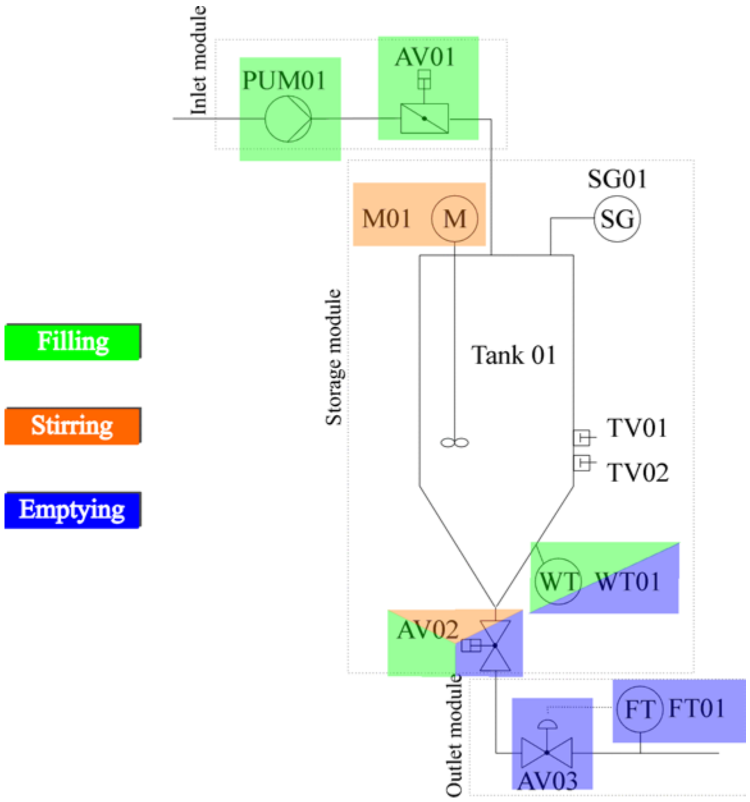


Figure 3.10. Mediating static component-component and dynamic component-process operations relations simultaneously by use of transparent colour coding.

From Figure 3.10 it is concluded that it is possible to code at least 3 entities by use of transparent colours. The static relations are still visible in the background though the focus is on the coloured dynamic relations. Whether this is useful in a real plant, where the density of components and process operations is higher, or it will appear as a mismatch of colours remain to be investigated.

Conclusion

From the examples of visualisation techniques developed and analysed by using the outlined design steps and tables, it can be concluded that the guidelines are useful as a tool for structuring the analysis and as a tool forcing the display inventor to make the design choices explicit. The formalism of the method is not complete meaning that occasionally common sense and experience must be used to argue for a certain design solution.

3.4. The TCF Framework and Vicente's Design Space

In the following, the TCF framework is compared to the design space of Vicente (section 2.1.7.2).

Summarised the design space for multilevel interfaces spans the dimensions of

1. display content (structured in an abstraction hierarchy),
2. a (window) system for integrating physical and functional representation,
3. the form of the information, and
4. means for interacting with the system.

It is obvious that the content and form aspects in the TCF framework correspond with dimensions 1 and 3. However in the TCF framework the content is organised according to the operator tasks, whereas the content is structured in an abstraction hierarchy in a multilevel interface, which is the background for the design space. Due to the organisation of information in an abstraction hierarchy, the multilevel interfaces are aimed at dealing with unanticipated events. The TCF method does not have such a specific aim but deals with the operator tasks of disturbance handling, production optimisation and production planning and scheduling, though not limited to these tasks.

The second dimension, the window system, is not dealt with in the TCF framework. The means for interaction (the fourth dimension) are integrated in the TCF method as part of the specification of the operator's activities for each task. In the TCF framework the form is dealt with in detail. Moreover, a method for using the existing display elements and guidelines for inventing new visualisation techniques are outlined.

3.5. Conclusions

Content in the framework

A framework for design of process displays has been proposed. Within the framework is a method for designing process displays and guidelines for inventing visualisation techniques. Further, the framework serves as a foundation for analysing and classifying existing and new process displays.

A method for designing displays

The starting point for the TCF design method is to use existing display elements in the final process display, i.e. building displays. This method is closely related to industrial practice and supports reuse of display modules, i.e. the aggregation of needed display elements, found as a design solution. The method is described on page 44.

Guidelines for inventing visualisation techniques

The guidelines are focused on inventing new display elements or visualisation techniques. Design steps are outlined and the possibilities for mapping given information into a form are systematically analysed and the results are given in tables explicating the possibilities of each design step. The design steps are shown in Figure 3.5 on page 61 and an overview of the design tables are in Table 3.10 on page 62.

Assessment of the TCF design method

The TCF design method using existing display elements has been illustrated by a simple example for a storage tank in a batch process. When the process operations, the operator tasks and their activities are well-defined as they normally are in batch processes it is believed, based on experience from a brewery, that the TCF design method can be applied on a real size plant. However, caution should be taken as it has not been evaluated on a real plant with batch processes.

The method has been used in the design of a supervisory display for the ejector system of a nuclear power plant (Pedersen and Lind, 1999). It is concluded that a specification of the operators' activities was difficult, because in a continuous process their main task is supervision. The supervision task was divided into the tasks of disturbance handling and production optimisation. Notice that existing displays for disturbance handing and optimisation can be used (see chapter 4 for these displays). A design solution based on existing displays is proposed in Paulsen, et. al. (1998).

In order to create a new display, Rasmussen's decision ladder was used to specify the activities within disturbance handling and it was possible to state the required display content for each activity in the decision ladder. The part of the framework dealing with the mapping from content to form was not developed at that time and therefore the form of the display was not dealt with in detail. A outline of the display for the identified content can be found in Pedersen and Lind (1999).

When the TCF design method was applied to a water treatment plant it was found useful as a procedure for how to organise the analyses and as a means for structuring the outcome of the analyses. From the analyses it became clear that existing display elements, suitable for the specific operator task at the water treatment plant, did not exist.

Conclusion about the TCF design method

In conclusion it is believed that the TCF method will help the industrial display designer in structuring the design process and will allow reuse of design solutions. If the operator's tasks and activities cannot be specified in detail, the method is not mature for industrial applications. The general problem of specifying the operator's activities in supervision has been outlined.

Assessment of the guidelines for inventing visualisation techniques

The design steps proposed for inventing new visualisation techniques have brought the theories of graphical modalities, visual dimensions, gestalt principles and the principles for cognitive support together. Further, information types in process displays have been identified. The examples of visual designs in section 3.3.3.1 have shown that the design steps and the combination of the theories have shed some light on the problem of mapping given information into a visualisation. More work on the possible combination of the information types, graphical modalities, visual dimensions and the gestalt principles can be done. Analyses of more visualisation techniques, also found outside the domain of process control and creation of more design examples will undoubtedly tighten up the relations and possible combinations within the information mapping problem. More work can also be done in specifying the subtypes for the graphical modalities.

Conclusions about the guidelines for inventing visualisation techniques

This first attempt to combine information mapping, i.e. mappings between information types and graphical modalities, with theories for visual perception has made it possible to explicitly state the opportunities for visualising specific information. It is believed that the design steps and the tables of design possibilities will help in making new visualisation techniques. Though it should be noted that more work can be done and therefore common sense and experience might need to be added when the guidelines are used. That is the design steps and tables are useful at an abstract design level but problems might be found going into detail.

Relating the TCF framework to ecological interface design principles

The backbone of the framework are the aspects of operator's tasks, the display content and the display form as shown in Figure 3.1 on page 44. The starting point for the TCF framework is the operator tasks and the information the operators need to perform their tasks. This distinguishes the TCF framework from the ecological interface design (EID) principles. EID is focused on unanticipated events mainly in energy systems. Therefore, the starting point for EID is to mediate the physical constraints of the plant because if a disturbance occurs the physical constraints will be violated and thereby visible to the operator. The information is structured in a goal-oriented hierarchy (the abstraction hierarchy) in order to support the operator in decision making during the handling of the unanticipated events.

Consequently, another difference between EID and the TCF framework is the display content. EID focuses on the causal relations in the plant, because they will be violated when a disturbance occurs, i.e. the focus is on the physics of the plant and the plant design solutions. The TCF framework focuses on providing the information that the operators need to perform their everyday tasks. Therefore, the display content identified by the TCF display design method is more oriented toward the plant processes during production than towards the design solutions when the plant was constructed.

It has been found that EID lacks methods for transforming given information (the physical constraints) into a visual form. The problem of information mapping is dealt with in detail in the TCF framework. Guidelines for possible combinations between information types (identified in process displays), graphical modalities, visual dimensions, gestalt principles and cognitive support are provided in the design steps for inventing visualisation techniques.

Finally, the EID researchers have recently investigated the problem of how to organise the information on the process display, i.e. how should information regarding physical and functional plant representation be presented. Should everything be on one display page or on separate displays? This problem of organising information in window systems and the layout of the individual display pages are not dealt with in the TCF framework.

It appears that the EID and the TCF framework deal with different problems of display design and therefore support each other. It is not a choice between one or the other but the choice depends on the display design problem at hand, that is some aspects are dealt with in EID, others in the TCF framework.

Chapter 4. Analysis and Categorisation of Displays

Contents

In this chapter some of the displays invented and used in the process industry are analysed according to the framework outlined in chapter 3. For each display the content and form are studied, using the identified information types and graphical modalities. The visual dimensions and the gestalt principles are discussed where appropriate. After such an analysis, the display is assessed with respect to which operator tasks it is suitable for. The generic categories of operator tasks from Table 3.2 are used for this classification. Moreover, the process domain for which the displays are developed is listed.

Other work

Burns and Vicente (1995) have made an analysis of existing displays with the main focus on the display content. They analyse which cells in the matrix of the abstraction hierarchy (c.f. Figure 2.8) each display supports. The visual form and the means for navigation are also treated in their report.

Delimitation

The displays encountered during this work and found relevant for process control are mentioned in the categorisation. Other displays unknown to the author might exist. The following visualisation techniques are assessed not to be directly applicable in process display but mentioned for completeness. Chernoff's faces, a kind of glyphs display, parallel coordinates (Budny, 1995), and the information mural (Jerding and Stasko, 1996).

Fisheye views as a part of non-linear graphical transformations have been studied (Furnas (1986), Churcher (1995), Keahey and Robertson (1996), and Zinser (1995)). Algorithms for implementation are given in the first three references. Fisheye views are regarded as navigation means similar to zooming and panning. It should be noted that the visual dimensions of size and position are distorted by the non-linear transformation and fisheye views are therefore best suited for conceptual diagrams where the relations between entities are in focus. Care should be taken if fisheye views are used on graphs where the size and position are the invariant properties.

Wistrand and Ahlberg provide means for interactive filtering and selection in their glyphs display (Wistrand (1994), Ahlberg and Wistrand (1995)), but this is not treated in further detail here because their domain have been databases mainly for marketing and advertisements. However, it is obvious to transform some of their ideas to the domain of process control.

4.1. Categorisation Criteria, Operator Tasks

Rationale for categorising by operator tasks

The displays are categorised according to the operator task they support. The operator task is chosen as the key for the categorisation because it is the first aspect in the TCF framework described in chapter 3. The use of the operator task as primary key for the categorisation implies that the alternatives for display builder can be reduced as soon as it is decided which operator task the display shall support.

A further specification of the operator tasks shown in Table 3.2 is given below.

Disturbance handling

The task of disturbance handling can be further specified into the following three tasks.

- **Failure detection**, that is the activation process (the first step in the decision ladder) making the operator aware that something unusual has occurred.
- **Evaluation and decision making**, i.e. assessment of consequences, possibilities and deciding what to do.
- **Failure location**, i.e. identification of where the disturbance has occurred. The identification can be on different abstraction levels of the plant models, for example, which process operation is influenced or which subsystem or component has failed.

Usually, a disturbance is caused by a component failure, including supplies of power, air, etc., but depending on the actual plant state different actions must be taken. In severe situations it is enough for the operators to know which process operations or subsystems are threatened so they can focus on bringing the plant in a stable state. Other times it is not critical and the operators can concentrate on locating the failed component.

Production optimisation

A display is categorised as useful for production optimisation if it is possible to see several main process variables and states and their relationships. Often such relationships are mediated in a geometric shape or pattern, which change its form according to the changes in the process variables and states. Such displays are known as object displays (Carswell and Wickens, 1987) or configural displays. A change of the shape or pattern is easily perceived due to the human being's pattern recognition capabilities (c.f. the discussions regarding rule-based behaviour in chapter 2). Therefore, such displays will also work in failure detection tasks, the first step in disturbance handling.

Moreover the time history of process variables will often be useful in production optimisation because the gradient or rate of change of the process variables are revealed. The trend of several process variables over time also mediates how a process variable influences other process variables. However, it is not a necessity that the time history of process variables is shown in production optimisation displays.

Production planning and scheduling

The main properties of a display for production planning and scheduling are relations, especially the interlocks between process operations and the relations between process operations and process equipment. The aspect of time is important, meaning that the dynamic relations between the process operations should be visible both in the past, present and in the future. If it is decided to start a process operation tomorrow it should be possible to see how it influences the other process operations running today and tomorrow. Planning and scheduling displays are relevant for batch processes and for start-up and shut-down in continuous process plants.

Support for intervention

Finally, it is considered if the operator has a possibility to control the plant from the display. Usually, the operators have to perform some control actions before any of the above-mentioned tasks are completed.

The most suitable task is written first in the categorisation below

In the categorisation below one display is often suitable for more than one of the tasks. The most suited task is mentioned first. The task of supervision includes both disturbance handling and optimisation. Moreover, notice that especially the task of production planning and scheduling differs from the other tasks and that no existing displays for this task have been analysed. One reason is that the task is most relevant in batch processes and that the majority of the research on process displays has been focused on the nuclear power industry.

The displays are mentioned in alphabetic order. The displays suggested in this work by the author are annotated with “(New)” after the display title.

4.2. Batch Tracking Display (New)

An idea to a batch tracking display is sketched in Figure 4.1. The idea evolved from Tufte’s descriptions of Japanese timetables for railways (Tufte, 1990).

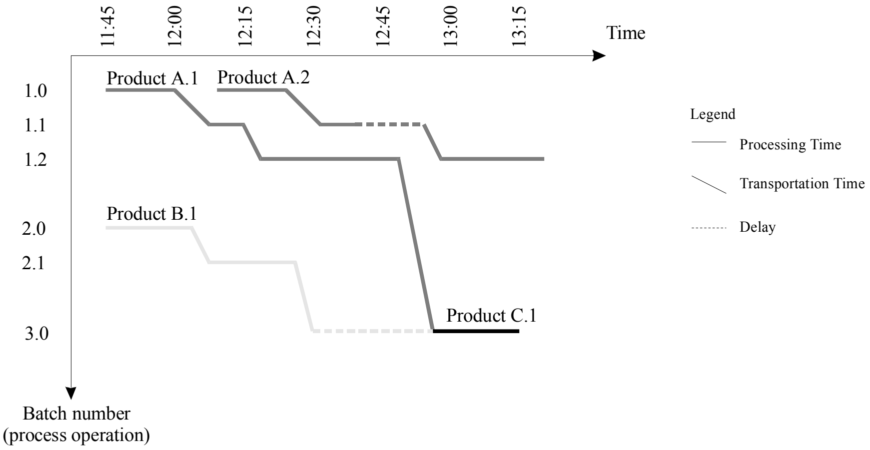


Figure 4.1. A sketch of an idea for a batch tracking display.

Operator Task: Planning and scheduling

Process Domain: Batch processes

Content (information types)	**Form** (graphical modality)
Process Operations (time history)	Graph
Batch products (time history)	Symbols (coloured lines)
Relations, process operation – batch products – time	Graph

Comments

The display shows the process operations (batch processes) along the y-axis and time on the x-axis. Colour coding is used to separate different groups of process operations. The time needed to complete a process operation is shown as horizontal lines and the time needed for transportation of material from one processing unit to another is shown as diagonal lines. In Figure 4.1 it is seen that the products from process operations 1 and 2 are mixed in process operation 3. It is possible to see when the processing units are ready for a new batch and delays in the processes are mediated (in Figure 4.1 by a dotted line).

This display is only a rough idea (from the author) and it has not been studied in detail due to the fact that both the case studies (water treatment and power plants) deal with continuous processes.

Reasons for the classification

The display supports planning and scheduling because it is possible to see the relations between the batch products and the processing units over time, making delays visible.

4.3. Colour Gradients Display (New)

A display based on colour gradients of process variables is developed in this work by the author and shown in Figure 4.2 (see section 5.1 for details).

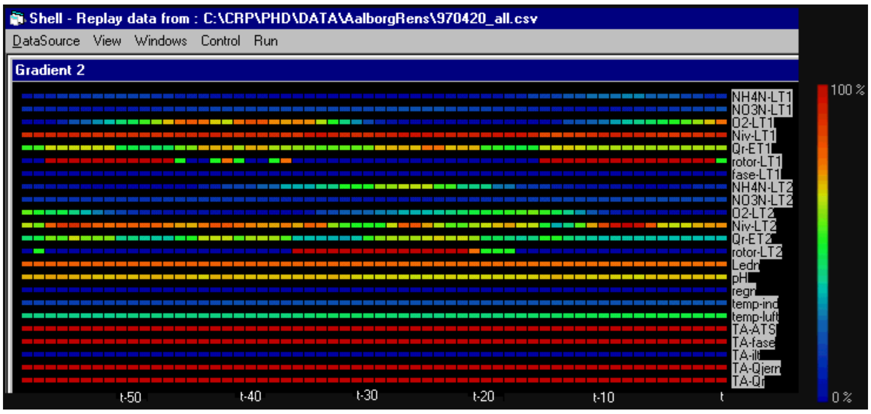


Figure 4.2. A colour gradient display.

Operator Task: (Production optimisation)
(Disturbance handling),
(Failure detection)

Process Domain: All systems

Content (information types)	**Form** (graphical modality)
Process variables (time history)	Symbols (colours) embedded in a graph
Relations, process variable – process variable	Colour patterns of symbols

Comments

The idea behind the display is to map the range of process variables to a colour gradient. For example 0 % of the range equals blue, 50 % equals green and 100% equals red, a value of 75% of the range will the be presented as (127, 127, 0) in the RGB (Red, Green, Blue) colour scheme ranging from 0 to 255.

The time history of the process variables is shown on the x-axis and the process variables are placed on the y-axis as shown in Figure 4.2. Due to the limited space needed to present the colour for a given value it is possible to present many different process variables and many samples of the process variables. Similar work is reported by Hashimoto, et. al. (1998) though their conclusion differs from the one below.

In practice it appeared to be difficult to see the difference between the nuances of the colours. This is in correspondence with Bertin who argued that colour (hue) is not a quantitative visual dimension (see Table 2.2) and should consequently not be used to visualise quantitative data variables. Therefore, it must be concluded that this display does not fulfil the intentions of providing an overview of many process variables simultaneously and fails to support production optimisation and failure detection in disturbance handling. The multi-variable supervisory display (in section 4.14 on page 89) circumvents this problem of colour perception and is therefore recommended as a supervisory display for many process variables.

Reasons for the classification

Due to the visualisation of the relations between process variables, the display was intended for production optimisation, because it should have been possible to see how a process variable influences other process variables. Failure detection should be supported when the colour deviates from the usual colour. Due to the problems of perceiving colour nuances, mentioned above, the display fails to support these operator tasks in practice. Moreover the display is not suitable for colour blind people.

4.4. Compact Trend Display

The compact trend display proposed by Azevedo, et. al. (1995) is shown in Figure 4.3.

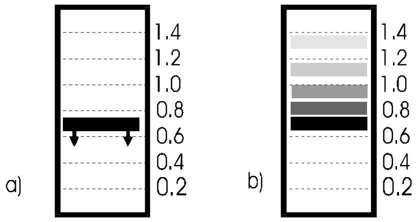


Figure 4.3. Suggestions for compact trend displays, which are to be integrated with other displays. Shades of grey represent the development over time (from Azevedo, et. al. (1995)).

Operator Task: Disturbance handling,
Failure detection
(Failure location)

Process Domain: All (developed for power distribution)

Content (information types)	**Form** (graphical modality)
Process variable (time history)	Graph

Comments

The idea is to present the time history in a more compact way than in trend curves. Trend curves are usually shown in a separate window so the operator has to navigate to such a window to see the time history of process variables. Compact trends are intended to be integrated into other displays e.g. mimic diagrams to allow the operator to get an idea of the trend of process variables without having to navigate to another window. The length of the time history is limited in these displays to perhaps a maximum of 8 to 10 samples in Figure 4.3b where the darkest bar represent the latest measured value at time *t*, the next darkest bar represent the value at time *t-1* and so on. In Figure 4.3a only a trend indication is shown.

Reasons for the classification

The compact trend display is categorised as a possible means for failure detection because it is possible to add expected values and alarm limits to the display. Moreover, for a usually steady process variable a deviation from the previous samples are mediated. If the compact trend display is positioned near the equipment on which the process variable is measured, the display will support failure location.

4.5. Dynamic Overview Display

Paulsen’s dynamic overview display for a pipe reactor is shown in Figure 4.4 (Paulsen, 1996).

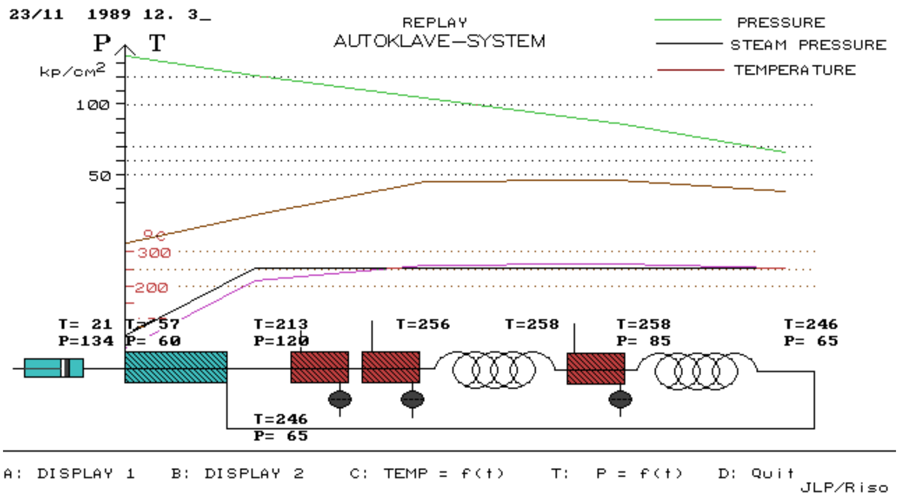


Figure 4.4. Paulsen’s dynamic overview display for a pipe reactor (received from Paulsen)

Operator Task: Disturbance handling,
    Failure detection
    Failure location
Production optimisation

Process Domain: Chemical and energy systems

Content (information types)	**Form** (graphical modality)
Process variables Temperature Pressure (Flow)	Graph
Components	Symbols
Physical constraint (assessment criteria) Saturated steam pressure	Curve embedded in graph
Relations, component – component	Conceptual diagram, component symbols for nodes and lines for relations
Relations, process variable – component	Symbols positioned at the x-axis of the graph
Relations, process variable – process variable	Graph

Comments

The symbols for the components placed at the x-axis of the graph represent the topology of the plant. In fact it can be regarded as a simple mimic diagram. The strength of the display lies in the relation between the process variables and components, yielding e.g. the temperature distribution over the plant. But it also gives a limitation when the components have to be placed on a line, that is the component's location must be ordered in a sequence because the components are placed on the x-axis of the graph.

Any type of process variable can be shown in this display as long as they are measured at several locations in the plant and there is a flow of production materials between the measurements.

Moreover, the expected distribution of a process variable can be shown as a dotted line behind the actual measurements, making the deviation from the expected distribution visible.

The saturated steam pressure, that is the physical constraint of the system, is calculated from temperature measurements. In order to avoid boiling in the pipe reactor, the pressure must be kept above the saturated steam pressure.

Reasons for the classification

The dotted line showing the expected values together with the relations between process variables and components make the display suitable for failure detection and location in the task of disturbance handling. The relations between the different process variables and the distribution of one process variable over the plant support optimisation, according the criteria made for a production optimisation display.

4.6. Ecological Interface for the Duress System

Vicente's ecological interface for the Duress system is shown in Figure 4.5 (Vicente and Rasmussen, 1990). The Duress system is briefly described in section 2.2.2.

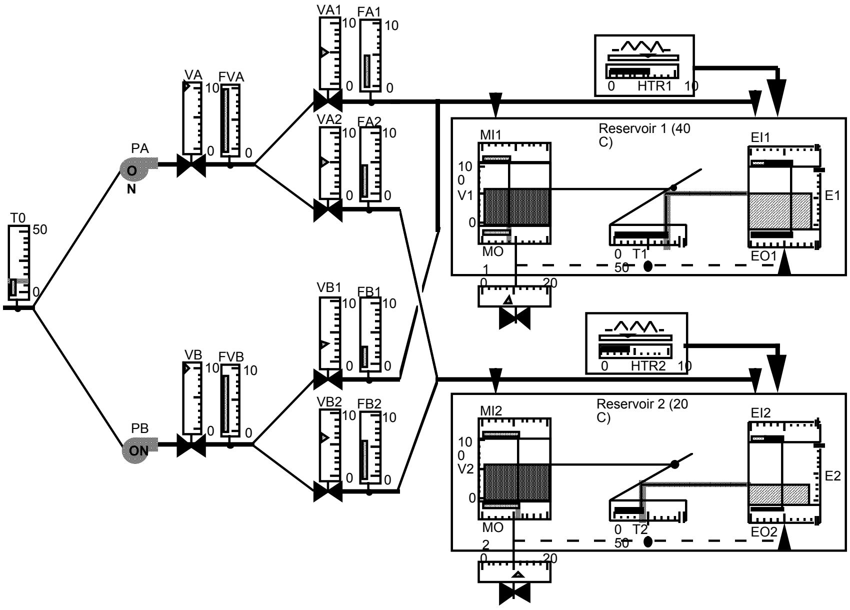


Figure 4.5. Vicente's ecological interface for the Duress system.

Operator Task: Disturbance handling,

- Failure detection
- Failure location
- Evaluation and decision making

Operator actions (supports intervention)

Process Domain: Energy systems

Content (information types)	**Form** (graphical modality)
Process variables Temperature Energy Flow Water level	Graphs (bar graphs and seesaw construction)
Status (of digital components)	Symbols (colour coding)
Components	Symbols
Intervention points	Symbol (triangle in bar graph)
Physical constraint Process dynamics	Seesaw construction
Relations, component – component	Conceptual diagram, component symbols for nodes and lines for relations
Relations, process variable – component	Position of bar graphs near or inside (energy and water reservoir) the component symbol in the conceptual diagram
Relations, status – component	Colour coding of component symbols (pumps)
Relations, process variable – process variable	Graph, the seesaw construction
Relations, intervention point – component	Position of bar graphs with intervention point symbol (triangle) near the component symbol in the conceptual diagram Invisible on the pumps. Operators change pump status by clicking on the pump symbols
Relations, intervention point – process variable	Lines in the conceptual diagrams representing the relation between the symbol for the intervention point and the bar graph for the energy or water level

Comments The aim of the display is to support diagnosis of unanticipated events. It is created from the ecological design principles (section 2.2). Its strength is the seesaw construction, which mediates the dynamic behaviour of the process. That is the mass and energy balance (first order differential equations) and the temperature equation describing the relations between energy, temperature and the volume of the water. This also means that the seesaw construction only can be used when the dynamic behaviour for the process at hand corresponds to the mass and energy balance and the temperature equation of an energy system.

Reasons for the classification

The relations between the process variables given by the laws of physics for the energy system are mediated by the seesaw construction. If a failure occurs that violates these relations (physical laws) it will be visible to the operator through the seesaw construction and the input-output relations in the mass and energy reservoirs. Therefore, the display supports failure detection.

It is the seesaw construction mediating the dynamic behaviour of the process that enables evaluation and decision making when unanticipated events (disturbances) occur. Further, the relations between process variables and intervention points combined with the seesaw construction make it possible for the operators to figure out which intervention points to manipulate in order to fulfil their intentions.

Due to the seesaw construction and the relations between process variables and components, the operator is able to induce the source of error roughly (failure location). From the display it is observed that the inlet pipe system, the heater and the outgoing flow influence the energy reservoir whereas the inlet pipe system and the outgoing flow influence the mass reservoir. The relation between the energy and mass reservoir is mediated by the seesaw construction.

The intervention points in form of triangle symbols in bar graphs allow the operator to control the plant from the display.

4.7. Ecological Interface for a Power Plant Feedwater Subsystem

Dinadis and Vicente (1996) created a display for a feedwater subsystem for a nuclear power plant based on the ecological design principles for interfaces. The display is shown in Figure 4.6.

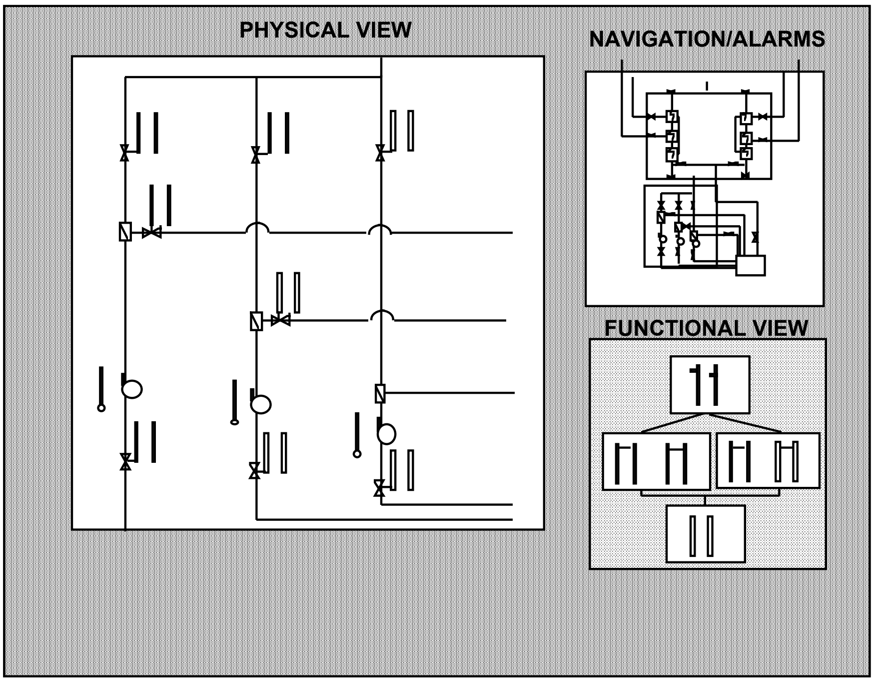


Figure 4.6. Dinadis' and Vicente's feedwater subsystem display for a nuclear power plant. The display is based on the ecological design principles.

Operator Task: Disturbance handling,

- Failure detection
- Failure location
- Evaluation and decision making

Operator actions (supports intervention)

Process Domain: Energy systems

Content (information types)	**Form** (graphical modality)
Process variables Temperature Pressure Flow Level	Graph (bar graphs) (in physical and functional view)
Status (of digital components)	Symbols (colour coding) (in physical view)
Components	Symbols (in physical view)
Process operations	Images (rectangles) (in functional view)
Intervention point (only one)	Symbol (triangle in bar graph) (invisible in Figure 4.6)
States (alarm)	Symbols (colour coding) (in physical, functional and navigation/alarm view)
Physical constraint (assessment criteria) conservation of mass	Line between bar graph of input and output of mass for sub-system (in functional view)
Relations, component – component	Conceptual diagram, component symbols for nodes and lines for relations (in physical view)
Relations, process variable – component	Position of bar graphs near the component symbol in the conceptual diagram (in physical view)
Relations, status – component	Colour coding of component symbols (in physical view)
Relations, states (alarm) – components	Colour coding of component symbols (in physical view)
Relations, states (alarm) – process operation	Colour coding of image (rectangle) representing the process operation (in functional view)
Relations, process operation – process operation	Conceptual diagram, images (rectangles) for nodes and lines for relations (in functional view)
Relation, intervention point – process variable	Colour coding, same colour of the intervention point (triangle) and the process variables influenced (invisible in Figure 4.6)

Comments

The display consists of three views: the functional, the physical and the navigation and alarms view.

The functional view contains what in this thesis is referred to as process operations. For a distinction between functions and process operations, see Appendix B and Pedersen and Lind (1999). Further, bar graphs are embedded into the images (rectangles) representing the process operations. The input and output of the mass for a subsystem are shown in the bar graphs. Further, each of the chosen subsystems follow the mass conservation law. Therefore, a disturbance in the subsystem is easily detected because the line connecting the input and output bar graph will not be horizontal if the mass balance is violated.

The content of the physical view is determined from a system analysis of the plant based on the abstraction hierarchy. It is the lower levels of the abstraction hierarchy that are mediated in the physical view. At the physical function – component level, in the abstraction hierarchy, the view is similar to a conventional mimic diagram.

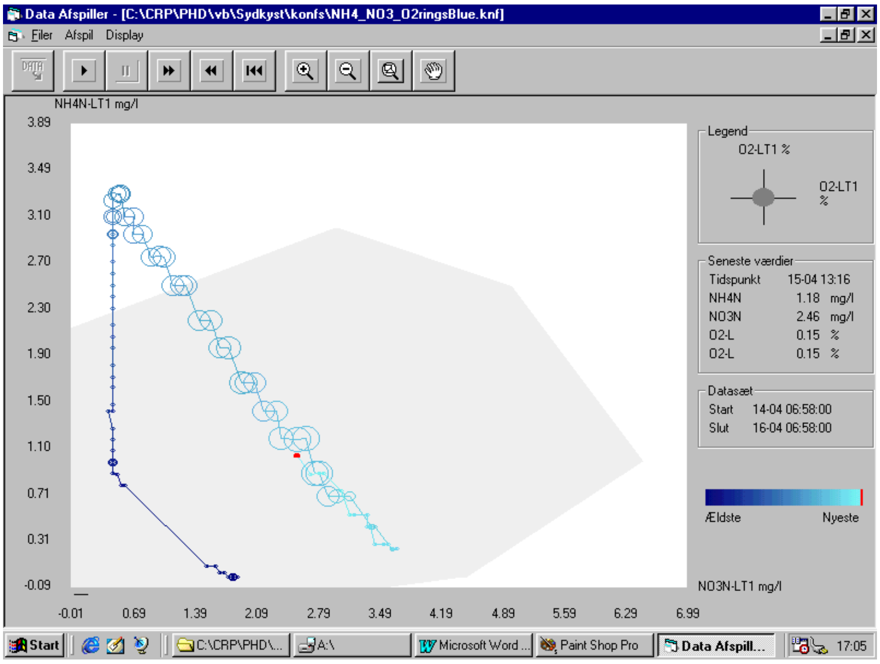
The navigation and alarm view is used to change the content of the physical view. The navigation and alarm view shows the relations between parts of the physical view. Colour coding is used to mediate alarms in the higher levels of the abstraction hierarchy (above physical functions).

Reasons for the classification

The use of colour coding for alarm states allow failure detection in all three views. The relation between the navigation and alarm view and the physical view makes failure location possible. The different levels of abstraction used in the physical view together with the functional view support evaluation and decision making.

4.8. Glyphs (in Process Displays, New)

The display developed by the present author for the water treatment plant is shown in Figure 4.7. For details regarding the design see chapter 5 and Pedersen and May (1998).


Data Afspiller - [C:\CRP\PHD\vb\Sydkyst\konfs\NH4_NO3_O2ringsBlue.knf]

Seneste værdier
Tidspunkt 15-04 13:16
NH4N 1.18 mg/l
NO3N 2.46 mg/l
O2-L 0.15 %
O2-L 0.15 %

Datasæt
Start 14-04 06:58:00
Slut 16-04 06:58:00

Figure 4.7. Glyphs display for a water treatment plant. A xy-plot embedded with circular markers. A colour gradient is used to show the development over time and zones of plant states are shown on the background for the primary graph. (A bright background is printed and a dark shown on the screen).

Operator Task: Production optimisation

Disturbance handling,

Failure detection

Process Domain: All (developed for water treatment plant)

Content (information types)	**Form** (graphical modality)
Process variables (time history)	Graphs embedded in graph
Constraints (assessment criteria) Operational states	Zones embedded in graph
Relations, process variable – process variable	The xy-plot shows the relations between the primary variables. The form of the marker (here a circle) shows additional variables

Comments

The primary process variables are shown in a xy-plot. The shapes of the markers show the secondary variables. Here a circle is used, but notice that any polygon or e.g. the polar star display could be used as markers. The development over time is shown by a colour gradient from light blue to dark blue. The marker for the latest sample is coloured red. Further, lines connect the markers from sample to sample in order to support the gestalt principle of good continuation. Zones are placed on the background of the primary graph to indicate areas that the process should be kept within. Only one zone is shown in Figure 4.7, but it is possible to add more zones and give some advice to the operators of what to do in case the process enters the different zones.

An outline of a circle is used so it is possible to see smaller circles within a bigger one. The problem of overlapping markers is partly solved by a zooming and panning facility. However, difficulties might appear if e.g. a polar star display is used for markers. That leads to another problem regarding the scaling of the secondary variable due to the relatively small size of the markers. It is possible to detect a change in size or an asymmetry of a few pixels but still the range of the process variable has to be mapped to a relatively small number of pixels compared to the pixel range of the primary variables on the x and y axis.

Notice that the embedding of a graph into another graph gives several possibilities to add additional information by use of the free channels of the graph modality (see Table 3.10). The perceptual consequences of adding information must be considered i.e. when free channels are used to add information, the perception of the display must be taken into account using the gestalt principles.

One problem with the graph of the secondary variables is that the scale is not visible, meaning that only the relative value to other visible samples can be judged. It is not possible to see how big the circles can grow. Therefore, experiments with visualisation of the scale of the secondary process variables have been made. Lines (in e.g. a grey colour) have been used but the crosses representing the scales for the elliptic markers become very focused when the markers are close to each other (in areas with a high density of markers). Four dots have been used to indicate the maximum and minimum value of the width and height of the elliptic markers, but due to the gestalt principle of proximity it was difficult to determine which markers the dots belong to. Finally, colour coding of the scaling axes have been used as alarm indicators. The axis of the process variable in alarm was coloured cyan when the value was below a predefined lower limit and pink when the value was above a predefined higher limit. For views of these experiments, see chapter 5.

Reasons for the classification

The display supports production optimisation because the relations between several process variables over time can be viewed simultaneously. The zones in the background of the primary graphs make failure detection possible.

4.9. Goodstein's Equipment Display

Goodstein's equipment display for a power plant is shown in Figure 4.8 (Goodstein, 1985).

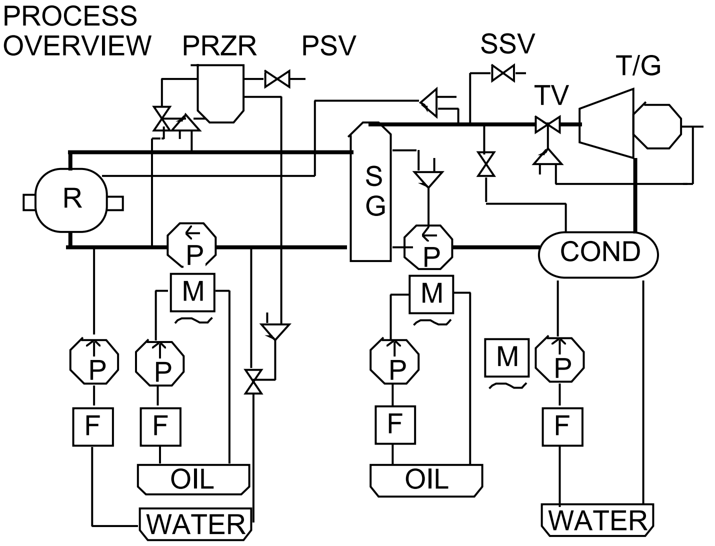


Figure 4.8. Goodstein's equipment display for a power plant.

Operator Task: Disturbance handling,

Failure detection

Failure location

Process Domain: Energy systems

Content (information types)	**Form** (graphical modality)
Components	Symbols and text (abbreviations)
States (alarm)	Symbols (colour coding)
Relations, component - component	Conceptual diagram, component symbols for nodes and lines for relations
(Dynamic) relations, (alarm) state - component	Colour coding of component symbols

Comments

This display is identical to a mimic diagram. It should be used together with Goodstein's functional display, making it possible for the operator to shift between a functional view and equipment (component) view of the plant. A component in failure is detectable by colour coding or by flashing.

Reasons for the classification

The display allows failure detection and location because the component in alarm can be easily observed and found due to the colour coding or flashing.

4.10. Goodstein’s Functional Display

Goodstein’s functional display for a power plant is shown Figure 4.9 (Goodstein, 1985).

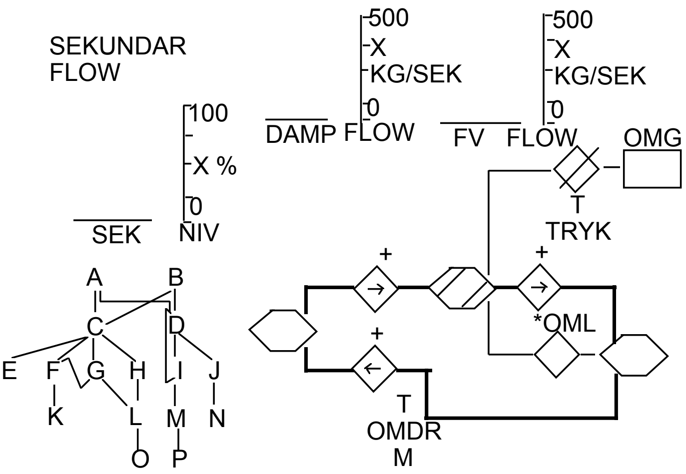


Figure 4.9. Goodstein’s functinal display for a power plant.

Operator Task: Disturbance handling,

Failure detection

Evaluation and decision making

Failure location (rough)

Process Domain: Energy systems

Content (information types)	**Form** (graphical modality)
Process variables Flow	Graph
Process operations	Symbols
Functions	Symbols (MFM[5])
States (alarm)	Symbols (colour coding)
Relations, process operation – process operation	A conceptual diagram embedded with symbols (letters) in a hierarchy
Relations, process operations – functions	The interaction between the process operation hierarchy (to the left) and the diagram with MFM symbols (to the right) mediates the relation. When a process operation is selected by the operator, the functions involved are shown.
(Dynamic) relations, (alarm) state – process operation	Colour coding of process operation symbols in the hierarchical conceptual diagram

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[5] Multilevel Flow Modelling (Lind 1990, 1994)

Comments

Goodstein calls the hierarchical diagram the functional alarm display. The letters A-P represent the plant functions during operation, which in this thesis is referred to as process operations. The hierarchical structure of the diagram corresponds to different levels of the MFM model of the plant (Lind, 1990, 1994). The other diagram is also based on MFM, and describes the plant functions as created during the design and building of the plant. The hierarchical diagram (to the left in Figure 4.9) describes the relation between the process operations. The diagram with MFM symbols (to the right in Figure 4.9) describes how the selected process operation is instantiated at an abstract information level, that is which and how the functions existing in the plant are used for this process operation.

The dynamic behaviour of the plant in the form of alarm states is embedded on the letters in the hierarchical display by use of colour coding. The letters represent the process operations. Moreover, the most important process variables are shown at the top of the display.

Goodstein's intention was to use the functional display together with the equipment display. The operators are able to evaluate the consequences of a disturbance and to decide what to do in the functional display (Figure 4.9) and are able to get detailed information about the plant construction, needed for failure location, in the equipment display (Figure 4.8).

Another aim of the display was to ease the information retrieval for the operator. The hierarchical diagram and the correspondence between the selected process operation and the appearance of the MFM diagram support this aim.

Reasons for the classification

Due to the relation between the process operations and the process operation – function relations, this display is suited for the part of disturbance handling dealing with evaluation and decision making, i.e. the operator can see which process operations are threatened if a low-level process operation is in alarm. Failure detection is supported by the colour coding of the process operation in alarm. Rough failure location is possible on the level of process operations and plant functions.

4.11. Lindsay's Display

Lindsay's display for a nuclear power plant is shown in Figure 4.10 (Lindsay, 1990).

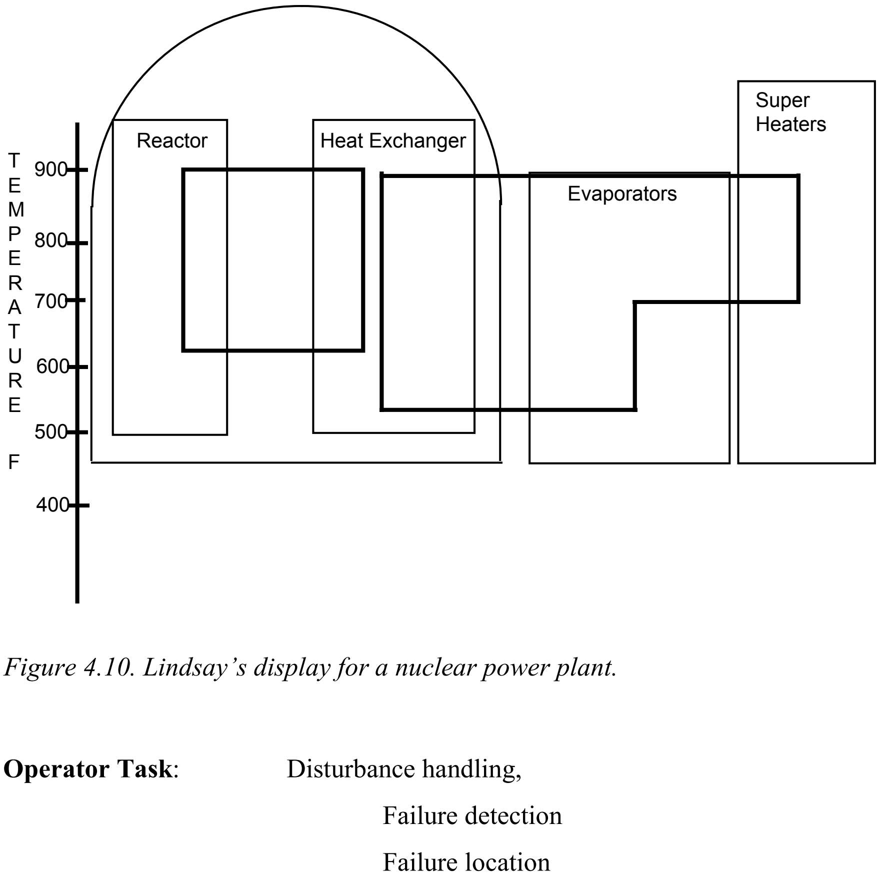


Figure 4.10. Lindsay's display for a nuclear power plant.

Operator Task: Disturbance handling,

Failure detection

Failure location

Production optimisation

Process Domain: Energy systems

Content (information types)	**Form** (graphical modality)
Process variables Temperature	Graphs (bar graphs)
Components	Images (sketch drawings)
Relations, process variable – component	Graphs embedded in the simple image of the components
Relations, process variable – process variable	Graphs

Comments

The graphs are one-dimensional and oriented vertically, that is the vertical lines in the graph polygons. There is a temperature measurement at each corner of the polygons. The temperature of the flow into the reactor is measured as well as the temperature of the outgoing flow. T_{in} and T_{out} are also measured on both sides of the heat exchanger, on the evaporators and on the super heaters. The horizontal lines represent the flow of water and steam in the primary and secondary system of the power plant.

It would be possible to place polygons representing the expected values in this display, making it possible to see the deviation for expected values and thereby support failure detection.

Reasons for the classification

The display can be used for failure detection in disturbance handling, if it is possible to see when a measurement deviates from its expected value. Moreover, the form of the polygons makes it easy to see if something changes. It is the embedding of the graph into the simple image of the components that makes failure location possible.

According to the chosen categorisation criteria production optimisation is possible because the relations between the temperature variables can be seen. For example, in case of fouling in the heat exchanger, the temperature of the outgoing flow on the secondary side will be lower than normal (and after some time the temperature out of the primary side will increase). Also the loss in the heat exchanger can be seen as the difference between the position of the top vertical line of the two polygons.

4.12. Mass Data Display

Beuthel, et. al. (1995) describes the mass data display for a power plant. The display is shown in Figure 4.11.

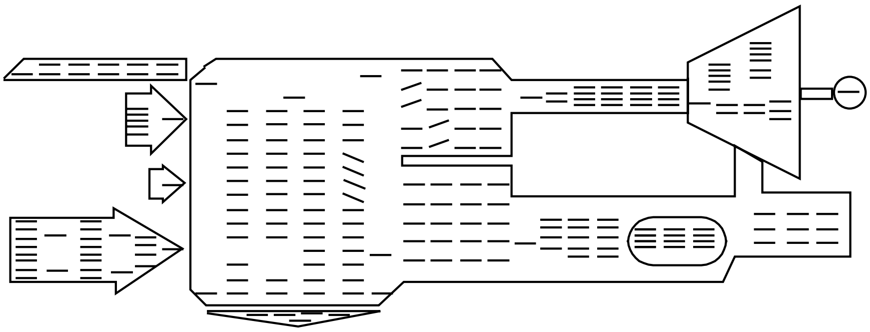


Figure 4.11. A mass data display for a power plant.

Operator Task: Disturbance handling,

Failure detection

Failure location

Process Domain: Energy systems

Content (information types)	**Form** (graphical modality)
States	Symbols (Orientation of lines) One symbol (orientation) for each state
Components	Image (sketch drawing)
Relations, component – states	Position of symbols embedded in the image
Relations, states – states	Grouping of symbols by orientation

Comments

The sketch drawing (image) shows the mass flow of the plant products. Further, main subsystems or components are shown in the drawing (e.g. the turbine in Figure 4.11), making recognition easier for the operator. The state of process variables and status indicators are shown by symbols. Beuthel, et. al. (1995) experimented with different symbols and concluded that the orientation of a line is the best perceivable symbol. Beuthel, et. al (1995) encodes 3 different states (above, below and normal). In Pedersen and Lind (1999) the derivative of the process variables is added (increasing, decreasing, steady).

The symbols are placed in different groups on the image, using the position of the symbol and the gestalt principle of proximity. The relations between different states are achieved by the visual dimension orientation, which supports the gestalt principle of similarity. This is further supported with the gestalt principle of orientation, stating that human beings perceive and group objects of similar orientation.

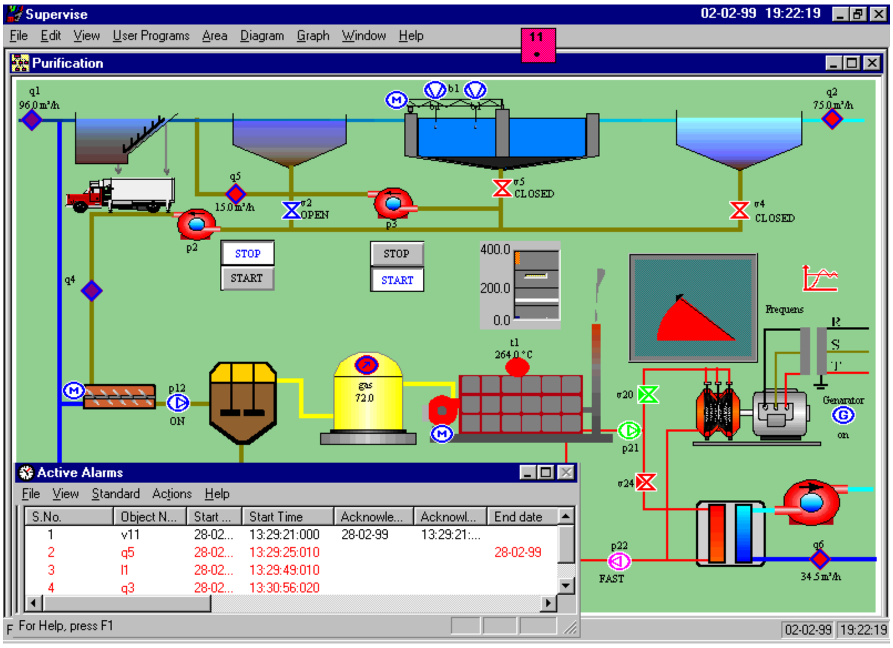
Another benefit of the mass data display is that it is possible to show the state of many components, subsystems, process operations, etc. simultaneously, due to the pattern recognition capabilities of human beings.

Reasons for the classification

A failure, here a deviation from the normal state, is shown by the orientation of the line. This supports failure detection. When the symbols are placed on a sketch drawing of the production flow of the plant, it is possible to locate in which part of the plant the disturbance occurred, making the display suitable for rough failure location. Even though the relationships between several process variables can be seen, the display does not support production optimisation. The reason is that the continuous process variables are divided into classes (states) and that the time history is not shown making a comparison between values of the process variables impossible.

4.13. Mimic Diagram

A typical mimic diagram, including an alarm list, is shown in Figure 4.12.



S.No.	Object N...	Start ...	Start Time	Acknowle...	Acknowl...	End date
1	v11	28-02...	13:29:21:000	28-02-99	13:29:21:...	
2	q5	28-02...	13:29:25:010			28-02-99
3	l1	28-02...	13:29:49:010			
4	q3	28-02...	13:30:56:020			

Figure 4.12. A typical mimic diagram including an alarm list (from the IGSS demo system).

Operator Task: Disturbance handling,

Failure detection

Failure location

Operator actions (supports intervention)

Process Domain: All systems

Content (information types)	**Form** (graphical modality)
Process variables	Text (digits), colour coding or graphs

Status (of digital components)	Symbols (often colour coding) or animation
Components	Symbols
States (alarm)	Symbols (colour coding) or animation (flashing)
Intervention points	Standard Windows input objects (buttons, sliders, combo boxes, etc.)
Relations, component – component	Conceptual diagram, component symbols for nodes and lines for relations
Relations, process variable – component	Text (digits) or bar graphs positioned near the component symbol
Relations, status – component	Colour coding of component symbols or occasional change of symbol
Relations, (alarm) state – component	Colour coding or flashing of component symbols
Relations, intervention point – component	Position of intervention point near or integrated with component symbol

Comments

This is the most common type of process display and it is based on the piping and instrumentation diagrams of the plant. The complexity of the alarm system varies, though most SCADA system providers make it possible to give priorities to alarms.

The display shows very detailed information of the plant topology and the actual value of process variables and the status of components. Therefore, the trained operator, knowing the functionality of individual or groups of components, will be able to derive the plant state.

Reasons for the classification

The alarm system and its coding of the component symbols in the conceptual diagrams make failure detection and location possible. The operator’s possibility to interact with the system by using intervention points is supported.

4.14. Multi-Variable Supervisory Display (New)

The multi-variable supervisory display proposed from this work by the present author is shown in Figure 4.13.

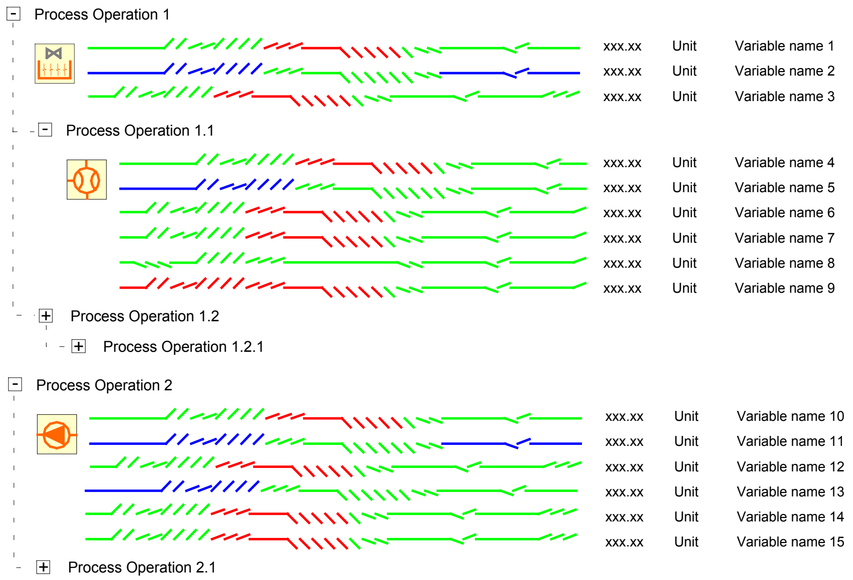


Figure 4.13. The proposed multi-variable supervisory display for the ejector and condenser system of the nuclear power plant, Barsebäck.

Operator Task: Disturbance handling,

Failure detection

Failure location

Evaluation and decision making

Production optimisation

Process Domain: All (example from energy systems)

Content (information types)	**Form** (graphical modality)
Components (modules)	Symbols
Process operations	Text
States (time history)	Symbols embedded in graphs
Process variables	Text (name, value and unit)
Relation, process operation – process operation	Conceptual diagram (tree view hierarchy)
Relations, process operation – component	Symbol embedded in conceptual diagram (tree view)
Relation, process variable - component	Position of text for name, value and unit of the process variable in the hierarchy according to the component
Relations, state - state	Grouping of symbols by orientation

	and colour

Comments

The display was proposed for the condenser and ejector system of the Swedish nuclear power plant Barsebäck, but can in principle be used in any working domain. The TCF design method is used to identify the process operations, the modules (of components) and the primary and secondary display content (which are process variables). The basis of the display is the tree view structure (conceptual diagram) shown to the left in Figure 4.13. The tree view structure supports the TCF design method because the hierarchy of process operations, symbols for modules and trends of states of process variables are identified and shown.

Process operations in form of text are embedded into the nodes of the tree hierarchy. Nodes can be expanded or collapsed as known from Microsoft's Windows system. A hierarchy of process operations is shown and a symbol representing the primary component in the module is shown for the top level process operations to mediate the relationship between process operations and component modules. For each process operation (at all levels) the value, name and unit of the related process variables are shown to the right in the display. The values of a process variable are divided into two types of classes (states). The alarm states are low, normal or high alarm shown by colour coding (blue, green and red). The other states are classifications of the derivative of the process variable. Five states are used (fast increasing, increasing, steady, decreasing and fast decreasing) and the orientation of the line segment (symbol) mediates these states.

The states of the process variables are shown over time. This makes it possible to see how a change in a process variable propagates through the plant and which other process variables it might influence.

The idea behind the display was to take advantage of the pattern recognition capabilities of humans and at the same time mediate the relations between process operations, components (modules) and actual measurements (process variables).

Reasons for the classification

Failure detection is supported by the classification of the process variables into states regarding the value (alarm states) and the derivative of the value (trend states) of process variables. The colour coding and orientation of the symbols representing these states make it visible to the operator when a disturbance occurs. The relation between process variables, modules of components and process operations makes failure location possible at different abstraction levels. Evaluation and decision making is supported by the tree view of process operations and the related component modules.

Production optimisation is supported because it is possible to see the relations between the states of the process variables over time.

4.15. Polar Star Display

A polar star display for a power plant is shown in Figure 4.14 (Burns and Vicente, 1995).

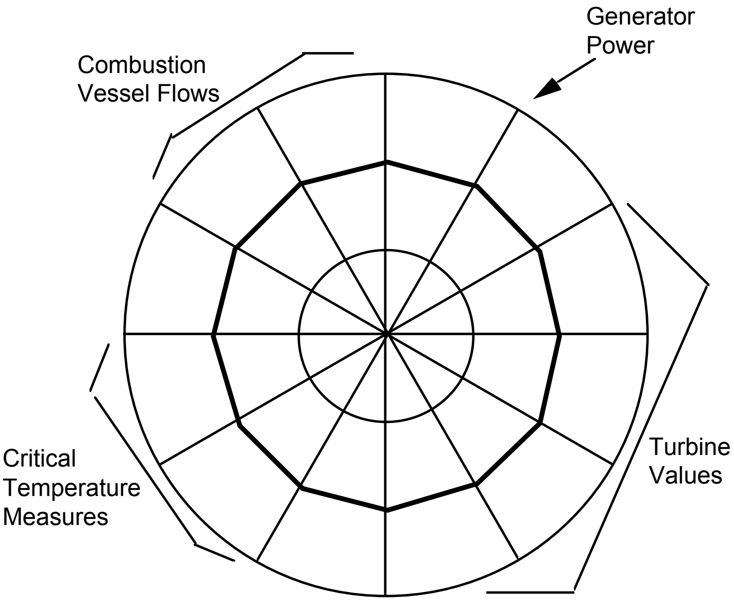


Figure 4.14. A polar star display for a power plant.

Operator Task: Disturbance handling,

Failure detection

Production optimisation

Process Domain: All (example from energy systems)

Content (information types)	**Form** (graphical modality)
Process variables	Graphs
Constraint (assessment criteria) Normal, equalised values of process variables	Curve connecting graphs
Relations, process variable – process variable	Form of curve connecting graphs

Comments

Carswell and Wickens (1987) refer to this type of display, where multiple sources of information are integrated into a single form, as object displays. They are also called configural displays.

The process variables shown in the polar star display are all equalised so the lines connecting the graphs form a symmetric shape when the actual values of the process variables match their normal values. Due to the gestalt principle of symmetry, it is easy to see a deviation from normal.

Moreover, the relationships between the process variables are clear, because simultaneous changes in several process variables will be noticed in the shape.

Reasons for the classification

A change in the shape is easily noticed and therefore the display supports the task of failure detection. Production optimisation is supported because simultaneous changes in several process variables can be distinguished.

4.16. Pressurizer Display

Weisang has created the display shown in Figure 4.15 for pressurizers in power plants (Burns and Vicente, 1995).

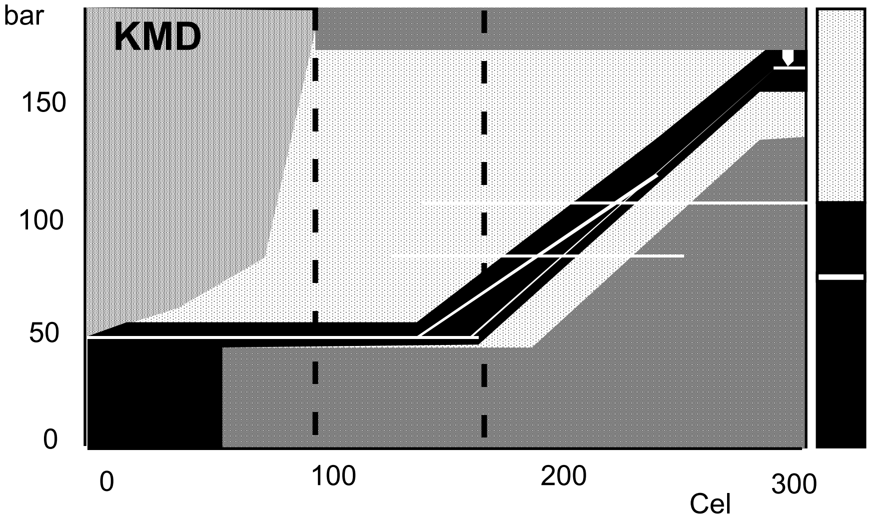


Figure 4.15. Weisang's pressurizer display for power plants.

Operator Task: Production optimisation

Disturbance handling,

Failure detection

Process Domain: Energy systems

Content (information types)	**Form** (graphical modality)

Process variables Temperature Pressure	Graph
Constraints (assessment criteria) Operational states (zones)	Zones embedded in graph
Relations, process variable – process variable	Graph

Comments

The analysis is based on the description in Burns and Vicente (1995). The display is a xy-plot of temperature and pressure, where the actual value is shown by a crosshair. The hatched zones embedded in the graph show different states of operations. The black zone from the bottom-left to the upper-right corner is the ideal state for the pressurizer. The operators should attempt to keep within this zone, also during start-up and shut-down.

To the right is a magnification of the area around the crosshair.

Reasons for the classification

The xy-plot shows the correlation between the process variables and indicates to the operator the ideal state of the process variables. The relations between the process variables are mediated and hence it possible to use the display for optimisation according to the categorisation criteria.

At the same time, the operator can see deviation from the ideal state making failure detection possible.

4.17. Rankine Cycle Display

Beltracchi's Rankine Cycle display in shown in Figure 4.16 (Beltracchi, 1995).

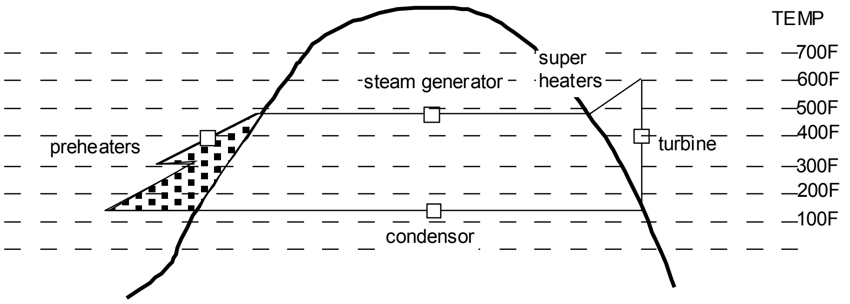


Figure 4.16. Beltracchi's Rankine Cycle display.

Operator Task: Disturbance handling,

Failure detection

Failure location

Production optimisation

Process Domain: Energy systems

Content (information types)	**Form** (graphical modality)
Process variables Temperature	Graph

Entropy Pressure	
Components	Symbols and text
Physical constraint (assessment criteria) Saturated water line	Curve embedded in graph
Relations, process variable – component	Symbols embedded in graph
Relations, process variable – process variable	Graph

Comments

The Rankine cycle is based on the temperatures and the pressures in the process. The entropy is along the x-axis and the temperature on the y-axis. The Rankine cycle describes the changes of phases from water to steam throughout a power plant. To the left of the saturated water line (the thick parable formed curve) is subcooled water and to the right is a two-phase mixture of saturated water and saturated steam. Colour coding is used to distinguish subcooled water and steam. The components embedded in the graph mediate in which part of the plant a change of phase takes places, i.e. the relation between component and process variables.

Reasons for the classification

The symbols representing the plant's subsystems are embedded into the Rankine cycle graphs and make it possible to see where a change in the temperature takes places. Therefore, the display can be used for failure location in disturbance handling. Moreover, the shape of the Rankine cycle will change and thereby attract operator attention and thus supports failure detection.

Throughout the Rankine cycle it is possible to see how the temperature in one part of the cycle influences the next part. That makes it useful for production optimisation. For example, if the temperature after the superheater could be higher, and the increase through the superheaters cannot be better, the temperature after the preheaters should be increased, as the temperature is constant through the steam generator.

4.18. Time Tunnel Display

Hansen's time tunnel display for a power plant is shown in Figure 4.17 (Hansen, 1989).

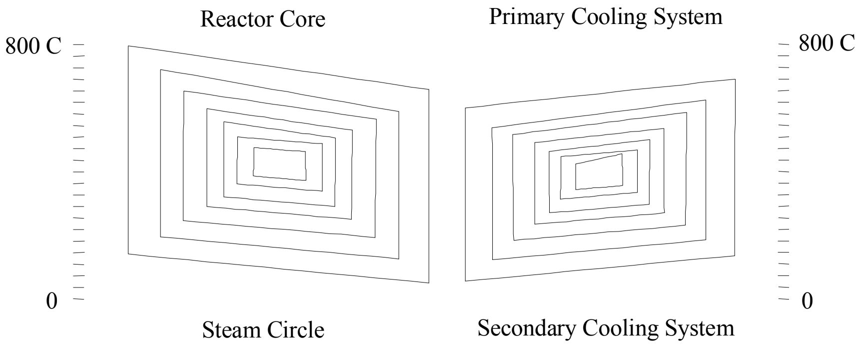


Figure 4.17. Hansen's time tunnel display for a power plant.

Operator Task: Disturbance handling,

Failure detection

Production optimisation

Process Domain: All (example from energy systems)

Content (information types)	**Form** (graphical modality)
Process variables (time history)	Graphs
Relations, process variable – process variable	Form of curve connecting graphs

Comments

The idea behind the time tunnel display is similar to the polar star or object displays, except that the development of the process variables over time is included. Moreover, the form of the display supports Gibson's ecological perception theory. Very briefly and simplified Gibson's ecological perception theory can be said to deal with the dynamics of the world as opposed to the gestalt principles mainly dealing with static visual features.

The third dimension is used to visualise the time history. The advantage is that the development of the relations between the process variables over time is mediated and that a change in this relationship is easily perceived as a change of shape. One difficulty with 3D projections on to the plane is that some graphical objects might be hidden behind objects in the foreground. Therefore, a means of navigating in the 3D space is required and needs to be learnt.

Reasons for the classification

Failure detection is supported because a change in a variable is seen as a change in the shape, which can be compared to the other shapes representing the development of the process variables over time.

The relations between the process variables and the development of these relations over time are mediated in the time tunnel display making it suitable for production optimisation.

4.19. Trend Curves

Trend curves are often used in combination with the mimic diagrams, either integrated in the mimic diagram window or placed in a separate window. A typical trend curve is shown in Figure 4.18.

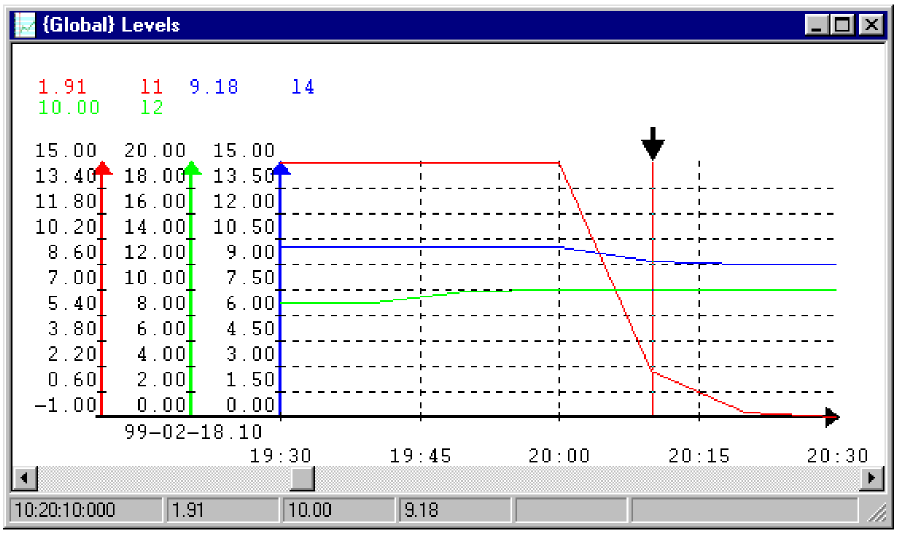


Figure 4.18. Typical trend curve (produced from the IGSS SCADA system)

Operator Task: Production optimisation

Disturbance handling,

Failure detection

(Failure location)

Process Domain: All systems

Content (information types)	**Form** (graphical modality)
Process variables (time history)	Graph
Relations, process variable – process variable	Graph

Comments

The display is used to see the development over time of process variables. From the display it is possible to judge the “level” of the variables, that is its percentage of its range, and to judge whether a variable is increasing, decreasing or steady.

When more than one process variable is shown in the same graph it is possible to monitor the relationships between the variables, which is used for production optimisation.

If the expected values of process variables are added to the graph or if the operators know them, it is possible to use the display for failure detection. Usually, the expected values are not integrated in the trend curves. Even though the display is used for failure detection and location. In case a disturbance has occurred and the cause cannot be found, trends of the relevant variables are used as an aid in determining the state of the process operations or components in order to locate the disturbance. Hence trend curves are used as a tool together with other display types in knowledge-based problem solving.

The visual dimensions of colour coding or texture are often used to distinguish the process variables. This gives a limitation of 5 to 8 variables for each trend window and less if expected values (set points) and alarm limits are added.

Reasons for the classification

According to the categorisation criteria the trend curve display is suitable for production optimisation because it reveals the relationships between process variables over time.

If expected values are added to the graph, failure detection will be possible from the display.

As mentioned above, it can be used for failure location during knowledge-based behaviour problem solving.

4.20. Summary and Discussion

Table 4.1 gives an overview of which display types are suitable for which tasks.

	Disturbance handling			Production optimisation	Planning and Scheduling	Operator Actions
	Failure detection	Failure location	Evaluation and decision making			
Ecological Interface for the Duress System	✓	✓	✓			✓
Ecological Interface for Power Plant Feedwater Sub-system	✓	✓	✓			(✓)
Mimic diagram	✓	✓				✓
Multi-Variable Supervisory Display (new)	✓	✓	✓	✓		
Dynamic Overview Display	✓	✓		✓		
Lindsay's Display	✓	✓		✓		
Rankine Cycle Display	✓	✓		✓		
Trend Curves	✓	(✓)		✓		
Polar Star Display	✓			✓		
Pressurizer Display	✓			✓		
Time Tunnel Display	✓			✓		
Glyphs Displays (new)	✓			✓		
Colour Gradients Display (new)	(✓)	(✓)		(✓)		
Goodstein's Functional Display	✓	(✓)	✓			
Goodstein's Equipment Display	✓	✓				
Mass Data Display	✓	✓				
Compact Trend Display	✓	(✓)				
Batch Tracking Display (new)					✓	

Table 4.1. The analysed displays grouped according to the operator tasks they support. The tasks in parenthesis are possible but the display is not well-suited for these tasks.

In Table 4.1 the displays analysed are listed according to the operator tasks they support. The order in which the displays are mentioned within a group of operator tasks is arbitrary. It is the grouping according to operator tasks which is interesting. Within a group of operator tasks it is not assessed which display is the better for the tasks. The purpose of the grouping is twofold; 1) it serves as an overview for the display designer in selecting an existing display for a certain operator task and 2) as the basis for analysing whether there is a correspondence between the display content and the operator task supported by the display.

Table 4.2 shows the correspondence between operator tasks and display content. The batch tracking display is not considered in Table 4.2 because the concept of batch products and the relations between process equipment, products and time have not been part of the identified display content. The display content was identified from displays for mainly continuous processes.

Opr. Task	Display Name	Time history	Process variables	States	Status	Components	Intervention points	Process operations	Functions	Physical Constraint	Constraint	Relations, component – component	Relations, process variable – component	Relations, process variable – process variable	Relations, status – component	Relations, intervention point – component	Relations, intervention point – process variable	Relations, state – component	Relations, state – process operation	Relations, process operation – process operation	Relations, process operation - function	Relations, process operation - components	Relations, state – state
FD FL E&DM OA	Ecological Interface for the Duress System		✓		✓	✓	✓			✓		✓	✓	✓	✓	✓	✓						
	Ecological Interface for Power Plant Feedwater Subsystem		✓	✓	✓	✓	✓	✓		✓		✓	✓		✓		✓	✓	✓	✓			
FD, FL, OA	Mimic diagram		✓	✓	✓	✓						✓	✓		✓			✓					
FD, FL, E&DM, PO	Multivariable Supervisory Display	✓	✓	✓		✓		✓					✓					✓		✓		✓	✓
FD FL PO	Dynamic Overview Display		✓			✓				✓		✓	✓	✓									
	Lindsay's Display		✓			✓							✓	✓									
	Rankine Cycle Display		✓			✓				✓			✓	✓									
PO FD	Trend Curves	✓	✓											✓									
	Polar Star Display		✓								✓			✓									
	Pressurizer Display		✓								✓			✓									
	Time Tunnel Display	✓	✓											✓									
	Glyphs Display	✓	✓								✓			✓									
	Colour Gradient Display	✓	✓											✓									
FD, (FL), E&DM	Goodstein's Functional Display		✓	✓				✓	✓										✓	✓	✓		
FD FL	Goodstein's Equipment Display			✓		✓						✓						✓					
	Mass Data Display			✓		✓												✓					✓
	Compact Trend Display	✓	✓																				

Table 4.2. An overview of the display content for each display analysed. The displays are grouped according to the operator tasks they support. The time history column indicates whether the aspect of time is part of the display content and the grey cells indicate what content is shown over time.
FD = Failure Detection, FL = Failure Location, E&DM = Evaluation and Decision Making, PO = Production Optimisation, OA = Operator Actions. (FD, FL and E&DM are parts of disturbance handling.)

Discussions

From Table 4.2 it is seen that the displays covering most operator tasks are also the displays containing most information. Other displays are more specific, only aimed at a few tasks and therefor contain less information.

Notice that even though some of the display content might be identical, the form of displays might differ significantly. An example is trend curves and time tunnels which have identical content but very different views.

One conclusion that can be made from the relations between operator tasks and display content in Table 4.2 is that components are needed for detailed failure location. However, as mentioned earlier failure detection can also be made at a higher abstraction level, e.g. location of the process operation in failure. This higher level failure detection is closely connected to evaluation and decision making in disturbance handling. A failure will usually take place in a physical item (component) and therefore components are needed as display content in order to locate the root cause of a failure.

Further, the displays supporting production optimisation mediate relations between process variables. However, this is not surprising because the classification criteria for production optimisation was that relations between process variables should be shown. The ecological interface for the Duress system also shows the relations between process variable but is not classified as supporting optimisation. The reason is that the relations between process variables, based on the laws of physics, are shown in order to visualise the occurrence of disturbances.

It should be noted that the ecological interfaces show more information than the other displays, i.e. more entities and more relations are mediated in the two ecological interfaces analysed. Though Goodstein's equipment and functional displays together show the same information as the ecological interfaces except for intervention points. Goodstein's functional display is the only one mediating functions and the relations between process operations and functions.

The multi-variable supervisory display is the only display, which explicitly visualise the relations between process operations and plant components. The process operation – component relations are implicitly shown in the ecological interface for the feedwater subsystem and in Goodstein's equipment and functional displays by giving the operator the opportunity to see the components (and functions) that are related to a specific process operation.

Only the ecological interfaces and the mimic diagram contain intervention points allowing the operators to control the plant from the interface.

Suggestion for further work

A table showing the relations between content and form is not constructed due to the fact that the taxonomy of graphical modalities can and should be further developed. Moreover, the relations between graphical modalities, visual dimensions and gestalt principles should be studied in more detail before a content–form table will provide an insight into the display design problem.

4.21. Conclusion

Fourteen existing and four new displays have been analysed according to the TCF framework. The overall categorisation of operator tasks and the identified information types have been found useful in the analysis and categorisation. Further, it has been possible to relate each information type to graphical modalities and when relevant the influence of the visual dimensions and gestalt principles has been discussed.

As shown in Table 4.1, groups of displays supporting the same operator task have been identified and the operator tasks supported by the individual displays have been made explicit.

From the analyses it is not possible to give any conclusion as to what display content is needed for a specific task. The reason is that the display content has been used, as part of the categorisation criteria, to determine what operator tasks a displays are suitable for.

Chapter 5. New Display Elements and Visualisation

Contents

The displays developed, by the author as part of the project, are described in detail. The focus is also on the development process, therefore the displays are mentioned in chronological order. The case studies and the problems involved in operating the processes and in the display design are described. Knowledge of the plant processes and the problems involved are mainly obtained through informal interviews and meetings with plant operators and other experts. Moreover, the TCF design method applied on the case studies are discussed. The implementation of prototypes and the problems in reusing display elements are mentioned.

The batch tracking display proposed in chapter 4 is not treated further because the idea has not been relevant for the case studies.

5.1. A Supervisory Display, No Specific Case Study

The first idea

In the beginning of the project, after the literature study, the intention was to create a supervisory display, which at the same time provided detailed information about process variables and information about the entire plant state. The idea was to take advantage of the pattern recognition capabilities of human beings and to map values of process variables to colours. Colours were used because a colour can be presented by a few pixels on the screen, which makes it possible to visualise many process variables and the time history of these process variables. The display in Figure 5.1 shows such a colour gradient display.

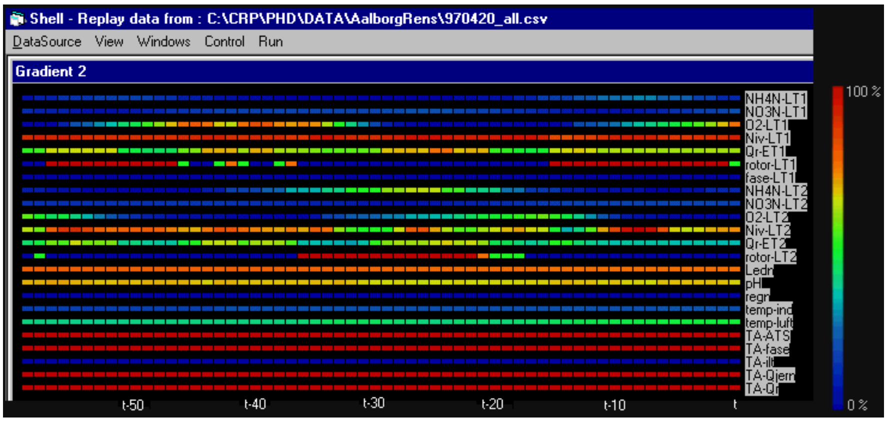
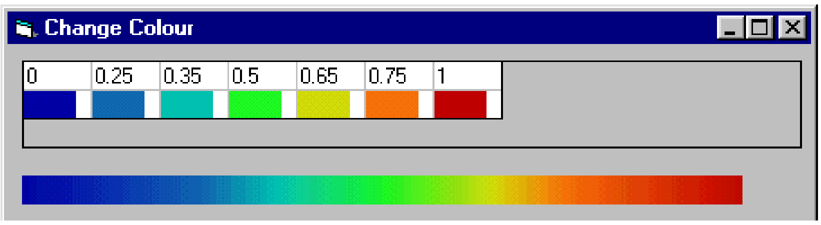


Figure 5.1. A colour gradient display. The time history is on the x-axis with the newest sample to the right. Each value of the process variable is mapped into a colour using the gradient shown to the right. Data are from a water treatment plant.

Mapping values to colours

In order to transform the value of process variables into a colour, a maximum and minimum range of the process variable must be known. Further the colour gradient must be defined. Linear interpolation in the RGB colour scheme was used as indicated in Figure 5.2.



0	0.25	0.35	0.5	0.65	0.75	1
🟦	🟦	🟦	🟩	🟨	🟧	🟥

Figure 5.2. Mapping the values of process variables to a colour gradient. The top row is percentages of the value range. For each percentage value a colour is defined. Between the percentage values the colours are blended using linear interpolation in the RGB colour scheme. The resulting colour gradient is also shown. The number of percentage values are determined by the user and "sharp edges" in a colour gradient can be made by entering the same percentage value twice and assigning different colours.

Difficulties in defining the colour gradients were encountered because nuances of the darker colours are more visible to humans than nuances in bright colours. Experimentation with different colour gradients have been made and the better ones are shown in Figure 5.3.

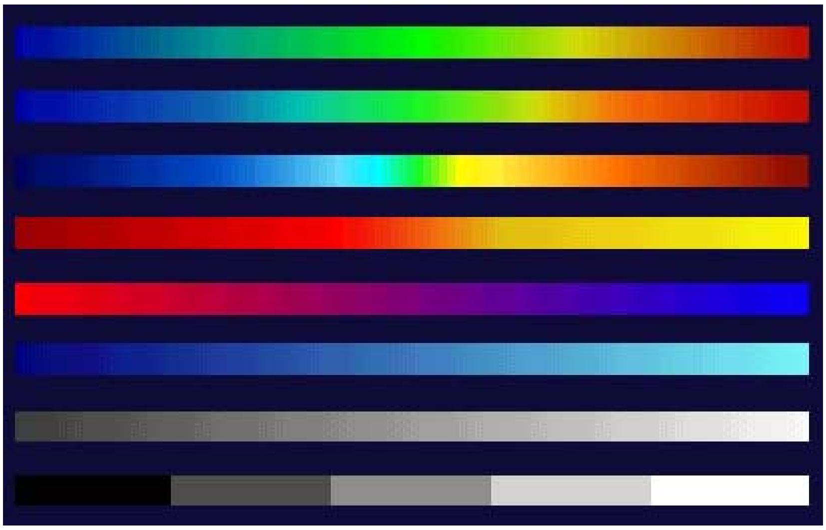


Figure 5.3. Some of the colour gradients defined and used in the project.

Notice how nuances in the bright green colour are more difficult to perceive than nuances in the darker blue and red colours.

Scaling problems

Further, the usefulness of a colour gradient depends on the value fluctuation of the process variables. The change of colours must be placed around the center of the fluctuation, meaning that the behaviour of the process variables must be known prior to the definition of the colour gradient. But at the same time a colour gradient cannot be applied individually to process variables because one colour must represent the same percentage value.

As an example consider two process variables. One varies from 45% to 55% of the value range and the other varies from 10% to 80% of the value range. It is almost impossible to define a colour gradient, which visualises both variations simultaneously.

Perception of colours

During the study of colours and colour schemes, it became clear that the background has a great influence on how colours are perceived. In Figure 5.4 the same colour gradient as the one shown in Figure 5.1 is used, but this time on a white background.

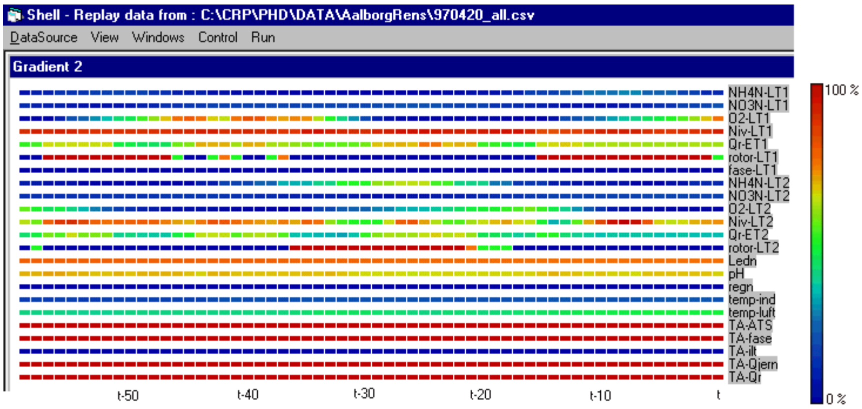


Figure 5.4. The same colour gradient and data as in Figure 5.1, but on a white background. Notice the difference in the sharpness of the colours. Data are from a water treatment plant.

Further it was noticed that the border around the rectangles, the size and the proximity of the rectangles influenced the visual perception. In Figure 5.5, larger rectangles with white borders a8re shown, still using the colour gradient from Figure 5.1.

9

Figure 5.5. The influence of size, borders and distance between rectangles. The colour gradient from Figure 5.1 is still used. Data are from a water treatment plant.

Visualising the derivative of process variables

The study of gestalt principles combined with the experimentation of size, border and background of the rectangles gave the idea to use the orientation of the rectangle (thin, short line segments) to indicate the derivative of the process variables. Knowledge about the mass-data display has also influenced this idea. This display is shown in Figure 5.6. The derivative is calculated from the sample before the actual sample and five states are defined: fast increasing, increasing, steady, decreasing and fast decreasing. The limits for this classification are the same for all the process operations in the display (10% and 3% change compared to the former value of the process variable). These limits should be set individually for each process variable as they can be considered as alarm limits on the derivative of the variable.

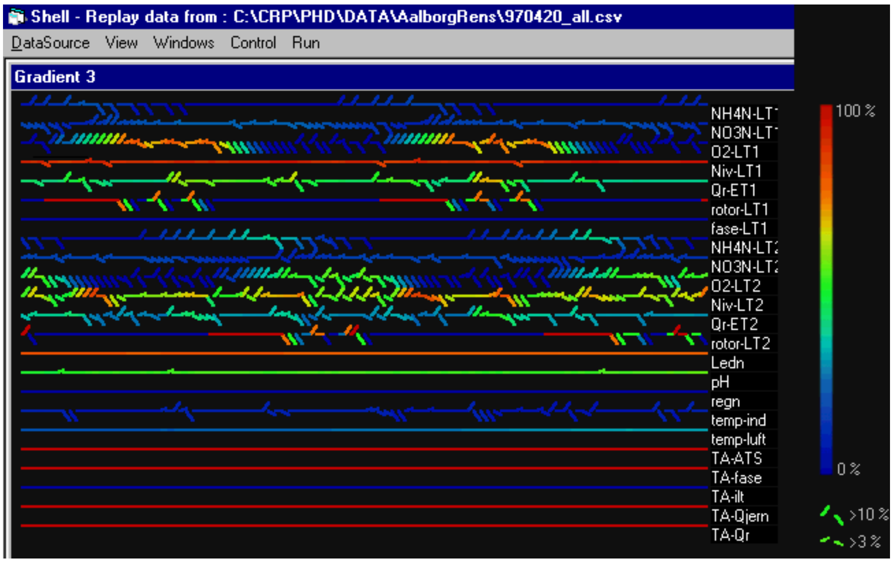


Figure 5.6. The orientations of the lines are used to visualise the derivative of the process variables. The derivative is divided into 5 states: fast increasing (more than 10% compared to former sample), increasing (more than 3%), steady, decreasing (more than 3%) and fast decreasing (more than 10%). The same limits are used on all process variables in the display. Data are from a water treatment plant.

Simplifying the view

Due to the problems mentioned with the colour gradients it was decided to only use three colours, which could easily be distinguished. This implies that the correlation between the process variables will not be visible meaning that the display does not support production optimisation. The propagation of a failure through the plant is still visible. The advantage of not using the colour gradient is that the display is easier to perceive due to the less amount of information in it. The display is shown in Figure 5.7. With this display it would be possible to use individual scales for each process variable because the colours are used as alarm indicators. Notice that more than three colours could be used, e.g. five colours to match the high alarm, high warning, normal, low warning and low alarm states. The alarm limits of the derivative of the process variables can still not be set individually, 10% and 3% are used for all process variables in the display.

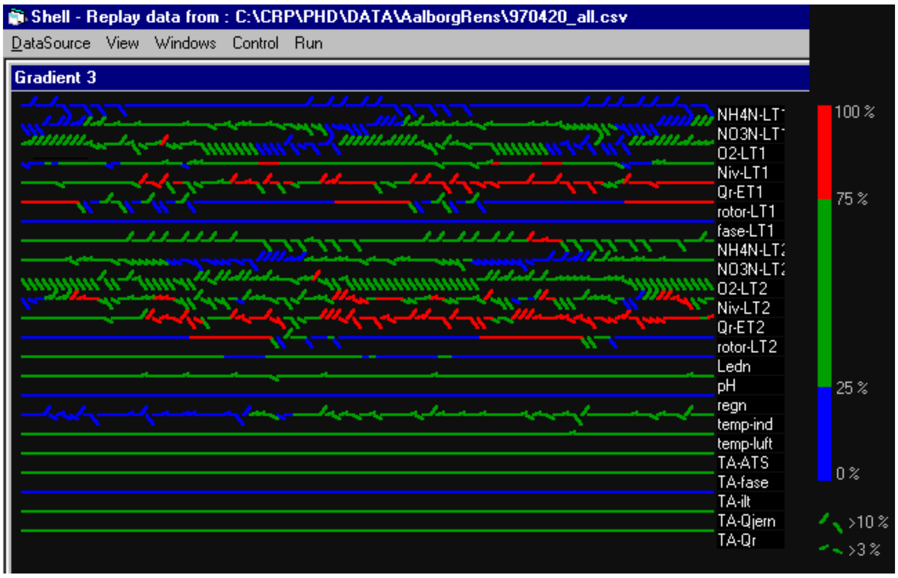


Figure 5.7. Three colours are used to visualise alarm states to reduce the amount of information in the display. The orientation of the line segments shows the derivative of the process variable. The alarm limits and the limits for the derivative are not set individually for each process variable. Data are from a water treatment plant.

Further prototypes of these displays were not developed. The display in Figure 5.7 is the basis for proposing the multi-variable supervisory display described in the next section.

5.2. A Supervisory Display for a Condenser and Ejector System

Background

The analysis and usefulness of the TCF framework in the design of a supervisory display for the ejector and condenser system for the Swedish nuclear power plant Barsebäck is described in Pedersen and Lind (1999). Based on this analysis and the prototype work with the supervisory display in Figure 5.7, the display shown in Figure 5.8 was proposed. A description of the display can be found in section 4.14.

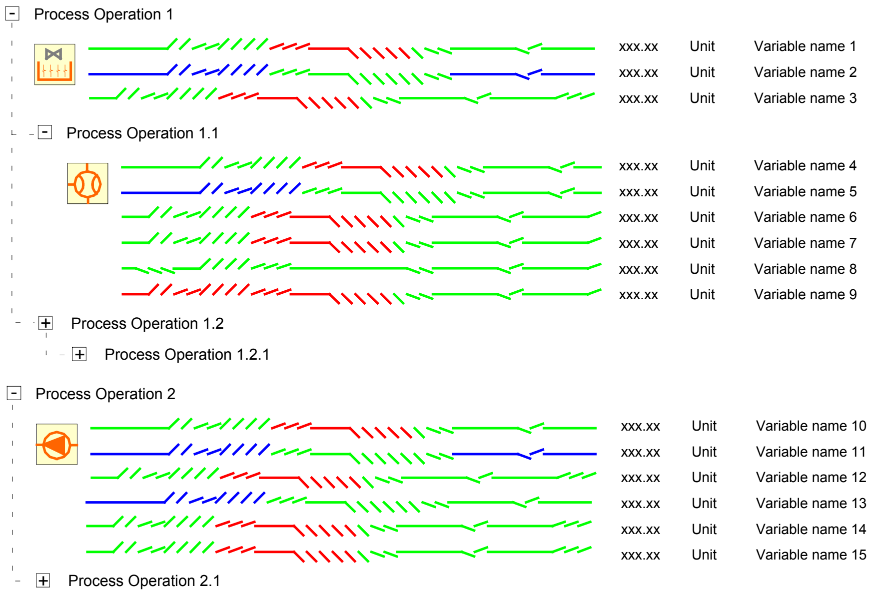


Figure 5.8. A Multi-Variable Supervisory Display.

Unfortunately there was not enough time to implement the hierarchical structure of the display and it has therefore not been tested on data from a process plant.

Finding correlation by operator interaction

Another idea inspired by the reading of Bertin (1981) was to let the operator shift the time period individually for each process variable and to let the operator permutate the process variables in order to investigate correlation between process variables.

In Figure 5.9 the colours are removed bringing the trends (increasing, decreasing) of the variables in focus.

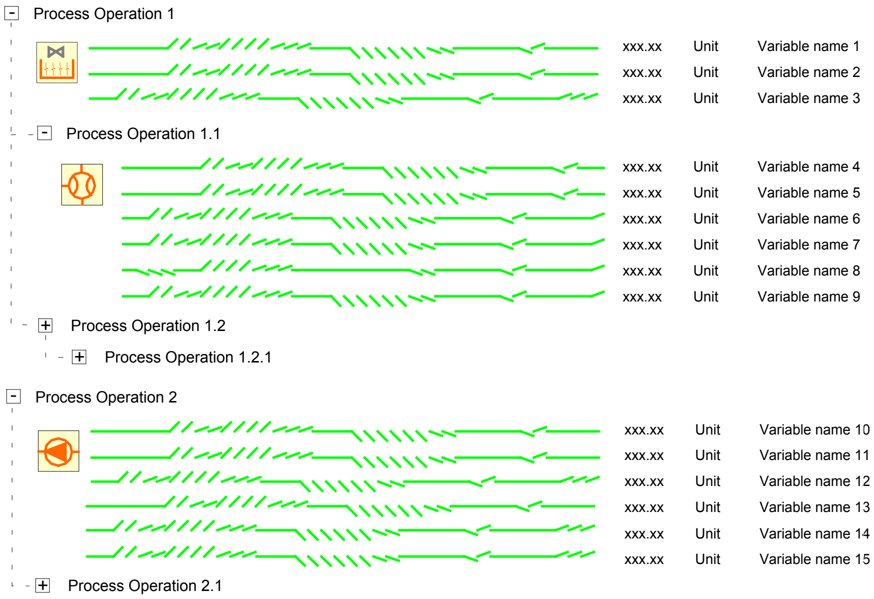


Figure 5.9. The removal of the colours used to mediate high and low alarms makes it possible to focus on the correlation between the trends of the variables.

By shifting the time for the individual process variables and by reordering the process variables, the correlation between the process variables becomes obvious (see Figure 5.10). Notice though that this is a constructed example and it has not been experienced how easy it is to find relations between real process data by time shifting and reorganising the order of the process variables. This is just to bring up the idea, which needs to be investigated in more details.

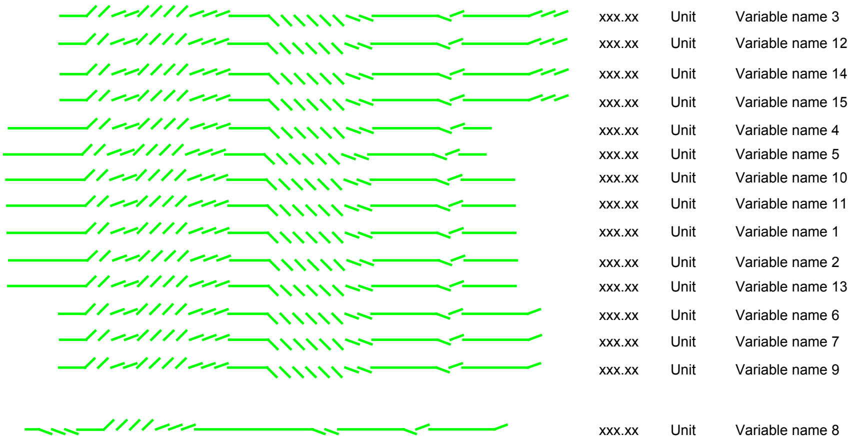


Figure 5.10. By time shifting and reordering of process variables the correlation between the process variables becomes obvious.

5.3. Software Implementations of Reusable Display Elements

ActiveX components support reuse

One of the aims of the project was to support reusability of display design solutions, also at the level of implementation. It was found that ActiveX components fulfil the requirements to software reusability, which is needed in display design. Further, ActiveX components make it possible to present different display content using the same view. The Common Object Model (COM) is the foundation for ActiveX components (Chappel, 1996).

The experience and some of the developed ActiveX components will be described in the following.

5.3.1. The Compact Trend in an ActiveX Component

ActiveX life cycle

ActiveX containers

The compact trend display shown in Figure 4.3b is simple and was therefore considered as a suitable display to implement as the first ActiveX component. The life cycle of an ActiveX component consist of a design-time followed by a run-time. Design-time is when the properties of the component are set and run-time is when the instance created at design-time is used in the container program. Notice that in order to use ActiveX components the program in which the ActiveX components are placed must be capable of acting as an ActiveX container. IGSS and the programs in the Microsoft Office package are among the programs capable of using ActiveX components.

Design-time options enhance reusability

Without going into implementation details, the strength of the ActiveX components is that they can be created very generally with many options, which can be set at design-time. An example of how the same ActiveX component can be configured in different ways is shown in Figure 5.11.

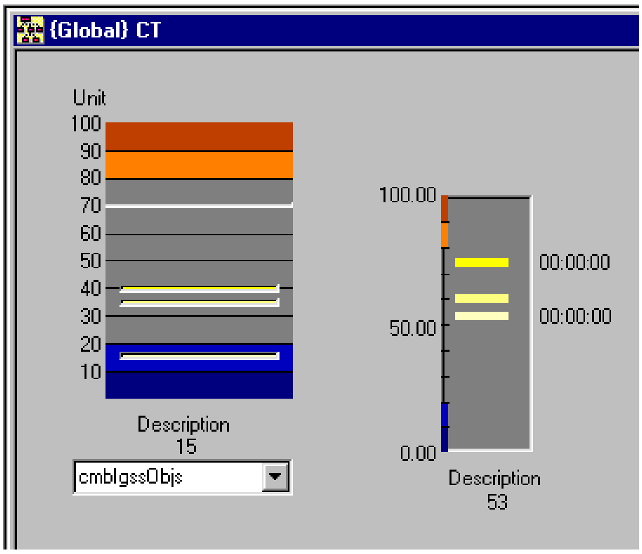


Figure 5.11. Two instances of the compact trend ActiveX component configured differently by setting properties at design-time.

Resizing

When placed in the container program the ActiveX component can be resized. Notice how the choices of different design-time options influence the size of the graphical elements within the ActiveX component. For example in Figure 5.11 the ActiveX components occupy two areas of the same size in the container program. The bar graph in the ActiveX component to the right becomes less wide because more digits are shown on the scale and because time stamps of the process variable are shown to the right of the bar. In case the labels for the time stamp will overlap due to a small distance between two bars only the most recent time stamp label is shown. The bar graph can be made of the same size by changing the size occupied by one of the ActiveX components.

The data interface

The data interface to connect process variables to the compact trend components is either made through Microsoft's Automation interface or directly by binding the value property of the compact trend control to an IGSS object in the definition module of IGSS. The advantages of using the automation interface is that the process variables connected to the ActiveX component can be changed during run-time, meaning that the operator is capable of determining the display content. The disadvantages is that code must be written, i.e. code which reads the available display content (here IGSS objects) and presents it to the operator (here in the combo box). The unit and description labels plus the alarm limit can be entered by the display builder or they can be fetched automatically from the IGSS object database, either through binding or through the automation interface.

Compact trends in mimic diagrams

The original idea of the compact trend display is that it should be integrated in other displays e.g. in mimic diagrams to show the latest values of a process variable to the operator. This is shown in Figure 5.12.

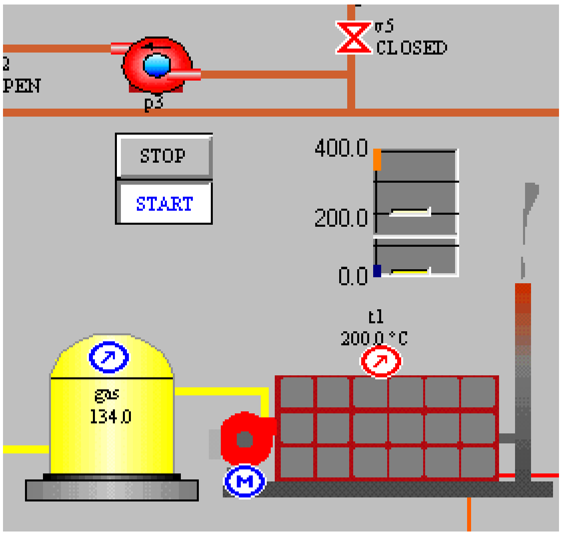


Figure 5.12. The compact trend display integrated in a mimic diagram.

A supervisory display made of compact trend display elements

Due to the possibilities of setting the properties at design-time and the reusability of the ActiveX components several compact trend displays can be combined into a supervisory display, as shown in Figure 5.13. The latest three samples are shown. The bar with the brightest colour is the latest sample and the two grey bars represent set points. The alarm limits are shown as blue and red coloured tics individually for each process variable.

The display allows the operator to see deviations from set points and fluctuations in process variables and is therefore useful for failure detection and partly for optimisation because the correlation between the trends of the process variable are visualised.

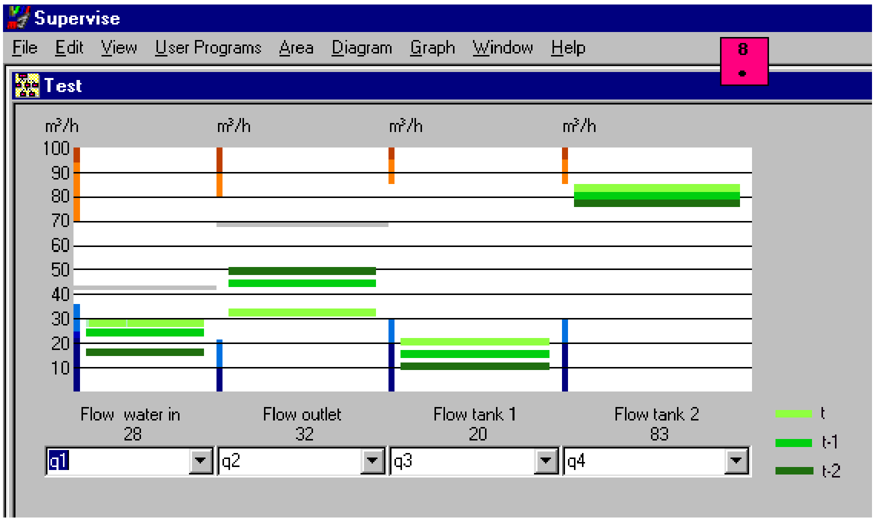


Figure 5.13. Several instances of the compact trend ActiveX component used in a supervisory display in the IGSS scada system. (Data are from the IGSS simulation file for tests).

5.3.2. The Star Plot Display in an ActiveX Component

The star plot display has been implemented as an ActiveX component. Two configurations have been used, one showing the process variables in a star and another forming a polygon (see Figure 5.14). The process variables are not equalised. Humans use the gestalt principle of closure to create the shape of the star to the left in Figure 5.14. In order to reduce the perceptual load of the operator the polygon to the right, immediately showing the shape, might as well be displayed.

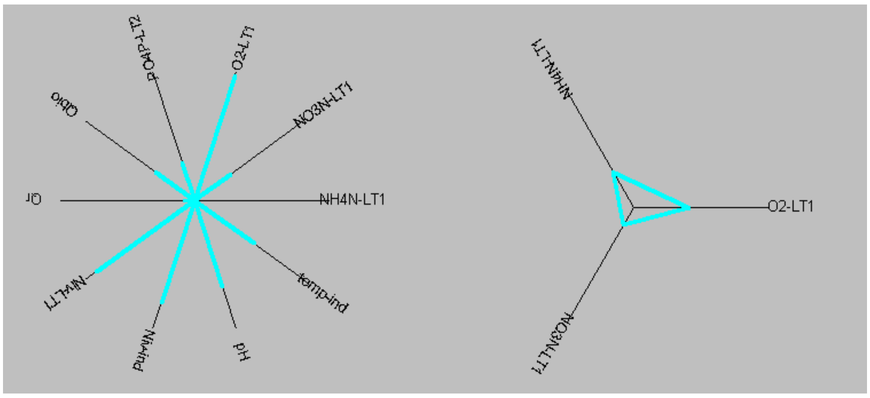


Figure 5.14. Two instances of the star plot ActiveX component.

Practical experiences with ActiveX components

The idea was to reuse this star plot ActiveX component as a marker in a trend curve. During the implementation of such a display it became clear that the data interface (COM interface) to an ActiveX component is rather slow, at least in Visual Basic version 5.0. Therefore it was concluded that in practice it was not possible to reuse a lot of ActiveX components in another ActiveX component. This means that the trend curve with star plots as markers must be created as a single ActiveX component where the star plot markers are implemented as (drawing) procedures inside the ActiveX component.

Another experience with ActiveX components used in the project is that the control of the versions of the ActiveX components can be a problem. ActiveX components are registered in the Windows registration database. An example, which causes problems, is when an executable file is made of a software project containing ActiveX components. If newer versions of an ActiveX component are made, overwriting the older version, the executable file is (naturally) no longer working. Another side of the same problem is when Microsoft's own ActiveX components no longer are supported but have been used in a software project, examples are the table component (grid32.ocx) and the label, which can be rotated (ielabel.ocx). Problems in registering these controls without getting the error that the licence is not valid have been encountered (perhaps upgrading from Windows95 to Windows98 caused the problem). These problems have not been dealt with in details because the objective has been to develop prototypes for new display elements.

5.4. Displays for Water Treatment Plants

Contents

One of the case studies was water treatment plants with a different behaviour and supervision problems than those found in power plants. The work done with regard to display design is described here. The procedure of knowledge acquisition about the plant problems is outlined and the usefulness of the TCF design method is discussed. The displays invented for the plants are described and it should be noted that this work was done before the theories of graphical modalities, visual dimensions and gestalt principles was studied in details. Finally the operator's comments and suggestions to improvements are listed.

5.4.1. Plant description

A flow chart of the plant is shown in Figure 5.15 in order to provide an overview of the main equipment and process flows in the plant.

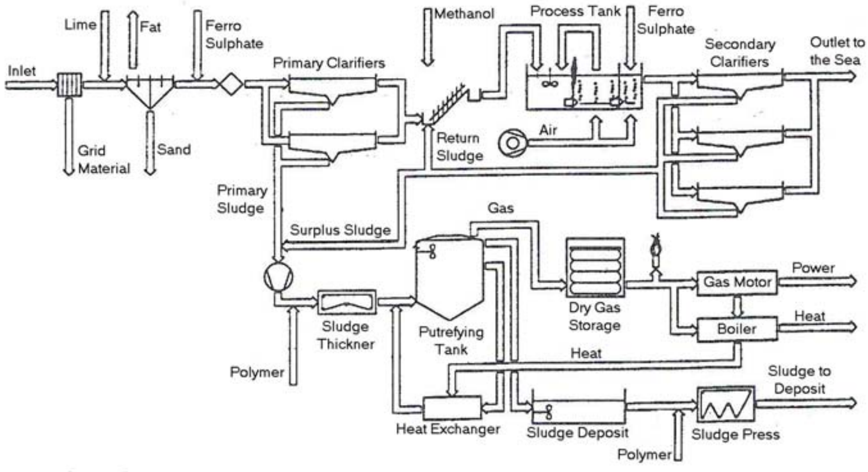


Figure 5.15. Process flow diagram for Sydkysten's water treatment plant located in North Zealand, Denmark.

The process in focus is the chemical and biological treatment in the de-nitrification and aeration tank. This is in fact one physical tank where two different processes take place. In the following it is referred to as the process tank.

Parts of the following plant description and some of the displays are also described in Pedersen and May (1998). However, other and more details regarding the plant and the displays are provided here.

The problem in focus

Simplified, the purpose of a water treatment plant is to remove nitrate (NO_3) and ammonium (NH_4) from the incoming water. Again simplified it can be said that ammonium is removed by adding oxygen to the process (called the nitrification phase) and that nitrate is removed in the de-nitrification phase where oxygen is not present in the process. These are basically the processes dealt with in this work. Carbon is needed in de-nitrification. Carbon enter the plant through the incoming water in form of organic material or it might be added in the form of methanol before the process tank. The simplified chemical equations describing the basic reactions in the process tank follows.

Nitrification $O_2 + NH_4 \rightarrow NO_3 + H$

De-nitrification $C + NO_3 \rightarrow N_2 + CO_2 + O_2$

For both processes the germs living in the sludge are needed. Nitrogen (N_2) and carbon dioxide (CO_2) dissolves in the air.

Problems not considered

The processes described above are only a part of the processes that the operators have to control. Phosphorus removal is not considered here. The problem of controlling the amounts of sludge that is transported back to the process tank and removed from the plant is not in focus. The problem of creating bio gas and heating from the removed sludge is not dealt with either. Besides these process oriented problems the operator have to deal with more practical tasks such as calibration of on-line sensors, maintenance and cleaning of the plant and generating reports to authorities.

5.4.2. Plant Knowledge Acquisition and the Use of the TCF Design Method

Informal Interviews (meetings)

The expert on water treatment plants Marinus Nielsen from the consulting company Krüger A/S was met several times. Krüger has specialised in designing and commissioning water treatment plant and therefore has comprehensive knowledge about factors influencing the performance of the plant.

Meeting the expert

The first meeting was to get an understanding of the processes of the plant and the problems involved. The main problem is to fine tune the parameters for the automatic control system in order to optimise plant performance, i.e. to keep well below the maximum limits for outlet of nitrate and ammonium and to use as little energy as possible.

The process itself is rather slow, it may take days before a change made to the automatic controller can be observed. An automatic control of the phase shift between nitrification and de-nitrification is only possible because of on-line measurements of ammonium, nitrate and oxygen concentrations in the process tank. Time delays of 20 minutes exist on these measurements. Factors like rainfall and the production of the industries in the neighbourhood also influence the performance of the plant. Finally notice that the operators are at the plant 8 hours per day.

Meeting the production manager

The production manager was met at the plant and during a walk around the equipment, its functionality was explained. Moreover it was experienced that a part of the operator’s daily activities is to look at trend curves similar to the ones shown in Figure 5.16 to assess the plant performance.

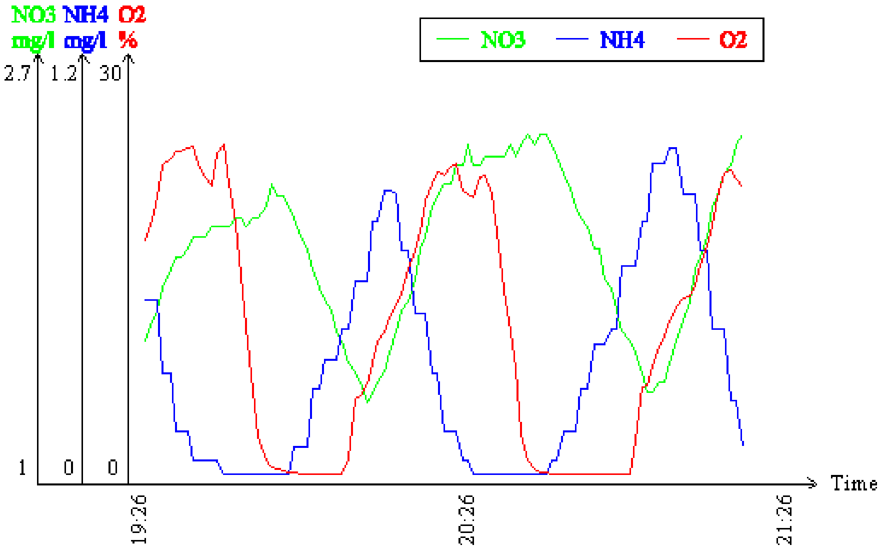


Figure 5.16. The existing display for the water treatment plant operator. Trend curves of the primary process variables, i.e. NH_4*,* NO_3 *and* O_2*. (Data are from Aalborg water treatment plant).*

Asking how the plant performance is evaluated, the answer was by looking at the trend curves for NO_3, NH_4 and O_2. The curves should look like the ones shown in Figure 5.16. If not we check the PH-value in the inlet, return sludge flow etc. Asking for more details about the trend curves it appears that the production manager uses the form of the curves in his judgement rather than reading the specific value for a given parameter. When deviations from normal are observed they are often caused by equipment failure, so it is seldom that the production manager adjusts the parameters to the automatic control system.

The purpose of the new display

According to the expert on water treatment plants, who analyses data from several different plants, there are cases where the production managers could improve performance. Therefore the aim was to develop displays which show the plant performance in a more understandable manner.

Using the TCF design method

Based on these initial meetings Table 5.1 representing the design steps in the TCF method was created.

Process operation	Module	Display content Primary	 Secondary.	Operator activity	Automated Task
De-nitrification (Nitrate removal)	Process tank (denitrification tank)	NO_3 ($\downarrow$) O_2 (= 0) phase	NH_4 ($\uparrow$) PO_4P Niv rotor	Assess performance, optimise	if $NO_3 = 0$ or $NH_4 > y$ then shift to nitrification
Nitrification (ammonium removal)	Process tank (aeration tank)	NH_4 ($\downarrow$) NO_3 ($\uparrow$) O_2 (> 0) phase	PO_4P Niv rotor	Assess performance, optimise Check amount of O_2	if $NH_4 = 0$ or $NO_3 > x$ then shift to de-nitrification
Phosphorus removal	Primary and secondary clarifiers	PO_4P ($\downarrow$) (sensor in process tank)		if $PO_4P > z$ then add ferro sulphate	Not considered
Aeration	Aeration tank	O_2 NH_4	phase rotor	if long phases check amount of O_2	Similar to nitrification
Sludge flow control	Primary and secondary clarifiers Return and removal sludge pump	Q_r		Not considered	Not considered
Water flow control	inlet middle pumping station process tank	Niv-ind Ledn pH temp Qbio NO_3 NH_4 PO_4P		Not considered	Not considered
Adding methanol	middle pumping station	NO_3		if NO_3 is to high add methanol	Not automated
Adding ferro sulphate	Primary and secondary clarifiers	PO_4P		if PO_4P is to high add methanol	Not automated

Table 5.1. The TCF design method used on Sydkysten's water treatment plant.

The focus is on the nitrification (including aeration) and de-nitrification process operations. The other process operations are not dealt with in the following.

Experiences with the TCF design method

The final step in the TCF method, choosing suitable existing display elements for the operator activities, was not made. The reason is that the aim was to design a new display, not to use existing display elements. Moreover from the decomposition made with the TCF design methods it became clear that display elements which suits this specific operator task did not exist.

In conclusion the TCF design method was useful as a means to structure the information retrieved during the meetings and from the analysis made afterwards. Furthermore it worked, as a procedure of how to proceed during the analysis, i.e. when the plant processes and the problems involved should be understood. Both the process problems and the operator's problems of controlling the plant are considered when the TCF design method is used.

5.4.3. Inventing a New Visualisation Technique

It is difficult to say how the idea of using ellipses as markers in trend curves came up, but it was rather early in the project probably during the literature study while reading about human pattern recognition capabilities and object displays.

Oxygen is the primary (controllable) variable

The first attempt to develop a display for the water treatments plant was to place the oxygen on the y-axis, because it is the variable which can be controlled, and the time on the x-axis. The NO_3 and the NH_4 process variables determined the height and width of the elliptic makers. The speed of the rotor determined the colour of the marker, which could be red, yellow and green, using the traffic light metaphor. The display is shown in Figure 5.17.

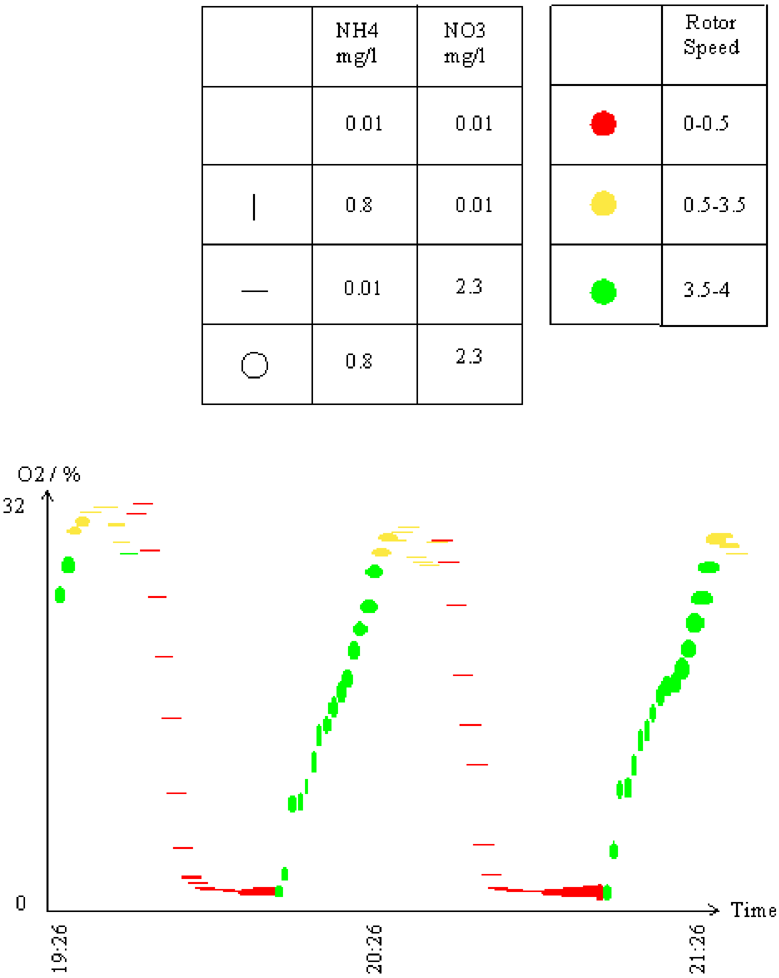
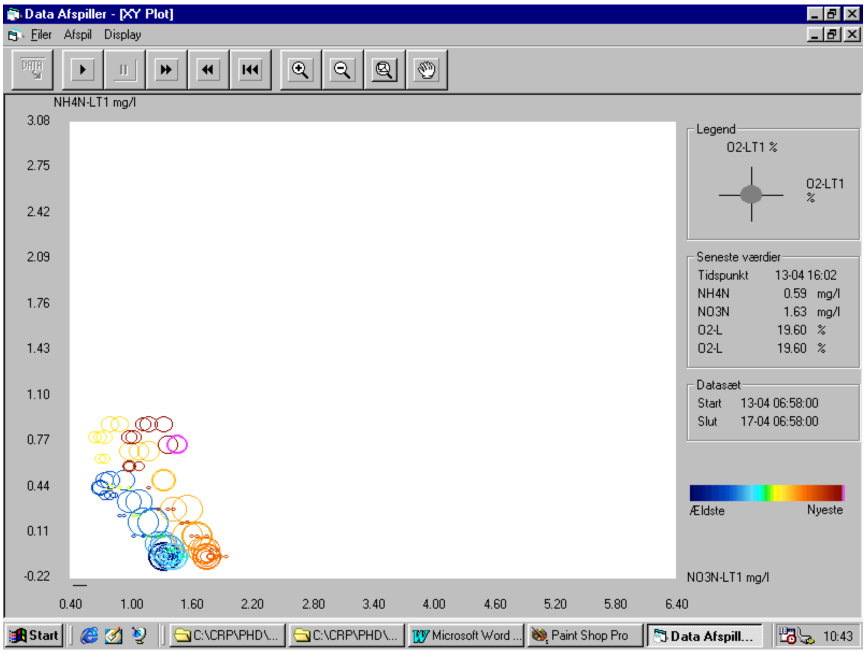


Figure 5.17. Oxygen as a function of time. Ellipses are used as markers where the height and width indicate the ammonium and nitrate concentrations, accordingly. The status of the rotor is mapped into colours. (Data are from Aalborg water treatment plant).

Nitrate and ammonium concentrations give more information about plant performance

From further talks with the expert on water treatment plants it became clear that the variables of interest are the nitrate and ammonium concentrations. Therefore these were placed at the primary axis and the oxygen on both the width and height of the markers, creating a circle. To visualise the development over time the markers were coloured by a colour gradient. The first attempt using the rainbow colours is shown in Figure 5.18.



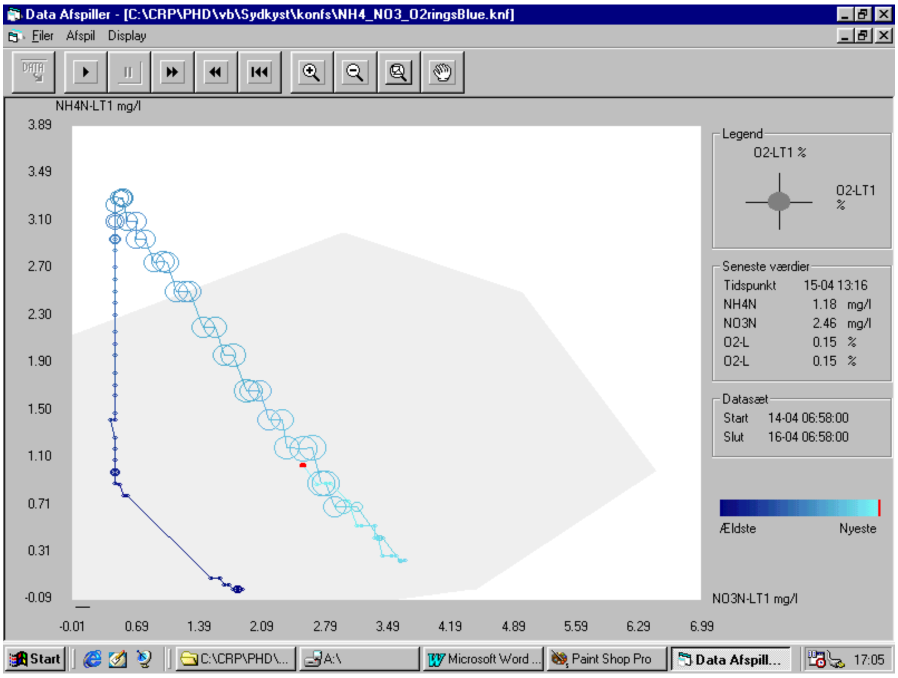
Seneste værdier
Tidspunkt 13-04 16:02
NH4N 0.59 mg/l
NO3N 1.63 mg/l
O2-L 19.60 %
O2-L 19.60 %

Datasæt
Start 13-04 06:58:00
Slut 17-04 06:58:00

Figure 5.18. The glyphs display for the water treatment plant. A colour gradient of rainbow colours is used to indicate the time history. (Data are from Aalborg water treatment plant. White background is printed, black is use on the screen).

The phase shift from nitrification to de-nitrification is shown as the “turning point” in the xy-plot. When the process is in the bottom of the picture (low amount of ammonium) the circles should be small because oxygen should not be added. In Figure 5.18 it is seen that this is not the case.

Figure 5.19 shows that the visual dimension of brightness is better than colour (hue) to visualise the time history. The reason is that time is an ordered data variable and therefore an ordered visual dimension should be used. From Table 2.2 it appears that brightness is an ordered visual dimension and colour is not. Moreover lines (using the gestalt principle of good continuation) connect the markers as an attempt to make the time history of the process variables even more visible. The expert explained that different plant states can be observed from the position of the markers in the $NO_3 - NH_4$ plot. Therefore it was decided to place a polygon in the background to indicate an area, in which the process should be kept.



Seneste værdier

Tidspunkt	15-04 13:16	
NH4N	1.18	mg/l
NO3N	2.46	mg/l
O2-L	0.15	%
O2-L	0.15	%

Datasæt

Start 14-04 06:58:00
Slut 16-04 06:58:00

Figure 5.19. An area is added to the background of the glyphs display for the water treatment plant to indicate operational zones. The visual dimension of brightness is used and the markers are connected by lines to indicate the time history. (Data are from Aalborg water treatment plant. White background is printed, black is use on the screen).

A data Replayer with zooming and panning facilities

In order to circumvent the problems of overlapping markers a zooming and panning facility was introduced. Further the operators were given the opportunity to replay the data. The idea was that the operators could replay the process variables collected through the night and zoom in if abnormalities were noticed. If both the amount of ammonium and nitrate is well below the prescribed limits and oxygen is not added when there is no ammonium in the water the details are less interesting. Hence the display should work both as an overview display to see disturbances and at the same time show the relation between the process variables supporting the operator task of production optimisation. Depending on the visual appearance of the data in the display it should be obvious if the parameters to the automatic controller need to be adjusted.

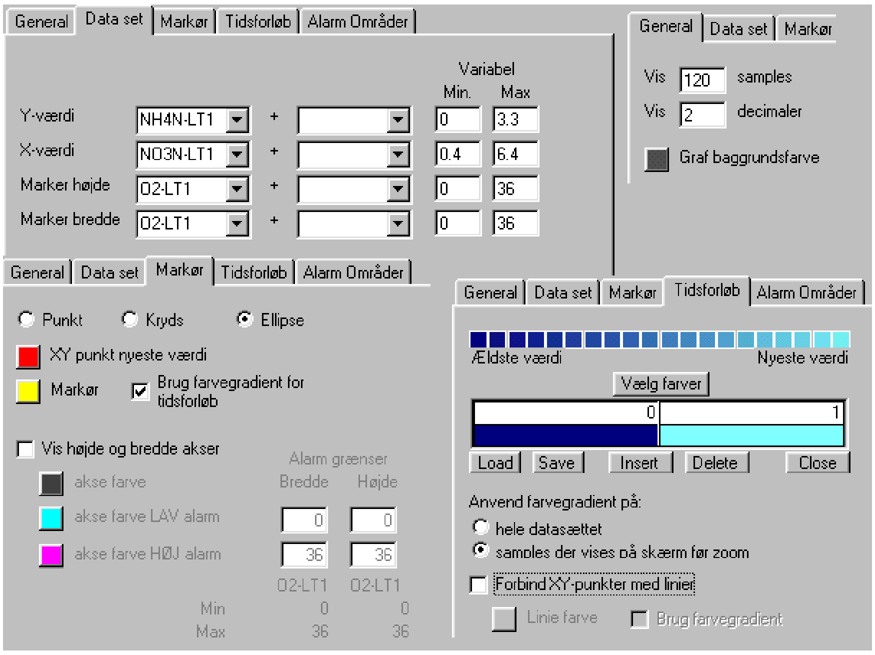
Description of the data Replayer

The data Replayer can receive data from either a database or from the IGSS scada system using the Automation interface.

Data are read into a buffer (e.g. 5000 samples long) and a part of these samples are shown on the screen (e.g. 500 samples). The length of the buffer is determined by the data read into the Replayer from a database or set by the user when the IGSS Automation interface is initiated. The number of samples shown on the screen can be changed any time together with the display configuration.

When a colour gradient is used the display can be set up to use the colour gradient on the visible markers on the screen or to use the colour gradient on the entire number of data collected for presentation. The last approach makes it possible to see approximately how old the part of the data set shown on the screen is. For example bright coloured markers represent new samples and darker makers represent the oldest samples in the buffer. The colour gradients are implemented as ActiveX controls allowing the user to create, load and save the defined colour gradients. For programming a method is provided, which retrieves the RGB colour values from a percentage value of the process variable range.

Figure 5.20 contains screen dumps from the dialogs used to configure the displays in the Replayer and is provided to give an idea of the possibilities.



			Variabel Min.	Max
Y-værdi	NH4N-LT1	+	0	3.3
X-værdi	NO3N-LT1	+	0.4	6.4
Marker højde	O2-LT1	+	0	36
Marker bredde	O2-LT1	+	0	36

Vis 120 samples
Vis 2 decimaler
Graf baggrundsfarve

○ Punkt ○ Kryds ● Ellipse
XY punkt nyeste værdi
Markør ☑ Brug farvegradient for tidsforløb

☐ Vis højde og bredde akser
akse farve
akse farve LAV alarm
akse farve HØJ alarm

	Alarm grænser Bredde	Højde
	0	0
	36	36
	O2-LT1	O2-LT1
Min	0	0
Max	36	36

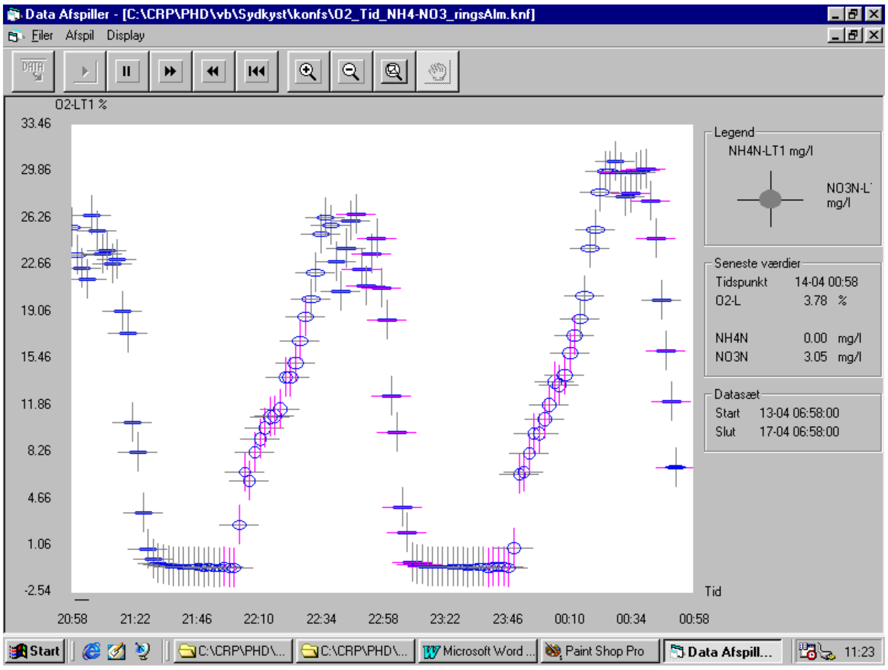
Ældste værdi Nyeste værdi
0 1

Anvend farvegradient på:
○ hele datasættet
● samples der vises på skærm før zoom
☐ Forbind XY-punkter med linier
Linie farve ☐ Brug farvegradient

Figure 5.20. Screen dumps of configurations dialogs from the Replayer (in Danish because it was used on a Danish water treatment plant).

Alarms and scales on the marker graph

Moreover attempts to visualise the scale of the variable on the markers have been made. The problem with not presenting the scale of the marker variable is that only the relative size between markers is visible. It is impossible to know how large an ellipse can be. In Figure 5.21 the scales are shown in a grey colour, and the axis become very dominant in the view of the display. Furthermore the colour of the axis is used as an alarm indicator. Three intervals are made on the process variable on the markers. A pink colour is use to show if the process variable is in the high alarm area and a cyan to show a low alarm.



Seneste værdier
Tidspunkt 14-04 00:58
O2-L 3.78 %

NH4N 0.00 mg/l
NO3N 3.05 mg/l

Datasæt
Start 13-04 06:58:00
Slut 17-04 06:58:00

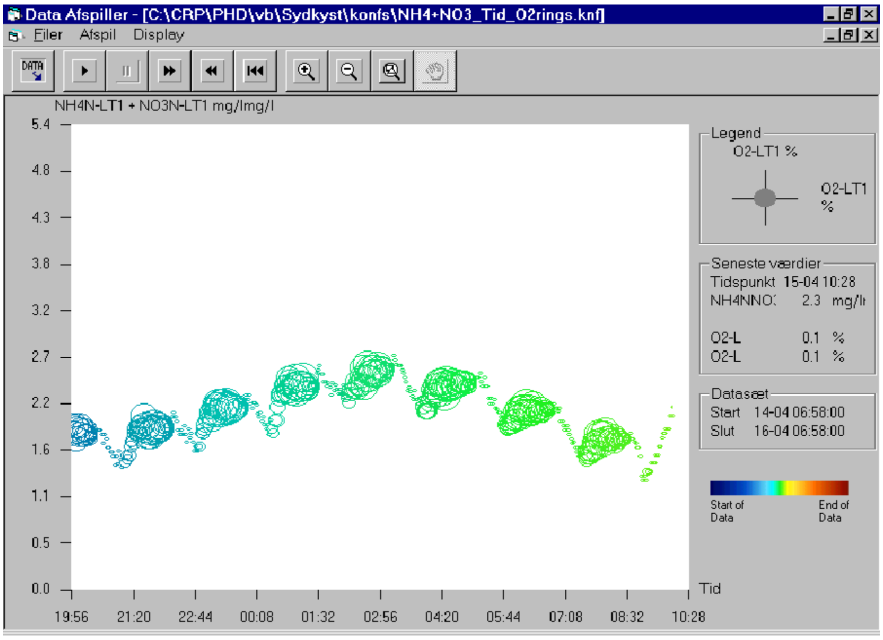
Figure 5.21. Axes are shown for the elliptic marker and alarms are indicated by colour coding of the axis. In principle the display is similar to Figure 5.17, though the rotor speed is not shown here. (Data are from Aalborg water treatment plant. White background is printed, black is use on the screen).

Even in this relative simple display where colour gradients and connecting lines between markers are not used, the display appears crowded and difficult to comprehend due the axis on the markers. Another attempt has been made using four dots to indicate the maximum size of the ellipses. Naturally this does not work when several ellipses are positioned near each other because it is impossible to see which dots belong to which ellipses.

Therefore it can be concluded that scales of the marker variable are difficult to visualise and should not be made as shown here. The consequence is that only the relative values between marker values are visible.

Focusing on plant load and phase shift

Finally the glyphs display have been set up to focus on the plant load by showing the sum of ammonium and nitrate concentrations on the y-axis. The time is shown on the x-axis. The oxygen concentration is shown on both the width and height of the markers making the phase shift visible. The colour gradient is applied to the entire data set meaning that the colours of the markers indicate how old the samples are. The display is shown in Figure 5.22.


Data Afspiller - [C:\CRP\PHD\vb\Sydkyst\konfs\NH4+NO3_Tid_O2rings.knf]

Seneste værdier
Tidspunkt 15-04 10:28
NH4NNO: 2.3 mg/lı
O2-L 0.1 %
O2-L 0.1 %

Datasæt
Start 14-04 06:58:00
Slut 16-04 06:58:00

Figure 5.22. The glyphs display set up to focus on plant load (NO_3 + NH_4) and phase shift (small and large O_2 circles). The colour gradient is applied on the entire data set using the colour to mediate the position of display window relative to the entire data set. (Data are from Aalborg water treatment plant. White background is printed, black is use on the screen).

Future work
Rug plots

Tufte (1983, page 135) mentions the idea of combining several xy-plot (also called scatter plot) as shown in Figure 5.23.

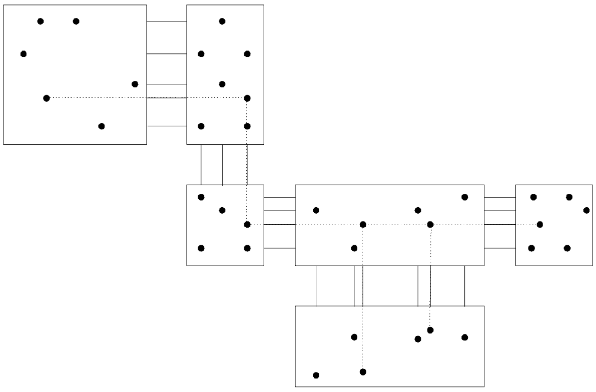


Figure 5.23. Rug plots are combination of xy-plots.

If the glyphs display are implemented as an ActiveX component in a similar way as the compact trend ActiveX control it will be very easy to create such rug plots. Not only the relation between the primary variables in the xy-plot will be visualised but also the relations between the form of the markers in the different xy-plot will be mediated. This should establish further possibilities to visualise correlation between process variables and thereby support the production optimisation task. Care should be taken using colours and the shapes of the markers in order not to create information mismatch and not to overload the operator.

5.4.4. Users comments

The expert

The expert has used the displays for a while and liked they idea though he preferred to used the well-known trend curves. As he said he knows exactly where to look in the 32 trend curves and by using these he also has the information about the sludge, bio gas and other process variables including rain fall.

Production managers, first impression

Three production managers from three different water treatment plants were introduced to the display in Figure 5.19, Figure 5.21 with and without scales on the markers and Figure 5.22. Two of them commented on the display informally and their comments are given below, referred to as PM1 and PM2.

Display in Figure 5.19

PM1 did not like the display in Figure 5.19, he could not see the cross between ammonium and nitrated as he is used to in the trend curves and therefore lacks information about the phase shift. The phase shift as the turning point in the xy-plot was not very visible to him and he argued that to many samples was displayed on a small area. Zooming in of the markers he could see the phase shift. In general he was focus on the length of a phase shift and that is in fact not directly visible in the display, however a longer phase time will be seen as markers closer to each other. He liked the idea that it was possible to see when the oxygen pump should be stopped, indicated by a small circle during low ammonium concentrations. Moreover he did not regard the amount of oxygen as an important parameter, because as he said in the nitrification phase as much oxygen as possible should be let in to the tank.

PM2 had a better understanding of the idea of presenting the time implicitly by connecting lines between the markers. He also liked the idea of presenting the amount of oxygen as the size of the markers.

Display in Figure 5.21

PM 1 liked this display, as the phase shift is clear.

The use of the shape of the ellipse as indicator for ammonium and nitrate was understandable to both production managers. PM2 suggest that triangles could be used as markers with other kinds of data.

Display in Figure 5.22

PM 1 liked this display better. The phase shift is obvious and so is the load of the plant.

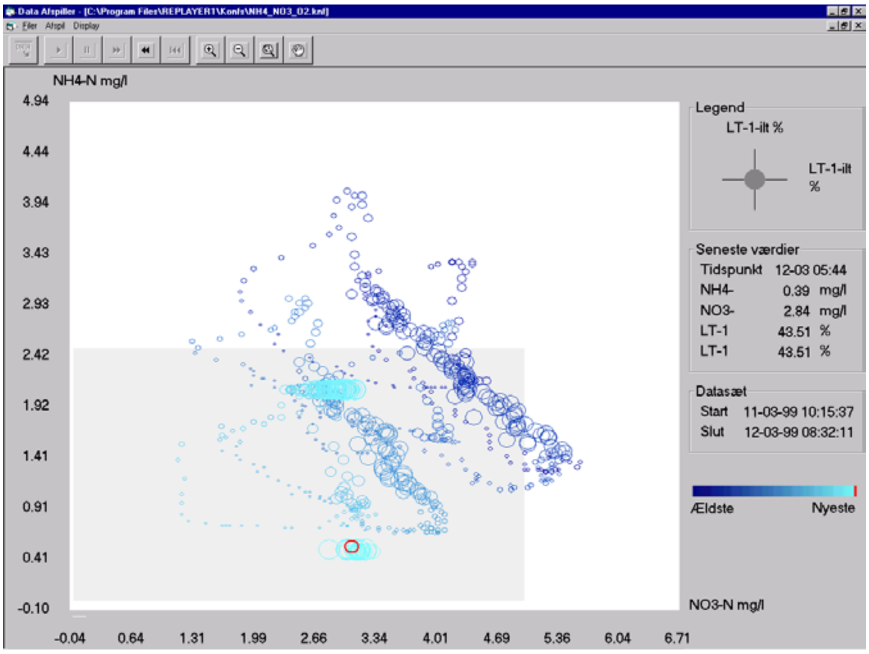
PM2 did not have any comments to this display.

They both liked the idea of using the colour gradient on the entire data set to use the colour of the markers as indication of the position in the data set.

PM 1 agreed to have the displays installed at his plant and would like to compare the display to the trend curves.

5.4.4.1. Observations from Sydkysten's Water Treatment Plant

The prototype of the glyphs display was set up on a separate operator station in the control room at Sydkysten's water treatment plant. In that way the production manager (PM1) could compare the new displays with the trend curves he was used to.



Seneste værdier

Tidspunkt	12-03 05:44	
NH4-	0.39	mg/l
NO3-	2.84	mg/l
LT-1	43.51	%
LT-1	43.51	%

Datasæt

Start 11-03-99 10:15:37
Slut 12-03-99 08:32:11

Figure 5.24. The glyphs display with data from Sydkystens water treatment plant. 12 hours of data are shown from 17:44 to 05:44. (White background is printed, black is use on the screen).

Comments

Figure 5.24 shows a situation from Sydkysten's water treatment plant. It is noticed that the track of the markers in the xy-plot is quite different from the one in Figure 5.18, showing usual data from Aalborg water treatment plant.

Further, it is observed that oxygen is added even though the ammonium concentration is low (big circles in the bottom of the figure). The production manager was not aware of this as his focus was on the ammonium and nitrate concentration and not so much on the oxygen. The production manager said the automatic control system determines when oxygen should be added and did not knew the strategies behind the automatic control algorithms.

Difficult to print

Another practical comment, which can be added, is that bright colours on a black background are easy to perceive on a computer screen, but make it difficult to print the display. A similar problem exists when the colour gradients must be printed in grey scales.

Some days later the following screen dumps were taken. Unfortunately the production manager did not have time to comment on these.

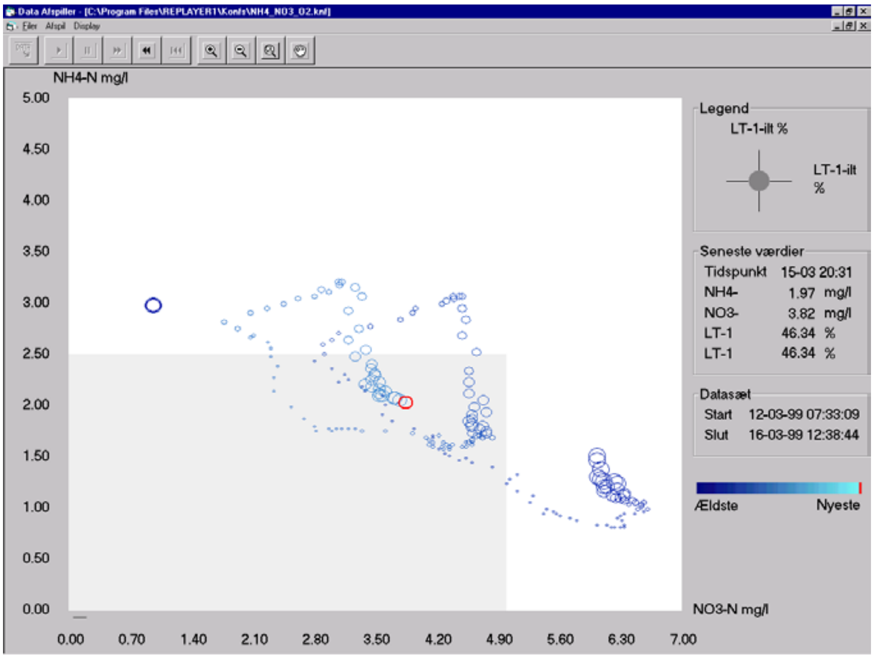


Figure 5.25. Another glyphs display, with data from Sydkysten's water treatment plant. 3½ hours of data are shown from 12:31 to approximately 16:00[6]*. (White background is printed, black is use on the screen).*

Figure 5.26. Trend curves from Sydkysten's water treatment plant. The red bar on the x-axis indicates approximately the time period shown in Figure 5.25.

Figure 5.25 and Figure 5.26 are two different presentations of the same ammonium and nitrate concentrations (however, only the time period shown by the red bar on the x-axis in Figure 5.26 is visible in the glyphs display).

---

[6] Due to a network failure the Replayer program has not received data from approximately 16:00, which can be observed by comparison to the trend curves. 8 hours of data are shown (from 12:31 to 20:31) but all data from 16:00 to 20:31 have the same values and are therefore shown in one point.

From Figure 5.25 it is obvious that the nitrate concentration has been high (around 6 mg/l) and has been reduced. It is also visible that the nitrate concentration increases during de-nitrification, which is unusual. During the move towards the upper left corner, as usual in the de-nitrification phase (no oxygen, small circles), the direction is changed towards to upper-right corner, which has not been observed in data from Aalborg water treatments plant.

Naturally the same observation can be made from studying the trend curves. It can be argued that the pattern in the glyphs display is more obvious, i.e. easier to perceive, than in the trend curves. In the trend curve it is more difficult to see when both the NO_3 and the NH_4 concentrations move in the same direction, and not as usually in different directions. However, a direct comparison is not possible because the time periods in Figure 5.25 and Figure 5.26 are not the same.

5.5. Conclusions

Supervisory displays have been developed and proposed. Attempts to map process values into colours were made in the so-called colour gradient displays. It was concluded that it is difficult to see colour nuances between especially bright colours. The orientation of line segments where used instead to show the trend of the process variables. Further the relations between process operation, plant modules and process variable are shown in the proposed Multi-Variable Supervisory Display (see Figure 5.8). The content of the display corresponds to the main concepts in the TCF design method. The supervisory displays are general and can be used for any processes. The colour gradient displays and the visual appearance of the orientation of line segments have been implemented and seen, based on data from different process plants. The hierarchical structure of the process operations has not been implemented and therefore the proposed supervisory display for the ejector and condenser system of the nuclear power plant has not been observed with plant data.

A display for production optimisation has been made (see Figure 5.19). The general idea of embedding a graph, here in form of the width and height of an ellipsis, into a another graph (xy-plot) can be used in any process domain. The display mediates the relations between several process variables in one view. The display has been tested and developed based on data from one water treatment plant. The final prototype has been implemented on another water treatment plant. The objective of the display was to notify the production manager in case plant performance could be optimised by adjusting parameters to the automatic control system. The display was able to show that oxygen was added when it was not needed due to a low the ammonium concentration. By adjusting the control parameters energy may be saved. The production manager was reluctant to the display as he found it difficult to see the development of process variables over time in the display and therefore preferred the well-known trend curves.

In the designs of the displays for the power and the water treatment plants the TCF framework was found useful as a means for decomposing the problems into the task, content and form aspects. The TCF design method was used in both case studies. In the supervision display for the power plant difficulties were found in specifying the actual operator activities during supervision. The decision ladder (Rasmussen, 1986) was used to specify the operator tasks and it was possible to define display content for each activity. In both case studies the aim was to develop new visualisation techniques, not using existing display elements, and during the attempts described in this chapter the problems dealt with in the guidelines for creating visualisation techniques were identified.

With respect to implementation ActiveX software components were found useful. By using ActiveX components reuse is supported in the following manners: (1) different content can be added to the same form, (2) the same fundamental visualisation technique can be configured in different ways and (3) an ActiveX component can be integrated with other displays. However, performance problems have been encountered when an ActiveX component is reused several times within another ActiveX component.

Chapter 6. Conclusions

The Task, Content and Form (TCF) framework

A framework for development and analysis of process displays has been proposed. The framework comprises a method for designing process displays and guidelines for inventing new visualisation techniques. The framework also serve as a foundation for analysing and classifying existing and new process displays.

The three aspects comprising the foundation of the framework are the operator tasks, the display content and the form of the display. Concerning the operator tasks, the main topics are operational goals, the process operations needed to achieve the operational goals and the activities the operators must perform to control the process operations. Generic categories of operator tasks are identified. The aspect of display content is divided into plant goals (when the plant is designed), the plant functionality required to accomplish the plant goals and the plant components providing the functionality. Within the aspects of operator tasks and display content, different levels of abstraction are used. Plant modules can be defined encompassing all abstraction levels in the display content. In the aspect of display form, different basic visualisation techniques (graphical modalities) can be aggregated.

A method for designing displays

The starting point for the TCF design method is to use existing display elements in the final process display. This approach is closely related to industrial practice and supports reuse of display modules, i.e. the combination of display elements, found as a solution to previous design problems. A design procedure and a template (table) supporting the procedure are provided.

The design method differs from the ecological interface design in that the TCF design method has its starting point in the operator tasks whereas the ecological interface design principles are focused on unanticipated events by presenting the physical constraints of the process to the operators. The lack of systematic principles, in ecological interface design, on how to create the display form mediating the domain constraints is pointed out. Within the TCF framework guidelines for mapping given content to a form, i.e. creation of visualisation techniques is outlined.

Guidelines for creating visualisation techniques

Guidelines for creating new display elements or visualisation techniques are given. Design steps are outlined and the possibilities for mapping given information into a form are systematically analysed and the result is given in tables explicating the opportunities in each design step. Information types found in process displays have been identified and categorised. Possibilities of presenting given information using graphical modalities are outlined. The semantic invariant properties of the graphical modalities are identified and the visual dimensions that can be used to add further information into a graphical modality are listed. Finally, it is outlined which of the visual dimensions that are related to the different gestalt principles and five principles for cognitive supported are mentioned.

Assessment of the TCF framework, and design method

In the design of the displays for power and the water treatment plants, the TCF framework was found useful as a means of separating and decomposing the design problem into the task, content and form aspects. The TCF design method was used in both case studies. For the power plant supervision displays difficulties were found in specifying the actual operator activities during supervision. The decision ladder (Rasmussen, 1986) was used to specify some of the operator tasks and it was possible to define display content for each activity. In both case studies, the aim was to develop new visualisation techniques and during these attempts the problems dealt with in the guidelines for creating visualisation techniques were revealed.

Categorisation of displays

Existing and new displays have been analysed according the TCF framework. Generic categories of operator tasks and the identified information types have been found useful in the analysis and categorisation. Groups of displays supporting the same operator tasks have been identified and the operator tasks supported by the individual displays have been made explicit.

New displays

Supervisory and production optimisation displays have been developed for power and water treatment plants. The displays are generic and can be used in other process domains as well. The supervisory displays have been developed and demonstrated on data from different process plants. However, the hierarchical structure in the final proposed multi-variable supervisory display has not been implemented and its functionality with plant data has not been tested.

The objective of the production optimisation display was to be able to make clear to the operator when parameters in an automatic control system should be adjusted. The final prototype has been implemented on a water treatment plant. The display was able to show that oxygen was added when it was not needed in the process due to a low ammonium concentration. By adjusting the control parameters energy may be saved. The production manager was reluctant to use the display as he found it difficult to see the development over time and therefore preferred the well-known trend curves.

Reusability of implementations

With regard to implementation, ActiveX software components were found useful. ActiveX components support reuse in the following manners: (1) different content can be added to the same form, (2) the same fundamental visualisation technique can be configured in different ways and (3) an ActiveX component can be integrated with other displays. However, performance problems have been seen when ActiveX components are reused several times within another ActiveX component.

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Appendix A. Project Topics and Goals

Table of Contents

Introduction

This appendix describes briefly the project topics and goals as planned at the initiation of the project. Figure A.1, on the page A.6, shows the relations between the project goals and the topics that were expected to be required to achieve the goals.

Rationale

The rationale for this appendix is to describe and visualise how the topics involved were organised. Moreover, it reveals the problems encountered in each group of topics by comparing the expected results with the actual results. This is included as an attempt to describe the process of knowledge acquisition involved in the project.

A.1. A Systematic Approach to Developing Guidelines/Methods for the Display Form

Purpose

Guidelines for the display designer

The purpose is to provide guidelines/methods to the display designer that enables a systematic selection between several visualisation techniques. The focus will be on process displays, but not limited to these as inspiration to visualisation techniques might be found in other domains such as clocks, car control panels, etc.

Expected result

The expected result is an overview of existing displays and visualisation techniques and an attempt to classify these with respect to the task and form. Moreover, guidelines/methods for systematic display design and ideas to visualisation techniques based on the analysis and assessment of the existing displays should be encountered.

Actual result

Categorisation according to operator task

The main result is a categorisation of displays according to the operator tasks they are suitable for. Moreover the display content and the graphical modalities (visualisation techniques) used in the display are identified. The analysis and categorisation are described in chapter 4.

Due to the categorisation of displays according to the operator tasks guidelines are provided for the display designer. The determination of operator tasks in form of process operations is the first step in the TCF (Task, Content and Form) design method described in chapter 3.

A.2. Development of a Modular Information Hierarchy Within the Framework of Cognitive Engineering

Purpose

to structure plant information

The purpose is to analyse the information the operators require about different parts of the plant and the interrelations between parts of the plant. The goal is to structure the plant information so that it will be available for different types of operators (e.g. maintenance staff and production planning staff will not need the same information, but there might be some information of common interest). An abstraction hierarchy will be used to approach this goal.

to support cognitive behaviour

The information required in the different cognitive behaviours during problem solving by the operators is also taken into account. Knowledge about human cognition will therefore affect the organisation of the display information.

to support reuse

Furthermore, the information should be structured so that it can be reused. One way to achieve the goal of reusability is to model the plant from the aspect of unit operations. Here unit operations refer to basic processes such as heat exchange, distillation, transportation etc.

Expected result

The expected result is a method to structure plant information into a modular information hierarchy based on functional modelling having unit operations as a starting point.

Actual result

See next topic group

For the actual results see the results for the next topic group. The two groups of topics melted together as the work progressed. Both topic groups were concerned with the development of a design method for the display builder and the display inventor. This is probably due to the fact that the basics for the TCF design method were formulated rather early in the project.

A.3. Developing a Design Method for Process Displays

Purpose

Formulate a design method

The aim is to combine knowledge from the modular information hierarchy and the visualisation techniques into a method for display design. The model-view-controller (MVC) paradigm from the object-oriented programming language Smalltalk will be used as a starting point for the construction of the method.

Expected result

This work should result in a method to systematic design of process displays and implementation of prototypes.

Actual results

The results described here encompass this and the previous topic group.

Three aspects provide the backbone of the design problem

The separation of the design process into three aspects proved early in the project to be useful. The aspects were inspired by the model-view-controller (MVC) paradigm from Smalltalk. The correspondence between the MVC paradigm and the proposed design method is as follows: the model matches the display content, the view the graphical form and the controller the tasks of operators. This is the backbone of the proposed design method at the level of specification. With regard to implementation, it appeared that the ActiveX technology from Microsoft provided a suitable architecture. Therefore, further study of the implementation aspect was not done.

The TCF design method supports reuse of design solutions at the level of specification

The main result is the proposed TCF (Task, Content and Form) design method proposed in chapter 3. A modular approach is made in the TCF design method, though process operations have been the starting point instead of unit operations. The reason is that process operations are at a higher abstraction level than unit operation and it is on this high level of abstraction that the operators usually operates the plant. A process operation can consist of several unit operations. It is the modular approach that supports reuse of the design solutions made from the TCF design method.

Information types were identified and categorised

The information found in existing process displays are identified and categorised in section 3.2.3.1. The focus has been on the information needed for operating the plant with regard to production. Other types of plant staff than the operators have been kept in mind during the work, though their information needs have not been treated in detail.

An attempt to bring the cognition and perception theories together was made

Rasmussen's framework for skill, rule and knowledge-based behaviour have been discussed and compared to semiotic approaches in section 2.3.2. Further the theories about visual dimensions and gestalt principles have been introduced in chapter 2. An attempt to bring the theories together and an outline of their interrelations is given in section 3.3 Inventing Displays Elements and Visualisation Techniques together with some examples of how the integration of the theories can be used in the design of process displays.

ActiveX components support reuse of software implementations

With regard to implementation, ActiveX components from Microsoft have been found useful and sufficient to encapsulate the graphical items needed in different display elements. Different content (of the same information type) might be connected to the same graphical form allowing reuse of the graphical view.

A.4. Interviews with Plant Operators

Purpose

The purpose with the interviews is to get a deeper insight in the task of the operators and their everyday problems.

to understand operator's problems

Expected results

The analysis of the operators' tasks and problems are expected to reveal which information the operators need on the different display types and how it should be displayed. This will be used in the development of the modular information hierarchy and hence the visualisation techniques.

Actual results

Formal interviews have not been carried out, because it was assessed that informal interviews without tape-recording was more appropriate and would make it easier to get in contact with the operators. The preparation for each meeting was a formulation of questions, which were answered during the talk.

Water treatment plant

Operator do not know when and how to optimise

In the water treatment plant, interviews with an expert on optimising the plant revealed that the problem was the operator's understanding of the process. The operators at the plant did not understand the process fully and were not aware when energy could be saved by fine tuning parameters to the automatic control system. This was confirmed by an interview with the operator of the plant. The glyphs (bubble) display developed and shown in chapter 5 was made to solve the problems identified through these interviews.

Nuclear power plant

Interviews were not possible

It was planned to make interviews with operators at a conventional power plant. During the project a possibility came up to work with the design of a supervisory display for the ejector system for the nuclear power plant, Barsebäck. It was decided to use this possibility even though it would not be possible to interview the operators. Instead meetings with the engineer working with the ejector system was made in order to understand the problems. The displays created from this work are shown in Paulsen et. al. (1998) and the problems involved in specifying the display content together with a suggestion for a supervisory display is made in Pedersen and Lind (1999).

A.5. Graphical Communication

Purpose

How to communicate graphically?

The aim is to achieve knowledge about basic methods and means for graphical communication. This includes an investigation of 3D-techniques and the use of animation on the operator screens.

Expected result

The result is an overview of the methods and means for communication through a computer screen.

Actual result

Integration of graphical modalities, visual dimensions and gestalt principles

The visual dimensions from Bertin (1983) were discovered and found useful as a starting point for describing the means for graphical communication. Further the graphical modalities of May in Pedersen and May (1998) and the gestalt principles were studied and an attempt to bring these theories together was made (see chapter 3). The possibilities of 3D-visualisation and animation were considered, although a detailed study of the theories and problems involved has not been made. Other topics dealt with in less detail were colour schemes, possible colour combinations and the use of metaphors.

A.6. A Survey of New Display Technology

Purpose

What are the possibilities?

The goal is to investigate in which direction the development of display systems is moving and what might be expected in the future. Special effort will be put into large screen displays, multimedia and virtual reality. Furthermore eye and operator tracking systems together with voice response systems will be considered.

Expected results

A list of possible new display systems is the expected result. The new display systems are compared with each other regarding what problems do they solve and how close the systems are to be applicable in industrial process environments.

Actual results See Appendix C	The report in appendix C describes some of the possible new technologies to be used in control rooms in the future. The maturity of these technologies are assessed together with their relevance for process control.

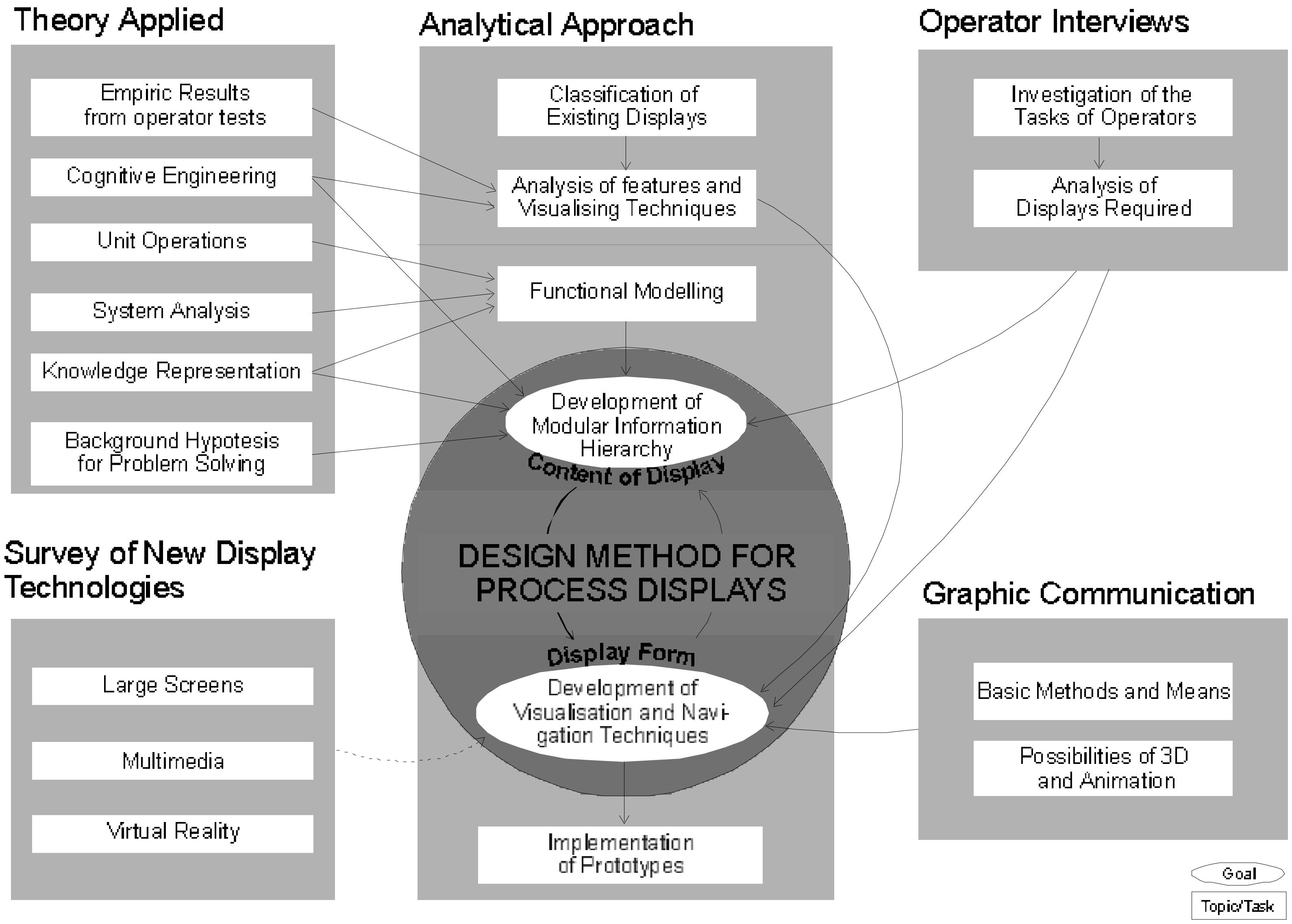

Figure A.1. Relations between project goals and topics as identified in the beginning of the project.

Appendix B. Terminology

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Introduction

This appendix is an attempt to clarify and define the terms often used when control systems are described. Definitions are needed to avoid misunderstandings when people do not put the same meaning into the same words, which is often the case when their backgrounds are different. Hence people might have a different definition of some of these terms; the intention is just to make clear what is meant here when the terms are used throughout the thesis.

Unfortunately it has not been possible to define all the terms without using definitions of other terms and moreover it has not been possible to make a straight top-down definition meaning that terms not yet defined might be used.

In general the physical items found in the plant such as components and signals are defined first. Then follows the more abstract concepts such as goals, functions and process operations. Examples are given, also inside the paragraphs containing the definition, because by examples it is easier to get the meaning through to the reader. A discussion regarding process operations and functions is also included.

The terms listed below are **not sorted alphabetically**. The index on the previous page is sorted alphabetically.

Control system	The control system is the agent, which reads the sensors, makes decisions and manipulates the actuators. The control system is divided into the automation system and the operator.
Automation system	The automation system is the system that handles either the entire control task or a part of it without human interference. The automation system consists of computers and Programmable Logic Controllers (PLCs), which are connected to the active components (sensors and actuators) and communicates with these on command of automatic controllers (regulators) or operators. Networks are used to make the connections between the PLCs, between PLCs and the SCADA systems, and between the SCADA system and administrative systems. Also pure mechanical construction used to control a process variable are regarded as an automation system. E.g. control of a liquid level by use of a float that adjust the opening of a control valve using a mechanical linkage.
Operator	Operators are the personal responsible for controlling and supervising the plant in order to secure the production. The control and supervision is either done through process displays or from control panels. In centralised plants the operators are situated in a control room and control the plant from distance. In de-centralised plants the operators control the plant from panels or process displays placed around the process equipment.
Process display	Process displays are the computerised information systems from which the operators control the plant. Process displays encompass the information content and the presentation of it, including windows systems. Typically process displays is shown on a standard computer screen, but other means such as touch panels and large screen are possible.

Man-machine interface	Man-machine interface (MMI) encompasses both process displays, control panels in the control room and in the plant plus the user interfaces of smart sensors.
User interface	See man-machine interface
Intervention point	Intervention points are the operator’s handles to the process. On process displays common intervention points are: push buttons, sliders, input boxes for parameters, etc.
Component	Components refer to the items that make up the plant, such as pumps, valves, pipes, tanks etc. Reference to software components such as ActiveX components will be explicit stated. Components can be divided into passive and active components. For development of process displays and automation systems the following definition is used: *Active* components are the ones, which interact with the control system, such as sensors, actuators and controllers (regulators). *Passive* components are everything else, like tanks, pipes, air supply hoses, electrical wires etc.
Process equipment	Process equipment is similar to plant components, but not as specific. The term is used to refer to plant components in general, not being specific about the kind of component and not referring to a modular (functional) division of the plant.
Process module	A process module is the part of the control system and the aggregation of plant components needed to implement certain functionality. E.g. a tank module can consist of the actual tank, the required instrumentation and the PLC hardware and software for filling and emptying the tank.
Process variable	Process variables are the analogue attributes of a process module or a component. E.g. temperature or oxygen content.
Status	Status is the digital attribute of a process module or a component. E.g. the pump can be on or off.
State	States are the conditions of a process module or component derived from the process variables and the status. E.g. a tank can have the following states: empty, partly filled and full, which can be derived from process variables (weight transmitters) or from the status of discrete level transmitters. Adding assessment criteria to the values of process variables and status can create alarm states. Common alarm states are high alarm, high warning, normal value, low warning and low alarm for process variables. Finally an automation program can be in different states like initialising, running, terminating, etc.
An example of physical items	A pump is a common component in process plants. The on/off switch placed near the pump in the plant is the actuator to the pump and receives its input from a person turning it. The pump’s sensor is the lamp, physically placed near the

switch in the plant, which indicates the status of the pump. The lamp can only be read by plant personal.

The push button placed on the operator's screen is the actuator to the pump and can be activated by the operator. In this case the push button is the actuator, because it sends a signal to the pump's starting unit, which tells it to run. This signal goes through the automation system and it is said that the plant is automated. The signal to the pump control unit could as well be sent from a controller within the automation system.

Goal

Goals are divided into operational goals and design goals.

Operational goals are desired plant states. At a high level of abstraction plant operational goals can be divided into goals regarding production, security and economy (Lind, 1990). Each of these goals can be decomposed into sub-goals, which are either other operational goals or design goals.

Operational goals exist in the context of plant in operation and are achieved by process operations.

Design goals are goals within the design process and are sub-goals to the operational goals. Design goals are achieved by the plant functions, which are implemented by use of components and control systems. Design goals exist in the context of plant construction.

Function

Lind (1990) defines a function as useful behaviour [of an artefact]. That is, an artefact has a set of behaviours and the ones that are useful for the task at hand are the functions of the artefact.

E.g. the behaviour of a centrifugal pump is to transfer energy to the liquid in form of both kinetic and heat energy. Usually it is the transfer of kinetic energy that is the useful behaviour of a pump i.e. its function is to transport liquid. In a thought example, the transference of heat energy might be the useful behaviour (in the case where the liquid should be heated), hence the function of the pump in this context is heating.

Usually a component is placed in the plant because of one and only one of its behaviours. With other words plant components have only one intended function.

Functions are static in the sense that the useful behaviour of a component does not change, because in most cases a component is chosen because of only one of it's behaviours, that is it has one intended function. When the status of a component changes its useful behaviour is still the same but it might not be enabled. E.g. the useful behaviour (the function) of a pump is still to transport liquid even though the pump might be turned off. The intended function of a temperature transmitter is to measure the temperature even though it might be disconnected from the automation system or be in other kind of failure.

Notice that functions can be useful behaviour of plant modules, that is aggregation of components.

Functions deal with the plant designer's intentions about how a certain operational goal can be achieved. Often the behaviour of the component, which realises a function, is explicitly considered whereas the behaviour of the component, when the function is not needed to achieve the operational goal is seldom considered explicitly. In that sense design solutions are static when the plant is in operation.

Process operation

Process operations exist in the context of plant in operation and are applied to fulfil operational plant goals.

Process operations are dynamic. A process operation can be in different states, like disabled, enabled, initialising, terminating etc. The state of a process operation is changed when the plant components are manipulated either by the automation system or the operators. The manipulation and thereby the state of process operations are controlled by the operational plants goals at a given time.

Process operations deals with the manipulation of one or more functions when the plant is in operation.

Process operations versus functions

It might be argue that the functions of a process modules or components are similar to a process operation. Though from the above definition where function is useful behaviour a mechanism for shifting from one useful behaviour to another is required to describe the dynamics in process plants.

For example within the goal context of transportation a transport function is required and therefore a component or group of components (a module), which is capable of performing this function is sought by the plant designer. The chosen implementation will also have other behaviours but they are not relevant within the goal context, meaning that only the intended transport function is sought. When a centrifugal pump is not running it behaves similar to an obstacle placed inside a pipe. This is not useful behaviour in the goal context of transportation and is therefore not considered (modelled) as a function because the obstacle behaviour it is not relevant for this or other goals.

As mentioned these considerations are made during design of the plant. When the plant is in operation the module, which applies the transport function might be in different states. A simple example is a transport function that is realised by a single pump component. The pump can be either on or off (its possible status). The status equals the state of the transportation function, when the time it takes to bring the rotor to the desired speed or to stop is not considered.

In conclusion during the plant design the designers consider the intended functions of plant modules that are needed to achieve the operational goals. When the plant is in operation the realised functions will be in different states depending and controlled by the operational goals, which must be achieved at a given time. Therefore to be able to deal with the different states of functions and to clarify the difference between plant design and plant in operation the concept of process operation is introduced.

Operator task

From Pedersen and Lind (1999) operator's tasks are, at a high abstraction level, defined as:

1. short-term goal setting to achieve operational plant goals by *performing process operation*.
2. *perform activities*, that is the actual sequence of actions the operator must make to execute the process operation.

Example of plant concepts

For example an operational goal could be to bottle x hl of beer. A operational sub goal is to transport the beer to the bottling machinery. A derived design goal is to be able to transport the beer. The design goal of beer transportation can be implemented by components that afford transport functions. Such components could be a pipeline with pumps or a truck with a driver.

The operational sub-goal of beer transportation is achieved by the process operation: beer transport.

The operator activity to perform the beer transport (the process operation) is either to start the pumps on the pipeline or to instruct the driver of the truck to move the beer, depending on the chosen design solution.

Display element	A display element is the aggregation of graphical modalities, which are suitable for a specific display content and a specific operator task. Display elements includes intervention points for the operator. Often display elements are actual software implementations (e.g. ActiveX components) as opposed to visualisation. Examples of display elements are trend curves or the software implementation of see saw construction from the ecological interface for the Duress system.
Visualisation	Visualisation is the conceptual design made from combination of graphical modalities and visual dimensions. Visualisation does not consider the interaction with the operator.
Modality	A modality is the invariant semantic type that can be use for expressing information across different channels of communications (media). For example natural language (a modality) can be expressed in the acoustic media (speech) as well as in the graphical (text) or the haptic (Braille text for the blind) media.
Medium	Media are the possible channels through which communication to human beings via their senses can be made. The most used media are the graphical, the acoustic and the haptic.
Entity	Entities are everything found in the description of a process plant except relations. Among the top level entity categories are physical plant items, plant concepts, quantities (numerical values) and events.
Relation	Relations are the links between the entities.

Appendix C. A Survey of New Display Technologies

Table of Content

Objectives

The aim of this report is to survey the display technologies, based on a three-week journey to Japan in November 1996 (the report was created in December 1996 and has not been updated to present time (1999)). First the basis of the technology is described and if the use of the technology is not obvious a scenario for how the technology can be applied in industrial process control is given. Then the technology is assessed with respect to whether it is useful for the plant personal and with regard to how close it is to be applicable in industrial process environments. The main groups of technologies are: multimedia, virtual reality, interaction and display devices.

The viewpoint taken when assessing the usability will not only be at the plant operators and their tasks but also at the other personnel at the factory, like maintenance, technicians, quality ensures, production planners and managers. This broad view makes it possible to consider how the different groups of staff can and must co-operate to ensure a safe, economical and optimal control of the plant.

C.1. Multimedia

The definition of multimedia is that more than one medium is used to exhibit a complete presentation.

C.1.1. Video

Description

Mitsubishi Electric has developed a prototype of a Highway Remote Management Support System where on-line video recordings are integrated into the monitors. The cameras (which will be placed along the roads) record the traffic and will, when something goes wrong, give the operators the possibility to replay the video for analysis. Further the system can calculate the distance from e.g. a burning car to any of the sprayers placed inside tunnels for fire extinction. It helps the operators to determine which sprayer to activate and to determine if there is space enough for rescue vehicles to enter the tunnel.

Usefulness in process control

There is no doubt that the video camera will be integrated in supervisory systems in the near future and it will be regarded as any other measuring device like e.g. flow sensors. As indicated by the traffic monitoring system the application areas will be fast changing spatial processes, which are difficult to monitor today. A second example in which video recording might be beneficial, is processes where today’s measuring sensors can not be placed due to extreme conditions, for example caused by heat or radiation. Another reason to use video recordings in a supervisory system is to enable to operators to see the real world and not only a model of it, e.g. by using mimic diagrams etc. in the control system.

Time horizon

Video recordings shown on television are already seen in control rooms today. The advantages of having the video sequences integrated with the supervisory system are that algorithms for pattern and movement recognition allows the system to respond autonomously. As these recognition algorithms are getting more and more developed in the near future we will see more use of video recording in process control.

C.1.2. Co-operative Work Support System

Description

At Mitsubishi Electric a prototype of a system for co-operative work support has been developed (Ohi and Muraoka, 1996). The aim is to let several groups of plant personnel, not located in the same place, communicate and work together through a computer network. The developed communication board appears in a window on the operator screen and equips every person with a unique cursor (colour coding). Users can now drag and drop parts of their screens (saved as bit maps) onto the communication board where it immediately appears for the other users. Notes and pointing gestures can be also be sent. For later evaluation of the team performance the sequence in which information entered the board can be replayed. The communication board is developed on a UNIX platform.

Usefulness in process control

The system has not been tested on a group of users, but it seems intuitive that communication by sharing pictures, video etc. is superior to telephone communication alone.

Time horizon

A basic communication board can be developed today. In short time it will also be possible to communicate by voice through the data network, hence a unified communication device is developed and the telephone will only be used in some cases. In future wireless communication to the laptops of the maintenance staff working in the plant might be developed and extend the application area of the communication board.

C.1.3. Digital Video Disc

Description

The Digital Video Disc or Digital Versatile Disc (DVD), experienced at the Digitalmedia World Exhibition, is a new high capacity data storage medium, similar to the Compact Disc (CD) but with higher capacity. DVD-ROM is available now for replaying movies. To play a movie on a computer it must be equipped with a MPEG2 video decoder and Dolby AC-3 audio decoder, as data must be compressed to store a whole movie on the DVD (max. 133 min.).

It is expected that an erasable DVD, the DVD-RAM will enter the market late in 1997 (Tactical Marketing Group). Again a MPEG2 video encoder is needed to store longer video sequences. (DVD-RAM drives will read and write to a 2.6GB DVD-RAM disc, read and write-once to a 3.9GB DVD-R disc, and read a 4.7GB/8.5GB DVD-ROM disc.)

Scenarios

When component manufactures provide information on DVD, like video sequences of how to repair the valve and the component specifications, it will be desirable to be able to integrate this information into the control system of the plant.

Another scenario is storage of data of the video recorded processes for a specified period, so it can be replayed in case of emergency or quality control (c.f. the highway monitoring system from Mitshubishi Electric Corporation where crashes can be analysed.)

Usefulness in process control.

The DVD makes it easier to distribute large amounts of data, which is relevant for parts of the plant personnel. Hence the personnel will get extended and more detailed information that should enhance their performance – however, the danger of information overloading is obvious. For that reason effective and easy to use search and filtering techniques must be developed. Furthermore a definition of an open architecture which makes it easy to enter, maintain and remove data will be required. The architecture must also provide user log-in facilities which will work as the top-level filtering of data access for the personnel. With all the information available a task for the management will be to define and limit the working areas for different plant personnel. E.g. it must be decided if operators should learn to change a valve by looking up type, place in storage, see the video of which bolts to undo, or it shall remain as a job for maintenance staff. In conclusion the opportunity to easily distribute data might help and support the plant personnel in doing their task and enhance their co-operation, but user friendly search and filtering mechanism must be developed.

Time horizon

Today it is possible to integrate on-line video recordings into the supervisory system as described previously. Later it will be desirable to store the video sequences for analysis. This can be seen in parallel to the early supervisory system, where it was possible to monitor on-line process values, and the later interest in storing these data, leading to the development of SCADA systems, see Figure C.1.

On-line process variables	Storage of process variables	On-line video sequences	Storage of video sequences
1970'ties	1980'ties	1996	1998?

Figure C.1. Historical development of supervisory systems

C.2. Virtual reality

What is it?

By virtual reality is meant an artificial environment, which is created within the sight for the human being. VR gives the user the possibility to see virtual worlds, which either can be realistic mappings of the real world or created artificial worlds. Several output devices from the computer system can be applied to create this 3D virtual environment. To interact with the system input devices are required. Some input and output devices will be described later.

Immersion

To indicate the degree of realism achieved by a certain virtual reality device immersion is used as a measure. The more the user cannot tell the difference between the VR experience and the reality, the more the immersion is obtained. The degree of immersion is determined by the input and output devices, so an increase of immersion usually result in an increase of cost (Bell and Fogler, 1994). For some tasks a high degree of immersion might not be appropriate, instead the VR devices can be used as means for presenting information.

C.2.1. Output Devices

Head Mounted Display (HMD)

This device has the appearance of a helmet with one or two built in miniature LCD or CRT tube screens built in (Figure C.2). See Bernatchez (1995) for more details.

Figure C.2. Head Mounted Display

The HMD permits a high level of immersion compared to other visualisation methods. Some models have the possibility of 'see through', meaning that the real environment also can be seen together with some additional information supplied by a computer. Hence the immersion is lower, but as mentioned this can be useful for some task.

Research using head mounted displays are performed at Kyoto University, where an eye-tracking device is connected to the display. Hence it is possible to see where the subject is looking, though in 2 dimensions only, missing the depth.

Crystal Eyes

Crystal Eyes refers to a special hardware device that allows the user to view three-dimensional objects by the use of a special display monitor mode and special stereo viewing glasses.

The basic principle is that the computer alternately displays the left-eye image and then the right-eye image on the same screen, while at the same time the glasses alternately block the vision of the left eye and then the right eye in synchronisation with the changing screen images. The synchronisation is made by an infra red light device from the computer system to the glasses. To reduce distracting flicker the vertical refresh rate of the video signal is doubled, with the drawback of requiring a more expensive monitor.

Figure C.3. Crystal Eyes

Sound

Sound can be combined with the visual output device to enhance the immersion. By using a 3-D audio system the user can sense the direction of the sound, which can be used to attract his attention.

C.2.2. Input devices

Input devices are mainly used for navigation in the 3D virtual environment. Execution of commands or functions is done from buttons or menus. Large amounts of data, like in word processing, is rarely entered in a VR environment. A 3D space gives 6 degrees of freedom (DOF), three translational and three rotational.

Data gloves

A common input device is the data glove where the hand and finger movements of the user's hands are determined by use of a tracking sensor (ultra sonic). This makes it possible easily to manipulate all 6 DOF. The glove might be equipped with tactile feedback capabilities.

Alternatives

Keyboards, mice and joysticks can also be used to navigate in 3D worlds

Keyboards, mice and joysticks are all developed for navigation in 2D space. The advanced of the mouse is that it can easily be move diagonally in a *limited* 2D plane (the computer screen) and there is a correspondent between the physical position of the mouse on the table and the cursor on the screen. That is the reason why mice and not joysticks are used for navigation in ordinary computer applications as the joystick lacks the relation from physical position to cursor position.

The idea behind the 3D virtual worlds is that it shall be possible to walk or fly around, hence the area of interest is not limited to the computer screen, but is the entire created VR world. Notice if we are only walking around in the 3D space, the navigation task is restricted to 2D and can be done by a 2D input device. In such cases the keyboard and joystick are superior to the mouse when it comes to navigation in ‘unlimited’ environments, as there is not a correspondence between the physical placement and the position in the virtual environment. A

2D device can be used to navigate in all three dimensions by use of another key, like pressing the Alt-key. Though it will only be possible to move in 2 dimensions simultaneously and only 3 degrees of freedom are available, most often the translational DOF are controlled this way. To reduce cost on the input device a joystick should be considered.

To manipulate the three rotational DOF a data glove or other special input devices must be used. The 3D Space Ball shown in Figure C.4 and the Phantom Haptic Interface in Figure C.5 are examples of such 3D input devices.

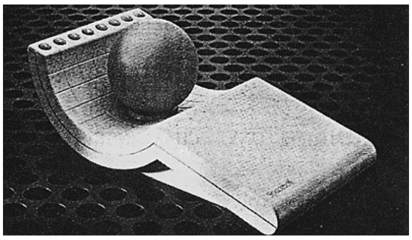

Figure C.4. 3D Space Ball

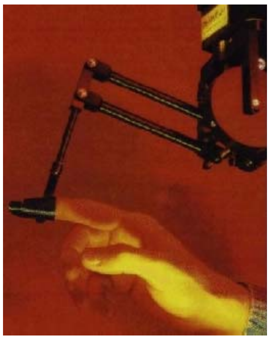

Figure C.5. Phantom Haptic Interface

Besides navigation using all 6 DOF the Phantom Haptic Interface also applies a variable resisting force so the user can feel when he grabs a virtual object.

Finally whole suits have been wired to track “all” movements of human beings. This is used in the entertainment industry for animation.

C.2.3. Scenarios

Transferring the real world to a new location

Video recording from the plant production feed to HMD together with sound will give a feeling of actually being at the plant (though the smell is missing). The user should be able to adjust the position of the plant camera, e.g. it should follow his head movements, which can be done be head trackers. Perhaps the user can point at an object he wants the camera to zoom on. That will allow people to get a good impression of the situation in the plants without being there physically. That might save operators many foot steps or experts will be able to give their judgements from home or at the head office. This means that the video signal must be sent real-time through e.g. the internet and/or intranet.

Remote Control

Another possibility is to model hazardous environments and let the operator perform his actions in the virtual world, away from the risky real one.

Research in this area is on going at Kyoto University, where the operator wearing a data glove (see Figure C.6) manipulates a robot.

Figure C.6 Remote control of robot by VR

Co-operative design using VR

At the Advanced Telecommunication Research Institute (ATR) they have developed a prototype of a design system where the created design is shown in a virtual environment. The designers are equipped with crystal glasses in front of a large screen and with data gloves. Objects can be grabbed and moved by hand, furthermore collision checks can be made so designers are notified if two elements are placed on the same spot. The aim is to let several designers, situated at different location, work together at the same virtual model of the design.

Supporting Maintenance staff

Another possibility is to use wearable computers equipped with a HMD to support maintenance personnel. This can be illustrated with the following quote from the application session of the Boeing Wearable Computer Workshop (Blackadar, 1996): “Maintenance of complex machinery, of "downtime critical" applications, will be targets for the wearable in the maintenance world. This market will require that all records be able to be brought to the industry, that smart, perhaps genetic algorithms be used to walk the user intelligently through the repair tasks, connectivity to remote experts will be a must. Having short video clips though not necessary would be useful. The wearable gear must be lightweight, not generate any head ache and, must not get in the way (low profile, embedded wiring.).”

If two way communication is necessary special keyboards, which can be operated by one hand only, have been developed. If it is required that the person have both hands free speech recognition will be needed.

C.2.4. Usefulness in process control

The main task in which VR is applicable is entertainment, design, learning, remote control and data visualisation. Only the last four tasks are relevant in the area of process control.

Design

When the design of the factory and control system is made in VR these models might be useful for the operators to get a one to one mapping between the process display and the real plant. Today mimic diagrams are used as the lowest (and only) level of abstraction of the plant. The mimic diagrams correspond to Rasmussen’s physical function level in the abstraction hierarchy and the VR environment will match the lower physical form level (Rasmussen, 1986). The likelihood of equivocations of components by the personnel doing the maintenance, which might be the plant operators, will be reduced.

Learning

A copy of the real world can be useful to maintenance staff to learn how to repair components. A possibility is that component manufactures provide illustrative assembling sequences (perhaps on DVD) which can be viewed and operated in 3D if the user wears crystal eyes. This will take place when PCs are sold with a pair of crystal eyes in the same way as PCs are sold with loud speakers and a microphone for multimedia purposes today. The next step will be to use HMD for on-line guidance of the maintenance staff as described above.

Remote Control

Another way to use a copy of the real world is for remote control. Prototypes of such system have been seen, but a lot of research work is needed before such systems are applicable for industrial application. Besides the use of remote control is limited to a few, critical process domains, such as space shuttles, surgery and extreme dangerous processes e.g. nuclear power plants and some chemical industries.

Data visualisation and exploration

The artificial world might be used to visualise and examine historical data of process variables either by operators, production planners or quality management. To get the best out of the 3D possibilities new visualisation techniques must be developed especially for this purpose.

Comments

A final note regarding all the mentioned and possible applications areas of VR is that it might be useful to distinguish between a cheap solution by using crystal eyes plus joystick and an expensive one consisting of HMD and data glove. The requirement for accomplishing a specific task should be considered and the simple and cheap solution might fulfil the needs in many cases, f. ex. for data visualisation.

C.2.5. Time horizon

The first applications, which are already developed beyond the prototype stage, are in design engineering, e.g. kitchen or car design. Right after follows the use of VR for educational purpose, where prototypes for visualisation of nuclear reactions exist at Kyoto University. Whether VR will be applicable for data visualisation and examination will depend on the usefulness of the visualisation techniques, which have to be invented. There is a good chance that maintenance staff will be learning by watching and operating on virtual component within the next decade. Eventually wireless HMD will be available and perhaps VR will be the new computer interface.

C.2.6. Software for implementing VR

WorldToolKit

The software used at Kyoto University is the WorldToolKit from Sense8 Corporation. The is also supported by Bell and Fogler (1994) in the following quotation:

“The software development package which we have chosen for most of our VR development work is WorldToolKit, (WTK), from Sense8 corporation. The main factor influencing that decision was the wide range of platforms supported. There are versions of WTK available for MS Windows, DOS, Silicon Graphics, and numerous platforms in between.

WorldToolKit is actually a library of C language routines, along with a few support files and demo programs. In order to use WTK, one must have C programming skills and an appropriate compiler/linker. Other supporting programs, such as AutoCAD and photo management utilities, can be very useful for developing the objects and images necessary to populate a virtual world.”

VRML

VRML stands for "Virtual Reality Modelling Language" and is a specification for defining three-dimensional environments on the World Wide Web.

That might be useful when the production specialist of world wide companies want to examine the production data from the plant located on the other side of the world.

Notice that VRML does not give a real 3D stereo image but makes it possible visualise 3D figures on a 2D plane of the computer screen by use of projections.

C.3. Interaction Devices

This section describes new ways of communicating with the computer. The main idea is that the computer by use of video cameras recognises the user and delivers information according to his wishes. Hence the traditional way of interaction by keyboard and mouse is abandoned.

C.3.1. Human gestures

Description

At the Advanced Telecommunication Research Institute a prototype system for demonstration is developed, where the computer system recognises the gestures of a human being and responds to these. The demonstration room is equipped with two cameras, one in the ceiling and another at the wall. On this wall a screen covering the whole wall (approximately 10 m^2) displays the responses of the computer. The demonstration scenario is as follows: The system identifies when a person enters the room and when walking around the system responds by placing plants on the screen in the foot steps. If the person stands still a tall flower will appear and dashing it with the arm will active some flies. These flies follow the hands, so the person can decide to have one or two groups of flies by rising one or both hands. When the hands are kept still for a while the flies will disappear.

So far it is possible to recognise coarse gestures, but the computer can not ‘see’ if the hand is open or closed. Further only one person can be recognised at the time.

Scenarios

One possibility is that operators can navigate on the screen by use of gestures. For example the operators could navigate in 2 or 3 dimension spaces by pointing and making rotating gestures by their hands. That will reduce the workload of the operators as they can concentrate on the task. Also from an ergonomic point of view this is beneficial because the soar shoulders from mouse navigation will be reduced.

Maybe it will be possible to judge the state of the plant from the gestures and behaviours of the operators. If they are laid back in their chairs chatting and smoking everything are probably fine and the system shall only show the most important information on the screens. If they are sitting right up in their chairs staring at the screen, they probably want some additional information about what is going on in the plant and the computer will supply recent trend curves and appropriate mimic diagrams. Finally if there are hectic communication among operators with many gestures and walking around from control panel to control panel something must be wrong and the system must provide as detailed information as possible but only for the section of the plant that is in alarm. Hence it can be derived from the operator’s gestures whether their cognitive behaviour is skill, rule or knowledge based (cf. Rasmussen, 1986).

Another futuristic scenario is that the computer can identify different persons and then log in for them when they enter a control panel in the control room.

Usefulness in process control.

Navigation by gestures will undoubtedly be helpful for the operator. Especially if the parts of the entire mimic diagram, are collected into one large mimic diagram in which the operators can pan and zoom by gestures, using the computer screen as their window to the diagram.

For 3D objects, like 3D plots of historical process values, hand gestures for rotations might be more intuitive than rotating by mouse on e.g. sliders. The reason is that, by use of gestures, it is possible to rotate both xy and the yz planes simultaneously.

Also for navigation (walking or flying) inside 3D virtual environments e.g. for examining relations between plant data, gesture navigation might be better than e.g. navigation by joystick. If a data glove is used it might be able to detect the gestures of the hand, so the cost of a video camera can be saved.

Judging the plant state from the operator's behaviour and gestures is an ideal, but difficult idea to realise, so it is not regarded as useful for the operators within the next decade. One problem is: what if some operators prefer to lie back in their chairs watching and considering the situation before taking action when then plant is in a critical state, then they will not get the information they need.

The usefulness of identification of operators when they enter the control panel is limited, as it does not take many minutes for the operators to log on to the system.

Time horizon.

As mentioned recognition of operators and their behaviour will probably not be realistic in the next 10 years. But identifying hand gestures with the aim at navigation should not be impossible with the technology and knowledge available today.

C.3.2. Facial expression

Description

The idea is that emotions of the human beings can be recognise from their facial expressions. To obtain the expression dots are painted on the face and then video recorded. By use of pattern recognition it can be judged whether the person is smiling, angry, sad etc.

Usefulness and time horizon

A similar scenario to the one above where operator's behaviour is judged from their gestures can be made. Again it is not likely that this technology will be able to support the process operators within the next decade.

C.3.3. Speech recognition and translation systems

Description

Research in the field of speech recognition, translation and synthesis is made at the Advanced Telecommunication Research Institute. The developed system was in 1994 able to translate a vocabulary of about 1000 Japanese words into English or German, when the sentences are spoken out loud and clear. The direction of the research is to enhance the systems performance so it can recognise everyday speech. There have been some improvements but there is still a lot of work to do.

Usefulness and time horizon

For that reason speech recognition is not regarded as being useful to the plant personnel in the short future, when the interference of noise from other operators, radios and people leaving and entering the control room is taken into considerations.

C.3.4. Visual Touch

Description

Another input device for video recorders and computers have been seen at Sony Show room in Tokyo, where the cursor is remotely controlled by wireless hand held pointing device (kind of similar to the laser pen known for pointing at the projections of overheads). To select an item a button exists like on a mouse.

Usefulness

That might be useful for operators to control the content of large screens. There must be some interlock so operators can not simultaneously change the large screen content.

Time horizon

The difficulties in applying the technology to large screen is unknown (not studied) and therefore it is impossible to judge the time horizon.

C.3.5. Voice Guidance

Description

Toshiba Corporation has applied voice guidance in their third generation of control centres for nuclear power plants. The system is named APODIA, which is the acronym for Advanced Plant Operation by Displayed Information and Automation. The objective is to give the operator more and better information about what the automation system is doing. Hence as the progress of the automation sequences it is spoken out loud (Makino et. al., 1996).

Usefulness in process control

This approach might be useful for the plant operators as long as the automation progress can be divided into larger, not detailed chunks. Otherwise the operators will be annoyed by the pronunciation of the next step of automation if it happens every 30 sec.

Another possibility is to add sound to major event in the process, like starting the main pumps or the opening of safety valves.

Time horizon

There should not be any difficulties in applying sound to the sequence of the automation system or process event with the technology available today.

C.4. Display Devices

The newer display devices for use in control centres are studied in this section. The devices are large screens, touch screens and flat displays.

C.4.1. Large Screens

Description

Newer technology has made it possible to create large screens, which can be connected to computer systems almost like any other screen. Usually large screens are made of several modules each of the sizes of approximately 50 inches. Today the technology is so developed that the screens are not very sensitive to light and the information can easily be read from even small angels and long distances. The drawback is minor colour differences between modules and the gap between the modules (a few millimetres). Furthermore the tubes have to be replaced approximately every 3 to 4 month if there are working 24 hours a day. The tubes generate heat so the control room has to be ventilated and finally the depth of such screens is about 2 meters without space for maintenance.

Usefulness in process control

The idea is that several operators can share the most important plant information on large screens, so everybody can see when a change occurs. A prototype system (APODIA) for nuclear power plants with 3 large screens (alarm, mimic diagrams and trend curves) has been developed and evaluated by Toshiba Corporation. The large screen display panel was evaluated highly and seemed to help performance of the operators greatly in emergency situations (Kawano et. al., 1996).

Time horizon

Large screens are available today but still so expensive that they will only be considered in large-scale plants having a central control room with several operators.

C.4.2. Touch Screens

Description

Several technologies exist for making touch screens, some of these are surface acoustic wave, infra light, resistive and capacitive, each with advantages and disadvantages. A special controller board is needed together with these screens. To avoid activation of undesired components an off-touch technique is develop for selection. When the user presses the screen the selected item is marked and is not activated until the finger is removed from the screen. If a wrong component or button is selected the finger is simply moved, still touching the screen, to an area where selection is not possible and then removed. The response time for touch screens (approximately 5 - 15 msec.). has now reached a level where they can be used for human-computer interactions in control centres.

Usefulness in process control

By using touch screens the operators have an easy way to navigate and enter digital input to the computer (adjustment of analogue set point, e.g. from a knob, can not easily be made from touch screen). Evaluation of touch screens in the APODIA system from Toshiba showed that operators where sceptic to whether they could operate the system from the touch screen, but their performance and comments after the test showed that they did not have difficulties using the touch screens. Neither did operators comment negatively on the response time (Kawano et. al., 1996).

The problem is that not all kinds of commands can be performed from touch screens as mentioned above, but for navigation between mimic diagrams the use of touch screens has proven to be effective and easy to use. Hence touch screens combined with ordinary input devices such as keyboard and mouse should be considered as input device for plant operators.

Time horizon

Touch screens have been on the marked for some years, but has not been widely used in control rooms. One reason is the slow response time of the first touch screens together with the traditionally reluctance to new technologies. Today time response is not a problem, so touch screens might be a good choice for both small and large scale plants.

C.4.3. Flat Display

Description and time horizon

Flat screen display can be made by LCD or plasma technology, where the last one is the cheapest to manufacture. Today several companies produce 20” flat display and larger displays will enter the market in short time according to Fujitsu.

Usefulness in process control

The advantages of flat panel displays are that they provide portability, space savings, and power reduction. However, they do not differ in functionality from CRT screens and will therefore not give new possibilities to ease the tasks of the plant personnel.

C.5. Conclusion

Multimedia

It is concluded that multimedia in form of video and sound soon will be seen in supervisory systems. Furthermore the possibility of data distribution on media such as digital videodiscs (DVD) will result in larger and more complex databases. These databases will besides plant data contain component specifications, videos and tutorials for maintenance of components, documentation for hardware and software implementation, production plans, energy plans etc. Different groups of employees will need to access different parts of the data and to exchange information through these databases. The interface to this huge amount of data will be provided by personal computers and probably as an integrated part of the SCADA system, as it contains the interface to the process data today. This means that new tools for searching and filtering together with tools for maintaining the databases will be required.

Virtual reality

Virtual reality (VR) is still in its early years (1996) and is expected to develop from design applications to learning by doing and data exploration in virtual worlds within the coming years. From there on it might be used for remote control where the operators act on the artificial world and eventually virtual reality might be used as complete user interfaces. The most interesting use of VR in process control is for data exploration, which might give better visualisation of the correlation between process variables. Another possibility is training of maintenance staff in virtual environments.

Possibilities for interaction

Interactions between human and computer are developed in two main directions: video recordings of gestures (including facial expressions) and speech recognition. Both technologies are far from been applicable in industrial control rooms. Though it should be possible to develop prototype systems for navigation on computer screens or in virtual worlds by use of simple hand movements. The problems with the existing prototype systems for speech recognition are that they can only understand a limited vocabulary spoken very clearly and it seems to be a while before better systems will appear.

Display devices

Large screens are available on the marked today (1996), but are so expensive that they will only be affordable in large-scale industries. Moreover they are only useful if several operators have to work as a team to run the plant.

The response time of touch screens has been reduced making them a choice as input device. Evaluation by Toshiba Corporation (Kawano et. al., 1996*)* has shown that operator did not have troubles using the touch screens.

Flat displays do not give new functions compared to CRTs, but takes up less space and power.

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CONCEPTUAL DESIGN OF INDUSTRIAL PROCESS DISPLAYS

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Abstract

Today, process displays used in the industry are often designed on the basis of piping and instrumentation diagrams without any method to ensure that the needs of the operators are fulfilled. Therefore, a method for a systematic approach to the design of process displays is needed. This paper discusses aspects of process display design taking into account both the designer's and the operator's points of view. Three aspects are emphasised: the operator tasks, the display content and the display form. The distinction between these three aspects is the basis for proposing an outline for a display design method that matches the industrial practice of modular plant design and satisfies the needs of reusability of display design solutions. The main considerations in display design in the industry are to specify the operator's activities in detail, to extract the information the operators need from the plant design specification and documentation and finally to present this information. The form of the display is selected from existing standardised display elements like trend curves, mimic diagrams, Ecological Interfaces, etc. To invent new display elements further knowledge is required. That is, knowledge about basic visual means of presenting information and how humans perceive and interpret these means and combinations. This knowledge is required in the systematic selection of graphical items for a given display content. The industrial part of the method is first illustrated in the paper by a simple example from a plant with batch processes. Later the method is applied to develop a supervisory display for a condenser system in a nuclear power plant. The differences between the continuous plant domain of power production and the batch processes from the example are analysed and broad categories of display types are proposed. The problems involved in specification and invention of a supervisory display are analysed and conclusions from these problems are made.

It is concluded that the design method proposed provides a framework for the progress of the display design and is useful in pin pointing the actual problems. The method was useful to reduce the number of existing displays that could fulfil the requirements to the supervision task. The method provided at the same time a framework for dealing with the problems involved in inventing new displays based on structured analysis. However the problems in a systematic approach to display invention still need considerations. To be published in Special Issue of Ergonomics, Time and Space in Process Control.

Keywords: MMI, process industry, user-oriented design method, HCI, GUI

Introduction

The most common way to present information in process displays used in the industry today is to use mimic diagrams. The mimic diagram is based on the piping and instrumentation (P&I) diagrams and uses dynamic symbols to indicate the status of each component or subsystem. There are several problems with this approach:

1. The content of the display is not explicitly considered because the presentation is based on the physical topology of the plant, which originates from the P&I diagram, hence the plant functions and operational goals are not mediated.

2. The one-sensor-one-indicator principle is generally used, so the operators have to derive the overall status by integrating information of the plant from several individual indicators.

3. Displays are often designed without explicit consideration of the operator's tasks and information needs.

These problems can only be solved by a systematic approach to display design. The approach should guide the designers of process displays in both the initial conceptual design and the implementation phase. The method must facilitate transfer of process knowledge to the display designer and must help to determine *what* information to present and the controls needed by the operators. Further, it must provide guidance on *how* to visualise the information and the controls. Finally, the methods should generate specifications that map naturally into implementation concepts for graphical user interfaces (GUI) and support modular reuse of design solutions. Reusability of design solutions is a must for the industry because of the high costs involved in designing completely new solutions. The layout of display elements is not considered here, because standards, such as Microsoft's GUI design guide, exist which treats the problems of grouping, navigation, consistency etc.

No methods exist that, to the author's knowledge, treat all the above mentioned requirements. Present methods do not convincingly facilitate the transfer of process design knowledge into display design. Modern industrial plants are highly modular, being composed of subsystems and associated controls and instrumentation for each process operation. A modular approach to process design is widely used in the industry as a means of reducing development costs. It is therefore essential that methodologies for display design can support that modularity. The use of abstraction hierarchies (AH) (Rasmussen, et. al. 1981) has been proposed for this purpose of modelling the functional structure of plants. However, the AH in its present form is only suiTable D.for the representation of the functional structure of energy systems. According to the experience of one of the authors (Lind), it requires considerable adaptation when used for other types of systems, such as e.g. batch processes or mobile robots. One major problem with the AH is the lack of conceptual distinctions between different types of means (e.g. with regard to product, process equipment and control aspects), and the lack of concepts to express the functional relations between the means. Since the modular composition of plants comprise an aggregation of product, process equipment and control aspects, it is obviously very difficult for the AH to represent the design rationale for many industrial plants. These modelling problems are currently under investigation as part of the Multilevel Flow Modelling (MFM) methodology (Lind, 1994). The general idea of abstractions is fundamental to the display design method presented here, except from the problems specific to the AH.

Ecological Interface Design (EID) (Vicente and Rasmussen 1990) provides a method for transforming the display content into a form, which supports the cognitive competence of the operator (Vicente and Rasmussen 1992). EID uses the AH to determine the display content and structure, focusing on treatment of unanticipated events. Mitchell, et. al. (1986) developed the operator function model to determine the appropriate display content based on a behavioural representation of the operator. None of these methods consider plant modularity on the implementation of the GUI and therefore fail to meet the industrial needs of reusability. However, the basic principles of EID may be useful as part solutions.

Aspects of Display Design

The following three aspects should be considered in a systematic approach to display design: 1) the operator's tasks, 2) the display content and 3) the form of the display. The tasks of operators and the content of the display are obviously dependent on the actual construction of the plant, on the allocation of tasks between the operator and the automation system and on the modular integration of plant subsystems and control system. These functional modules are referred to as *process operations* and are illustrated in Figure D.1.

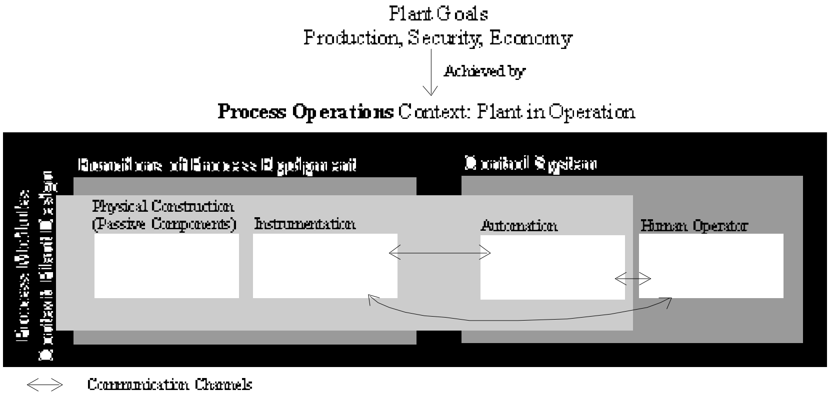


Figure D.1. Process operations combine equipment functions and the control system functions.

The plant can be divided into *process modules,* which is often done during the design and construction of the plant to enable reuse of the plant design solution. Process modules are representations of the physical construction, the instrumentation and the automation algorithms. Representations of the plant are needed to define the operator tasks and the display content. Examples of plant representations can be P&I diagrams, block diagrams, and goal-function hierarchies. Process operations are related to the operation of the plant, whereas the process modules are related to the construction. In other words, process operations can be regarded as the operational functionality of the process modules.

The three aspects are clarified below.

Operator tasks are defined when the plant and the automation system are designed. Operator tasks include: 1) short-term goal setting to achieve plant goals by performing *process operations*, i.e. the tasks needed to accomplish the long-term production, economical or safety goals of the plant stated by management (an example of a process operation in a brewery could be to move beer from storage to the bottling machinery to fulfil the production goal of bottling a given amount of beer per day). 2) Perform control *activities* i.e. the actual sequences of actions the operator must make to execute the process operations (e.g. to push the start button for the transport program and monitor the flow). With respect to operator tasks, it is important to consider both how the operator should interact with the automated systems and how the systems should respond back to the operator.

Display content (i.e. the information conveyed) can be divided into 3 groups.

- Information about the plant components, e.g. location and type of measurements or relations between components. This information is derived from the plant model where the important attributes of the plant with regard to the operator's tasks are selected.

- Information about the states, events and history of the plant, that is for example expected values of measurements or the development of process variables over time.

- Controls, that is, the intervention points through which the operators can operate the plant.

Display form is the graphical or textual presentation of the content. The graphical items representing, for example, plant components or the state of process operations (the content) can be decomposed into entities such as lines, boxes, menus, buttons, trend curves, pictograms, Ecological Interfaces etc. Different aggregation levels are found within these entities. The aggregated entities such as trend curves or Ecological Interfaces are referred to as display elements, which are created from combinations of low level entities such as lines and boxes.

Points of View

Process displays can be considered from two points of view: from the designer's and from the operator's. A method for display design must obviously include both viewpoints.

The Designer's Point of View

The designer's point of view can be divided into the man-machine interface builder in the industry composing process displays by use of already existing display elements and into inventors of new display elements.

The industrial display builder faces the following problems: When a new plant is designed or an existing is reconfigured, the task allocation between the automation system and the operator should be considered as well as the decomposition of the plant into modules. These decisions influence the operator tasks and therefore the content of the display. Hence the people designing process equipment, automation system and displays have to co-operate.

In practice, the automation and display builders are within the same company and receive the specification for the automation software and the process displays from the plant designers. A task analysis is seldom explicitly considered and another company generally specifies the process equipment and its instrumentation. This division of tasks between companies makes the transfer of plant design rationale into display design difficult.

For the display inventor the problems are focused around the topics of human perception and cognition. The display inventor must have a good model of the operator to be able to predict how the operator will react to different combinations of display content and form. The display inventor should be able to state which operator task an invented display is suitable .for, in order to ease the display builder's task of selection between available display solutions. Moreover the display inventor should be able to argue systematically for the choices of visual means and how they influence the operator's perception and cognition.

The Operator's Point of View

Norman (1988) states that the fundamental principles of designing for people are to 1) provide a good conceptual model and 2) make things visible, i.e. the capabilities or so-called affordances (Gibson, 1979) of the artefact must be visible, c.f. out of sight – out of mind. Figure D.2 shows the conceptual models involved.

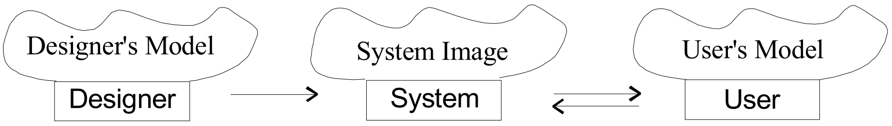


Figure D.2. Conceptual models in designing for people.

It is important that the display reflects the design model, i.e. constrains and decisions made during the plant design must be visible to the operators. For example during plant design it is decided to place hand operated valves between process modules (pipe sections) to ease maintenance; during plant operation the hand operated valves are assumed to be full opened. If the hand operated valves are not shown on the display they might not exist in the operators model of the plant. The consequence might be that the operators will not be able to detect the cause of error when the flow through the pipe is reduced because the valves have been closed during maintenance.

Norman (1988) sums it up to: if the system image does not reflect the design model in a clear and consistent way the user will end up with the wrong mental model.

This is exactly the problem with the current design of process displays in the industry. The only way the operators can communicate with the plant is through the process displays, which therefore should reflect the designer's model. The content and the form of the display are essential to ensure that the operator develops a good conceptual model of the plant. The operator's situation is illustrated in Figure D.3.

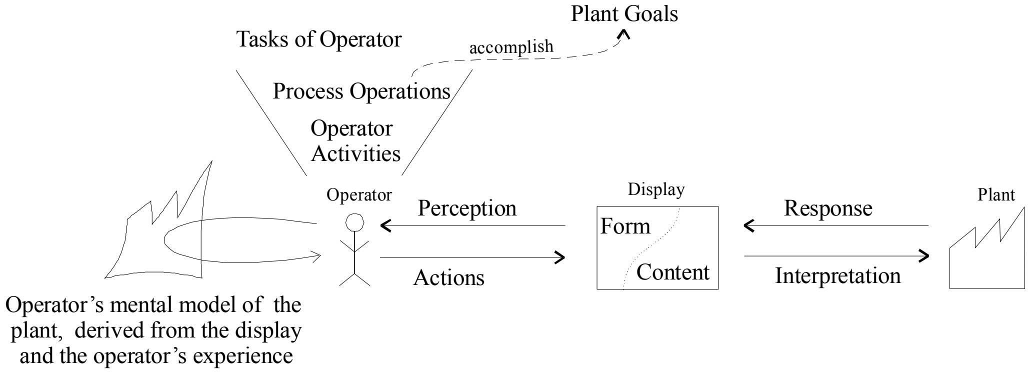


Figure D.3. The operator's world.

The operator activities (i.e. the actual sequence of actions to execute process operations) are in most cases performed on the display. Moreover, the operators have to evaluate and schedule which process operations they have to apply, both in familiar and unfamiliar situations, to fulfil the plant goals.

A Conceptual Design Method

The display design method discussed here is restricted to the three aspects: 1) operators' tasks, 2) the content and 3) the form of the display. The design method does not consider the task allocation between automation system and operator. The reason is that the process modules and thereby the process operations are decided during plant construction and can usually not be changed by the automation and display builder. This is the industrial practice today and improved methods to display design must take that into account, i.e. be evolutionary rather than revolutionary.

The objective of the method is to yield the right specification for the displays. Further, the method must support reuse of designed process displays in all 3 aspects mentioned above.

The idea behind the display design method is the Model-View-Controller (MVC) paradigm from the programming language Smalltalk, which has provided the conceptual basis for modern GUI implementations including ActiveX components. In the MVC paradigm, an item in the interface is modelled by three software objects: a model, a view and a controller. The MVC is based on object-oriented programming, but an object-oriented approach does not ensure that the specification solves the problem. Therefore, the idea was to use the MVC paradigm for developing of the specification, i.e. for analysis of the application and as a conceptual basis for implementation of displays.

The model, view and controller of the paradigm correspond to the content, form and operator's tasks as shown in Figure D.4. The benefit of applying the MVC paradigm is that the operator's tasks, content and form of the display are separated. Hence the display content comprise different attributes of the plant modules depending on the operator tasks and different display elements can be applied to the same content. A display element is a specific form of presentation.

This leads to implementation specifications for the display elements. The characteristics of display elements must be encapsulated, and it must be possible to integrate existing and newly developed display elements. The ActiveX technology from Microsoft fulfils these requirements. The ActiveX technology is based on the Component Object Model (COM) which supports the object-oriented characteristics, including encapsulation and aims to create a market for reusable software components (Chappel, 1996). From prototype development of display elements (in Visual Basic 5.0), it is experienced that the ActiveX technology provides a good and easy-to-use tool for developing display elements either by using basic graphic elements or by aggregating existing display elements. (To develop very complex ActiveX display elements e.g. for visualisation in 3D with zoom and navigation facilities, other programming languages must be used.) In conclusion, the ActiveX technology provides the means to develop reusable display elements and let the display designer focus on the specification for display elements and not so much on the aspects of implementation.

Outline of the Design Method

The ideal sequence in the construction of process displays in the industry is first to perform a process and task analysis from which the content of the display is defined. Having defined the content, the form can then be chosen. The dotted line in Figure D.4 illustrates the progress of a typical design process.

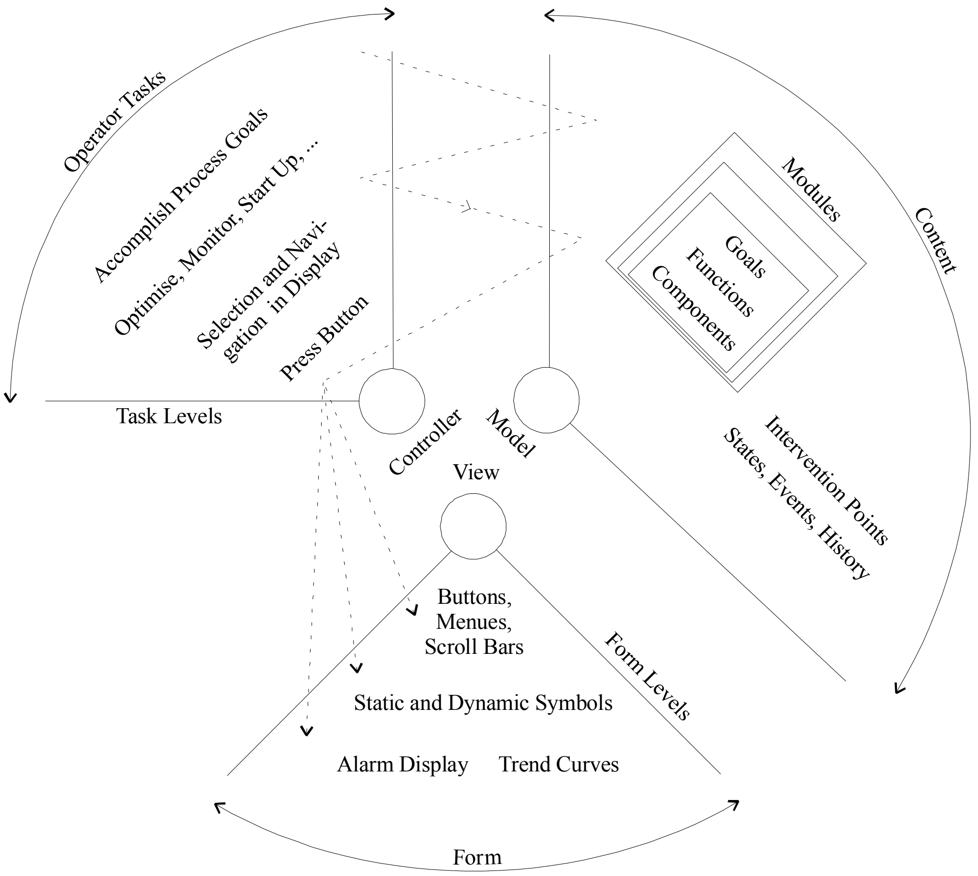


Figure D.4. Mapping the design aspects to the MVC programming paradigm. Different levels of aggregation are shown together with a typical design sequence (dotted line).

The division of the plant into modules provides a decomposition of the display content. If the

process modules correspond to units of process operations, it may be possible to reuse a display design within or between process domains. Notice that different operator tasks are associated to each module. For example, a heat exchanger process is used in different process domains and is associated with tasks such as: start-up, monitoring and shut-down.
A classification of process operations would therefore be useful as a template for the display builder (and partly for the plant and automation designers), aiding with the first steps in determining the content of the display. A more detailed task analysis of the process must be made before the content of the displays can be specified at a level from which the detailed form can be extracted.

A more detailed procedure for the design method is illustrated by the following example. The suggested steps in the design are written in *italic.*

Example

This example is a storage tank shown by the simplified piping and instrumentation diagram in Figure D.5.

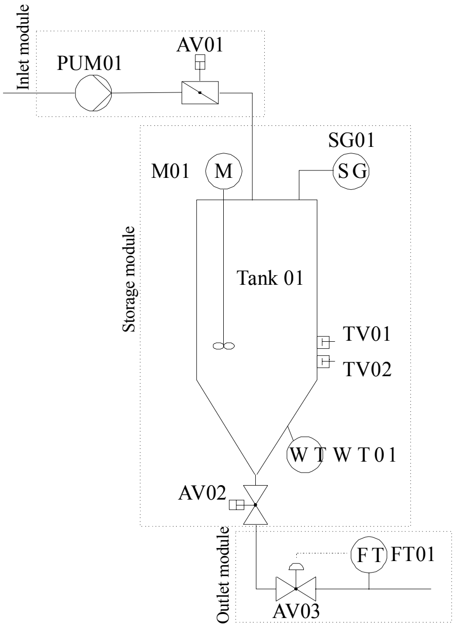


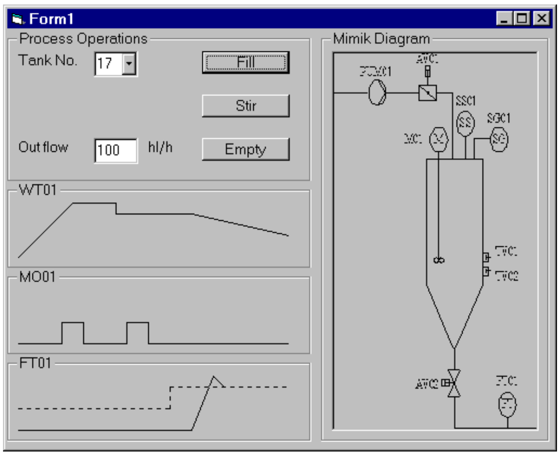
Figure D.5. P&I diagram for storage tank.

The production goal is to store material for some time before reusing it in the process. To fulfil the production goal, three *process operations are identified*: filling, stirring and emptying the tank. The operations cannot be performed simultaneously and are here assumed to be automated, i.e. a program for each operation exists in the process computer. Stirring is performed periodically and the flow is controlled when emptying the tank. The process *modules are identified* to allow reuse of the plant, automation and display design. Three modules are defined as shown with the dotted lines in Figure D.5. Next the *modules are associated with the process operations* as shown in column 1 and 2 in Table D.1. *The content of the display is then decided for each process operation* by selecting module attributes. The modularization will make this step easier in large plants. The plant's response to changes in some process variables are reflected in others, determined by the causal relation between the process variables. The process variables, which inform about a change, are classified as primary whereas the ones referring to actuators are secondary as indicated in Table D.D.1. The *operator activities are then determined* and will, as mentioned, depend on the task allocation between automation system and operator. See Table D.D.1 for the activities related to each process operation. Finally, *the form of the display must be chosen*. The form will depend on the number of process operations the operator must supervise simultaneously and the complexity of the activities. There are several possibilities for the layout of the display, but the problems involved are not treated here. As shown in Table D.1, several graphical items can be chosen for each category of operator activity.

Process operation	Module	Display Content Primary	Display Content Secondary.	Operator activity	Graphical items
Filling	Inlet, tank	WT01	PUM01 AV01 AV02	1. Choose tank number 2. Start filling program 3. Monitor filling process	Combo box or input box Command button Bar graph or trend curve
Stirring	Tank	M01		1. Choose tank number 2. Start stirring program 3. Monitor motor speed	Combo box or input box Command button Trend Curve
Emptying	Outlet, tank	FT01	AV02 AV03 WT01	1. Choose tank number 2. Enter desired outlet flow 3. Start emptying program 4. Monitor emptying	Combo box or input box Input box Command button Bar graph or trend curve

Table D.1. Relations between process operations, modules, display content, operator activities and graphical items.

Figure D.6 contains the graphical items and a suggested layout to initiate and monitor the operations from the example.



Tank No. 17

Out flow 100 hl/h

Figure D.6. Suggested display for the example.

So far the display has been constructed from predefined graphical items, meaning that the top-down design process ends when predefined display elements are available. Hence only the right display specification has been achieved. Moving down to implementation, consider a configural display element which takes two flow variables (content) as input and visualises them as an ellipse (view). The purpose of the MVC controller is to relate the radii of the ellipse to the flow variables. This can be implemented in an ActiveX component making it possible to reuse this display element (form) with another content, for example temperatures or integrate it in e.g. a trend curve.

Applying the method to a real plant

The aim of the first example was to analyse the considerations involved in composing a display that matches the tasks of the operators. The example is very simple and based on experiences from process displays in breweries where the operators are responsible for planning and executing the available process operations. Breweries can be characterised as a batch process.

In the following example, the proposed method is applied to a condenser system of a power plant. The aim is to analyse and discuss the problems with the method in continuous processes, such as power plants, where the main objective for the operators is to supervise the plant, i.e. handle disturbances and optimise the plant performance. In case of severe disturbance, the operators have to decide if the plant must be shut down. This analysis is rather profound and it can not be expected that industrial display builders have the resources to make such analysis. The reason to make the analysis is to get a better understanding of the problems, which is needed to be able to invent new and better displays. Furthermore deeper analyses of the existing displays are needed in order to be able to state which operator task they are applicable for. Therefore these analysis are aimed at the display inventor rather than the display builder.

Supervision of a Condenser System

The objective is to develop a display for supervision of a condenser system in a nuclear power plant. This example is taken from the Swedish nuclear power plant, Barsebäck. The focus is on the procedure and considerations made during the analysis.

Figure D.7 shows a simplified piping and instrumentation diagram of the condenser system. To get a high efficiency of the power conversion, the pressure in the condenser must be as low as possible. This is obtained by keeping the temperature as low as possible in the condenser and removing the non-condensable gases with an ejector system.

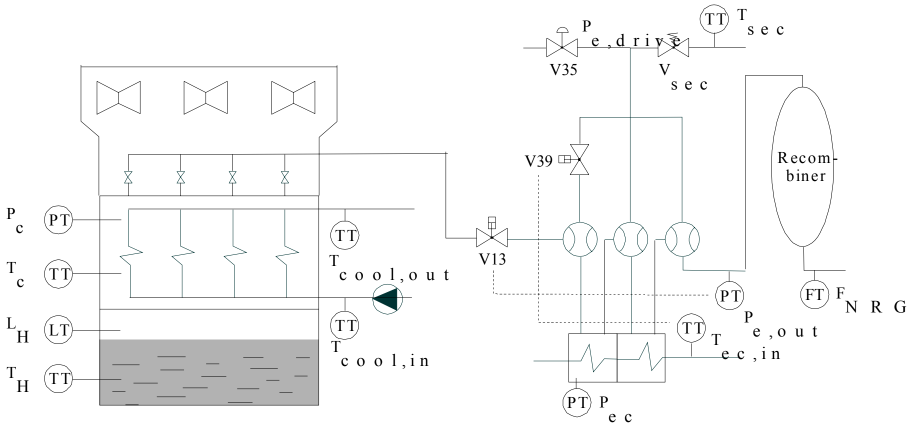


Figure D.7. Simplified piping and instrumentation diagram for the condenser and ejector system.

The design procedure outline in example 1 was followed. The results of the first steps are shown in Table D.2.

Process Operation	Module	Display Content	
		Primary	Secondary

Process Operation	Module	Display Content	
		Primary	Secondary
1. Condensation of steam from low pressure turbines	Condenser Hotwell	P_c L_H	T_c T_H
1.1. Keep low pressure			
1.1.1 Keep low temperature in condenser	Coolant water pumps	$T_{cool, in}$ $T_{cool,out}$	
1.1.2 Prevent ejector steam running back into condenser	Ejector	$P_{e, out}$	V13
1.1.3. Removal of non-condensable gases	Ejector	$P_{e,out}$ $P_{e, drive}$ T_{sec} F_{NRG}	V35 V_{sec} P_{ec}
1.1.3.1 Prevent overload of second stage of ejector	Ejectors	$T_{ec,in}$	V39
1.1.3.2 Control of coolant water to ejector condensers (spring-control valve which opens when coolant flow is larger than required by ejectors)	462-bypass pipe		

Table D.2. Relations between process operations, modules, and display content related to components for the condenser system of Barsebäck.

A few comments are given to these steps before the main problems are treated.

1. Process operations were identified from written descriptions (from Barsebäck) of the functions of the equipment and the automation system.

2. The modules were also determined from the functional description, because the functional description was organised according to the nuclear systems of Barsebäck.

3. From a list of logged process variables and a study of the piping and instrumentation diagrams the component (measurement) content of the display was decided. An expert on nuclear power plants, Ms. Jette Lundtang Paulsen, Risø National Laboratory, classified the variables into primary or secondary and their causal relations were analysed.

4. The determination of the operator's activities was more difficult. Generally they can be described as follows: if an unusual situation occurs, take remedial action. Otherwise keep production at optimum. This very broad definition of activities does not explicitly indicate which state, event and history content the operators needed and therefore impede a specification of graphical presentations.

The general problem of determining the operator's activities is analysed in further details below. First the main operator tasks in the two process domains are compared and defined. Then a decomposition of a part of the supervision task is made.

Operator tasks and process domains

Two domains exist: continuous and batch processes, where batch process can be regarded as the planning and scheduling of several continuous processes. In Table D.3 process types are combined with broad definitions of operator tasks.

Process type	Operator task
Continuous	disturbance handling production optimisation
Batch	Production planning / scheduling Activation of process operations

Table D.3. Broad classification of operator tasks in different process domains.

Supervision includes both disturbance handling (unanticipated events) and production optimisation. The main operator tasks are shown in Table D.4 together with the main content and form. It should be noted that this is a very broad classification and further differences are expected to be revealed when these tasks are analysed in further detail.

Operator task	Content	Form
Disturbance handling	State of process operations	Overview displays
Production optimisation	Correlation between variables	Configural displays
Production planning / scheduling (decision-making)	Relation and interlocks between process operations	Hierarchies and networks
Activation of process operations	Intervention points to automation system or components	Means for parameter input and start or stop of processes

Table D.4. Broad classification of operator tasks, display contents and forms.

In disturbance handling, the operator must get a quick overview of the overall state of the plant. This means that for each process operation it must be indicated whether it is in the expected state or not.

In performance optimisation, the correlation between variables must be visualised which implies configural displays.

The production planning task is decomposed into decisions of operator's action, i.e. to decide which process operation to start, stop or maintain and the actual activities to perform these tasks.

Analysis of Operator Activities in Disturbance Handling

The operator's task is to monitor the state of the system and, in case of deviations from the expected state, decide whether to locate the source of disturbance and then plan what to, or in case of a severe fault bring the system in a stable condition and before locating the disturbance. Having decided the needed actions, that is which process operation to start, stop, maintain or change, the activities connected to the process operation must be executed. This corresponds to the decision ladder of Rasmussen (1986), which has the following operator activities:

1. **Detection** of need for action

2. **Observe** information and data

3. **Identify** present state of the system

4. **Interpret** consequences for current task, safety, efficiency, etc.

5. **Define task;** select change of system condition

6. **Formulate procedure;** plan sequence of actions

7. **Execute;** co-ordinate manipulations

The last three tasks are equivalent to the scheduling problem in batch processes. Though there is an important difference between selection of process operations in batch processes which is an everyday task and selection of process operations in a continuous process which is an infrequent event caused by a disturbance that might be severe.

The content of a disturbance handling display

It is proposed that a display for disturbance handling should support the first four operator activities. Suggestions for display content for each operator task is given below.

1. **Detection** of need for action
   To get the operator's attention either the *deviation from a normal operating point* (early error detection) can be shown or *alarms* can be used to indicate that a given limit is exceeded.

2. **Observe** information and data
   The relevant data must be easy to get, hence *grouping of variables* either by process operation or by the physical layout of the plant is required.

3. **Identify** present state of the system
   Minor deviations from the normal operation point can probably be accepted. Therefore further indication of system state must be visualised, that is an evaluation against predefined criteria must be made. First, the system's state must be defined. Today, alarm systems often work with five system states (low alarm, low warning, OK, high warning and high alarm). These system states are connected to each process variable individually. In more advanced systems, it is possible to group alarms and thereby give an indication of the state of entire process operations. In conclusion, criteria for evaluating process values must be defined to monitor the state of each process variable.

   Further, the *development* of process operation states *over time* is useful for the operator to identify the overall state of the system.

4. **Interpretation** of consequences for current task, safety, efficiency, etc.
   To be able to decide what to do, the relations between the process operations, the relations between the plant modules and the relation between plant modules and process operations must be visualised to the operator.

The Form of a Disturbance Handling Display

So far it has been possible systematically to give arguments for the specific content of disturbance handling displays. Moreover the content identified is consistent with the content of the display in Paulsen et. al. 1998, hence it seems possible to identify generalised content for different display types independent of the form of the display. Determination of the specific form of displays is a remaining problem for the display inventor, because it should be possible to argue systematically for the choice of visualisation means in order to avoid time and cost consuming operator tests.

The determination of the possible graphical elements for each content and the selection of the best available display element are tasks that requires knowledge of human perception. To illustrate this problem some suggestions could be:

- Deviation from normal can be shown by the position or orientation of lines or by colour coding.
- Development over time can be visualised, e.g. in trend curves or time tunnels or by animation.
- Grouping of variables can be shown in hierarchies or related to pictograms of either process operations or plant modules.
- The state of the system or the individual process variables can be visualised by colour codes, but also other graphical dimensions like position and orientation are possible.
- Relations between process operations or plant modules can be shown using hierarchies or networks.

The selection between these general types of visual presentation needs more attention. Furthermore, the detailed design of the presentation requires considerations.

Based on the analysis of the task and content the display builder must choose one or more display elements among the existing. The Overview Display invented by Paulsen (1996) supports many of the requirements stated during the task and content analysis in the previous sections (see Table D.5).

Operator Activities	Content	
	Paulsen's Overview Display	Mass Data Display
Detection of need for action	Deviations from normal value	Deviations from normal value, that is deviation from the normal pattern made by the variables
Observe information and data	Actual values of process variables ordered by components or sub systems. Relations between a process variable types (like pressure, temperature or flow) and plant components.	Actual values of process variables ordered by the topological layout of plant components
Identify present state of the system	Process variables above or under normal value	Process variables above or under normal value and indication of increasing or decreasing variable
Interpretation of consequences	Consequences are not directly mediated.	Consequences are not mediated.

Table D.5. Paulsen's Overview Display and the Mass Data Display analysed for operator activities and display content for a disturbance handling display

The activity of interpreting the consequences of a disturbance is not directly mediated in any of the displays but experienced operators might induce consequences from knowledge of the component's functionality and previous experiences.

The form of the display is shown in Figure D.8.

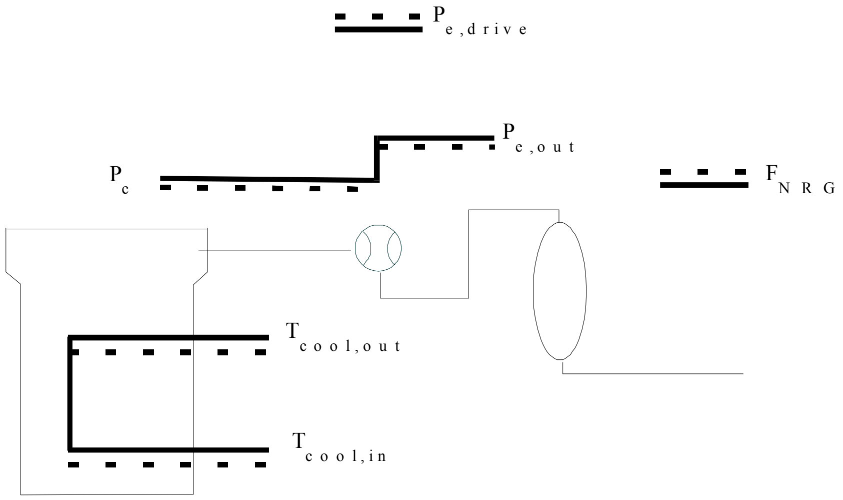


Figure D.8. Disturbance display for the condenser system of Barsebäck based on Paulsen's Overview Display.

Regarding the form, a solid line represents the actual process value and a dotted line represents the normal value. Symbols are used to present the components or subsystems. The use of standardised symbols makes it possible for the operator to memorise to components and perhaps its functionality in the plant.

An alternative to Paulsen's Overview Display is the Mass Data Display from Beauthel et. al (1995), because it also fulfils several of the requirement to a disturbance handling display, see Table D.5.

Notice that nearly the same information can be found in the Mass Data Display as in Paulsen's Overview Display. Though the number of variables represented is different. In Paulsen's display only the key variables for the process are visualised whereas every single measurement is shown in the Mass Data Display. Furthermore Paulsen's display shows the relations between process variables and plant components (in the way the process variables are placed around the pictograms of the components and connected with lines if appropriate) meaning that a component's influence on process variables can be seen. An example of the Mass Data Display for the condenser system is shown in Figure D.9. (The original Mass Data Display from Beuthel, et. al. (1995) is extended with the derivative of the of process variables as shown in the legend.)

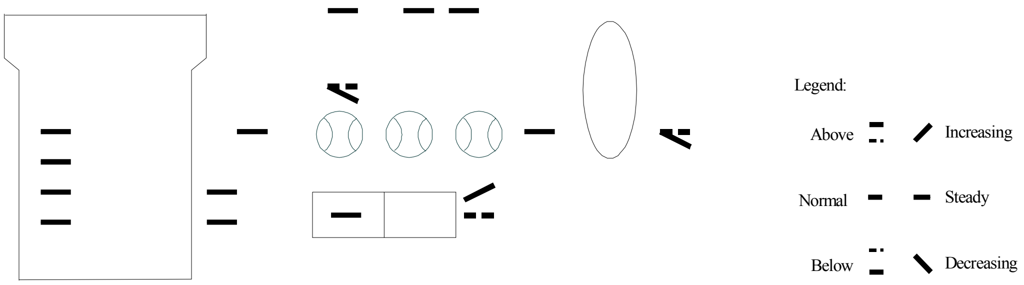


Figure D.9. Mass Data Display from Beuthel et. al. (1995) applied to the condenser system.

Beauthel et. al. (1995) undertook experiments with different forms and concluded that the orientation of small lines gave the clearest impression of the behaviour of the process in opposition to the shape of squares and colour of circles. Moreover the layout according to topological relations are easier to conceive by less trained person than the layout in table form where the each process variable type (energy, temperature etc.) is place in a horizontal row.

Both displays fulfil the first 3 requirements to the content of a disturbance handling display and fail to support the interpretation activity, where information about relations between process operations is part of the required display content. The relations between process variables and plant components in Paulsen's display might be used for interpretation of plant consequences at the component level, but it requires that the operators have an understanding of the functionality of the components. An attempt to create a display, which also fulfils the last requirement, is shown in Figure D.10.

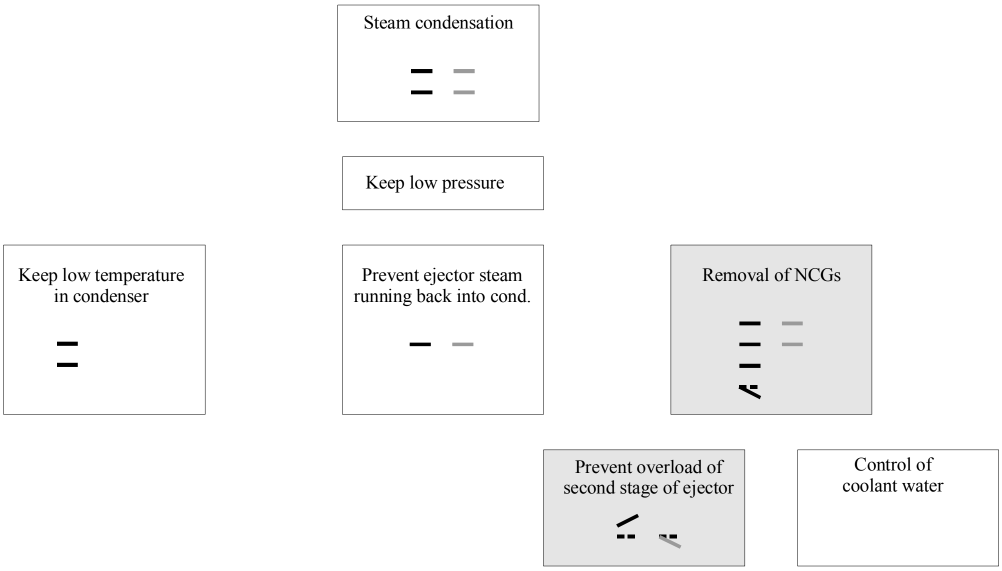


Figure D.10. Disturbance handling display for the condenser system. The hierarchical structure of the process operations is combined with the pattern recognition capabilities of the Mass Data Display.

The display in Figure D.10 is focused on the process operations identified (c.f. Table D.2). The hierarchical relations between the process operations are represented by the locations of the boxes representing the process operations. It is the hierarchical relations between the process operations that enable the operator to interpret the consequences of a disturbance. Moreover the pattern recognition feature from the Mass Data Display is maintained and in case one of the process variables in a process operation deviates from normal the box for the entire process operation change colour. This is to ease the detection of need for actions. Further colour coding can be added to visualise the number of deviations in each process operation, this will help the operator to identify the present state of each process operation.

Compared to Paulsen’s Overview Display and the Mass Data Display the main difference is that the display content is ordered by process operations instead of by plant topology. This display content is related to the operator activity of information and data observation. If the operator shall be able to interpret the consequences of a disturbance, it is seen from the analysis, that information about higher level functionality must be available. In other words if the operator must make decisions about what to do in case of disturbances the display content must be centred on process operations and their relations. If the operator on the other hand have to locate the cause of the disturbance lower level information about plant components and plant topology is the required display content.

Conclusion

The approach to designing process displays, proposed here, separates three aspects: operator task, display content and display form and is consistent with the modular approach to plant design used by the process industries.

Furthermore a seamless transition from conceptual design to implementation is proposed. The method supports reuse of design solutions and it is experienced that the ActiveX technology both provides a suitable tool for developing new display elements and facilitates reusability. Hence display elements can be created either by aggregations of existing display elements or from scratch.

The approach is illustrated by a simple example in the domain of batch processes and applied to a condenser system from the continuous process domain of nuclear power plants.

During this study, the design method provided a framework for analysing the problems step by step, because of the separation of the three aspects.

The first problem encountered was the general lack of specifications of operator activities. What is the exact purpose of the display ? To answer this question, the decision ladder of Rasmussen was used to determine the operator activities for a disturbance handling display and a display content was suggested. The structured analysis of task and content reduced the number of suitable displays. The Overview Displays of Paulsen (1996) and the Mass Data Display by Beuthel et. al. (1995) fulfil most of the requirements to a disturbance handling display. Further the structured analysis made it possible to suggest another display, which fulfil all the display content requirements to a disturbance handling display. The suggested display is not tested, but it is argued that it will be suitable for decision making during disturbances, whereas Paulsen's Overview Display from the example and the Mass Data Display probably are more suitable for failure detection and location, even though Paulsen's display in general supports interpretations of consequences at the component level. To asses one form of a display again another is not possible without more study on the basic visual means of presentation and human perception.

It has been possible to give arguments for the type of knowledge which is needed in the display design process (usually, this knowledge is implicit). The advantage of a systematic design approach is that different design alternatives can be evaluated when the design decisions are explicitly stated.

Acknowledgement

Jette Lundtang Paulsen, Risø National Laboratory contributed to this work with the system analysis of the condenser system and by providing useful insight on display design through innovative examples.

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VISUALISATION IN PROCESS CONTROL

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Abstract: The problem of analytical assessment of visualisation is separated into a problem of information mapping and a problem of cognitive and perceptual support. These problems are analysed and discussed in this paper. It is argued that presentational modalities (i.e. semantic invariants) must be identified in order to be able to construct a taxonomy of graphical displays and their potential to visualise certain types of information. The problem of assessing displays analytically is illustrated by two new displays developed for a water treatment plant. In these displays, one graphical type is embedded into another. Common graphical modalities are identified from displays used in the process industry in general. Presented at the 7th IFAC Symposium on Analysis, Design and Evaluation of Man-Machine Systems, Japan 1998.

Keywords: man/machine interfaces, displays, process control, supervisory control, cognitive science, structured analysis

1. INTRODUCTION

Two important but unresolved problems in the analysis and design of Man-Machine Systems are (1) the cognitive support for multi-modal interactions and representations, and (2) the semantic and cognitive principles for selecting presentations for given representations in the design of man-machine interfaces. Representations refer to what is shown on the display, i.e. the display content and presentations refer to how the selected representation is visualised, i.e. the form of the display. The first problem deals with choosing a representation of the domain, which enhance the user's understanding of the possibilities available and support problem solving within the working domain. That is, the selected display content must match the task of the user. Skill, rule and knowledge based operator behaviour (see Vicente and Rasmussen, 1992) are concepts which relates to this problem.

The focus of this paper is on the latter problem. Information mapping, which considers the semantic part of problem (2), has become actualised by recent attempts to construct Intelligent Multimedia User Interfaces (IMUIs) with the ability to chose between different relevant presentations of the same information (or at least to suggest the best ones to the user). The relevance of these attempts are not limited to the development of IMUIs, but is relevant in general for design of interfaces to man-machine systems.

The cognitive principles of problem (2) deal with how the user perceives the developed interface and what the user deduces from this perception. These cognitive principles are mainly concerned with how items appear on the screens and how they are interrelated. The cognitive principles involved in this can be described by gestalt principles and semiotics. Fig. 1 illustrates the relations between these main problems.

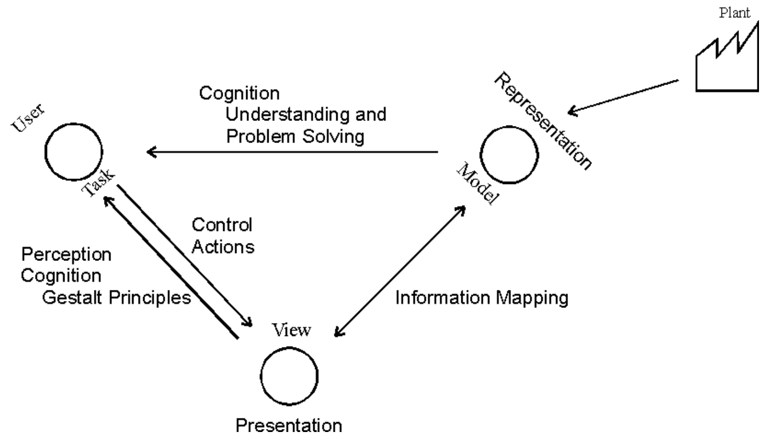


Fig. 1. Main problems in the relation between user, representation and presentation of a working domain (in this case in process control).

The user's control actions are shown for completeness, but not dealt with in this paper. Information mapping in Ecological Interface Design is where differential equations are mapped into a geometric figure (see Vicente and Rasmussen, 1990).

In order to address that question a description of available representations and the different types of presentations are needed. Being more specific the types of information existing in a given domain and the available visualisations must be identified. In short a taxonomy of information types and presentation objects is required. The taxonomy must besides mapping representations to presentations also consider the perceptual and cognitive dimensions of the presentations. Such a taxonomy will help the display designer in selecting the right presentation objects for a certain display content, where the display content is derived from an analysis of the user's task.

The display designer must be aware of the perceptive and cognitive aspects of a presentation object to be able to assess advantages and disadvantages of the object for a given representation. These perceptive and cognitive aspects must be stated clearly so the display designer can consider them explicitly and not as today in an ad hoc manner.

The explication of modalities together with perceptual and cognitive effects of visual means will not only work as a guideline for the display designer but it might also reveal paths for development of new presentation objects which deals with the unintended effects or limitations of existing visualisations.

An example is used to illustrate the problems of analytical display assessment before some preliminary work on the problem of information mapping in the domain of process control are presented with a limitation to the visual media, i.e. to visualisation of information. Later principles for structuring the cognitive and perceptual part of the problem are outlined before the conclusion.

2. AN EXAMPLE OF INFORMATION MAPPING IN PROCESS CONTROL

To illustrate the problem of analytical assessment of displays an example from a water treatment plant is used. The focus is on the problem of information mapping but also the aspects of cognition and especially perception will be commented.

Simplified the main problem in water treatment plants is to remove nitrate (NO_3) and ammonium (NH_4) from the water coming into to the plant. The chemistry of the removal process in an alternating plant (see Thornberg, et. al., 1993) is that during a denitrification phase (no oxygen) nitrate is transformed to nitrite (N_2), which disappears in the air. During a nitrification phase, where oxygen is added, ammonium is transformed to nitrate. Hence denitrification decreases the nitrate concentration and the ammonium concentration increases due to the inflow of ammonium. During nitrification the nitrate concentration increases and the ammonium concentration decreases.

The process is automated meaning that a control program manages the shift between the denitrification and nitrification phase. A time delay exists (20 min.) for the on-line measurements of nitrate and ammonium. The plant is supervised by humans 8 hours per day during normal working hours. One of the tasks of the production manager is to monitor the process and optimise it by adjusting parameters to the control system. From an interview with the production manager he explains that they look at yesterdays plants performance when they come in the morning. Asking how he judge the plant performance, the answer is: by looking at the trend curves for NO_3, NH_4 and O_2, they should look like the ones shown in Fig. 2. If not we check the PH-value in the inlet, return sludge flow etc. Asking for more details about the trend curves it appears that the operator uses the form of the curves in his judgement rather than reading the specific value for a given parameter. When deviations from normal are observed they are often caused by equipment failure, so it is seldom that the production manager adjusts the parameters to the control system.

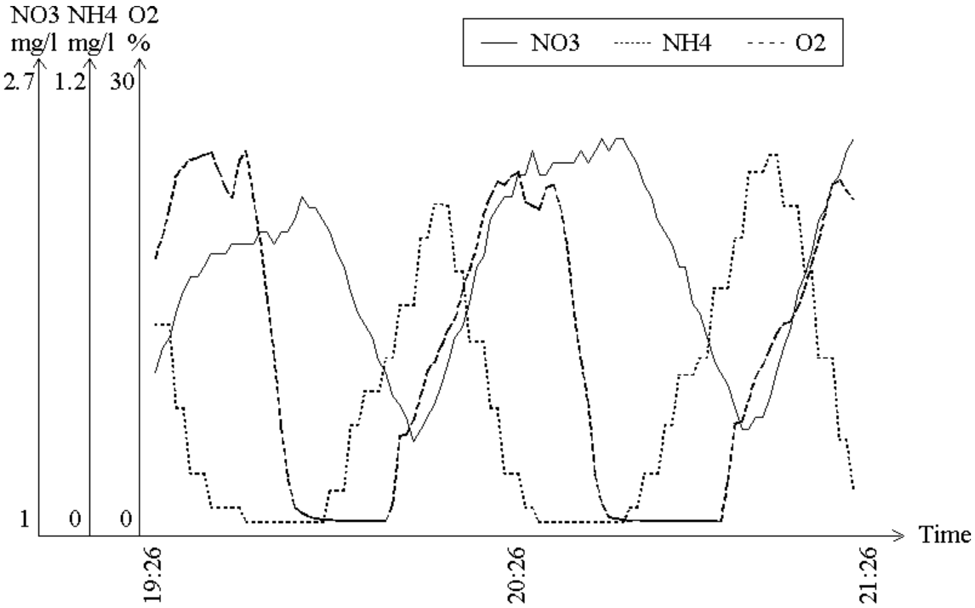


Fig. 2. Main display for a water treatment plant. From these trend curves the production manager judge the plant performance. (On the supervisory screen colours are used to distinguish the curves, not different line styles as shown here.)

According to an expert on water treatment plants, who analyses data from several different plants, there are cases where the operators could improve performance. Therefore the aim was to develop displays which show the plant performance in a more understandable manner.

The normal or expected value could be shown in the trend curves making it easier to observe deviations from the normal operation point. One problem with this approach is the load of the plant depends on the weather (high load in the start of a rain fall) and on the industry in the surroundings of the plant (e.g. high load once a week when tanks are cleaned, low load during week-ends and vacations). A high load will be observed as higher concentrations of nitrate and ammonium.

Another problem is that placing other curves representing the normal values for each trend curve in Fig. 2. will make it even more difficult to perceive, because it is already crowed by the three curves.

An individual y-scale is chosen for each variable, because their operation ranges are different. Table 1. shows the admissible and typical range of the main variables (the typical range is calculated as 3 standard deviations from the mean value).

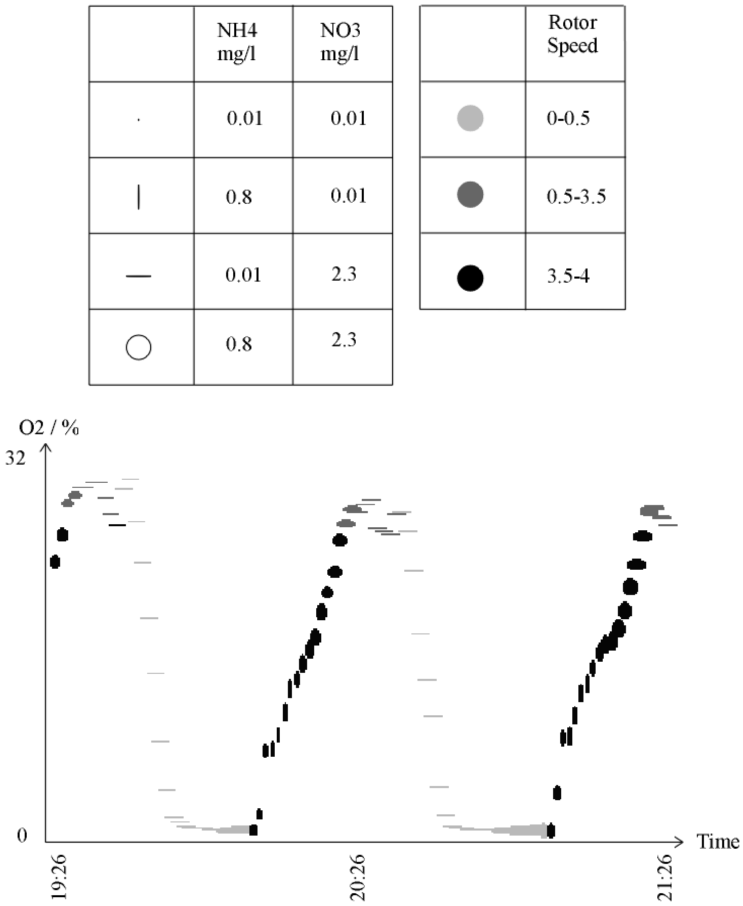
	Admissible Range		Typical Range		
Variable	Min.	Max.	Min.	Max.	Unit
NO3	0	6.4	1	2.3	mg/l
NH4	0	3.3	0	0.8	mg/l
O2	0	36	0.3	30	%
rotor	0	4			-

Table 1. Main variables and their ranges.

The rotor variable is the one which can be indirectly manipulated through the parameters to the control system and the result can be seen in the concentrations of nitrate (NO_3), ammonium (NH_4) and oxygen (O_2).

The development of these variables over time are the ones which must be visualised. This information can be mapped into many different forms. Two are shown and discussed in the following.

In Fig. 3 the oxygen concentration is the primary variable plotted as a function of time. The nitrate and ammonium concentrations are the secondary variables shown by the markers for the oxygen concentration. Visually the form of the trend curve is perceived together with the form of the markers (vertical markers when oxygen concentration increases, and horizontal when it decreases).



	NH4 mg/l	NO3 mg/l
·	0.01	0.01
|	0.8	0.01
—	0.01	2.3
○	0.8	2.3

	Rotor Speed
●	0-0.5
●	0.5-3.5
●	3.5-4

Fig. 3. Oxygen as a function of time. Ellipses are used as markers where the ammonium and nitrate concentration is indicated by the height and width accordingly. The status of the rotor is mapped into colours (here grey scales).

Making the reverse mapping from form to content this means: when the nitrate concentration (width) exceeds a given limit, the nitrification phase is started, that is the rotors are running (black colour) to add oxygen. The nitrification phase should stop as soon as the ammonium concentration (height) is low enough. When the ammonium concentration is low the markers are flat. Some fluctuation can be seen on the tops in Fig. 3, indicating that even though the ammonium concentration is low the rotors are running - wasting energy. (This is corrected at the plant without use of this display.)

With this display the production manager needs to learn two things: (1) flat markers means that the rotor should stop (light grey colour) (beginning of denitrification phase) and (2) high markers means that the rotor should start (black colour) (beginning of nitrification phase).

This graphical construction is a rather dense and complex graph, that makes some information directly perceivable, but does so at the dispense of other types of information (the numerical values of the NO_3 and the NH_4 concentrations). Also it has the disadvantage of focusing the attention on the level of oxygen (the primary graph), which does not inform the production manager about the load of the plant.

In Fig. 4 another mapping of the nitrate, ammonium and oxygen variables over time is shown.

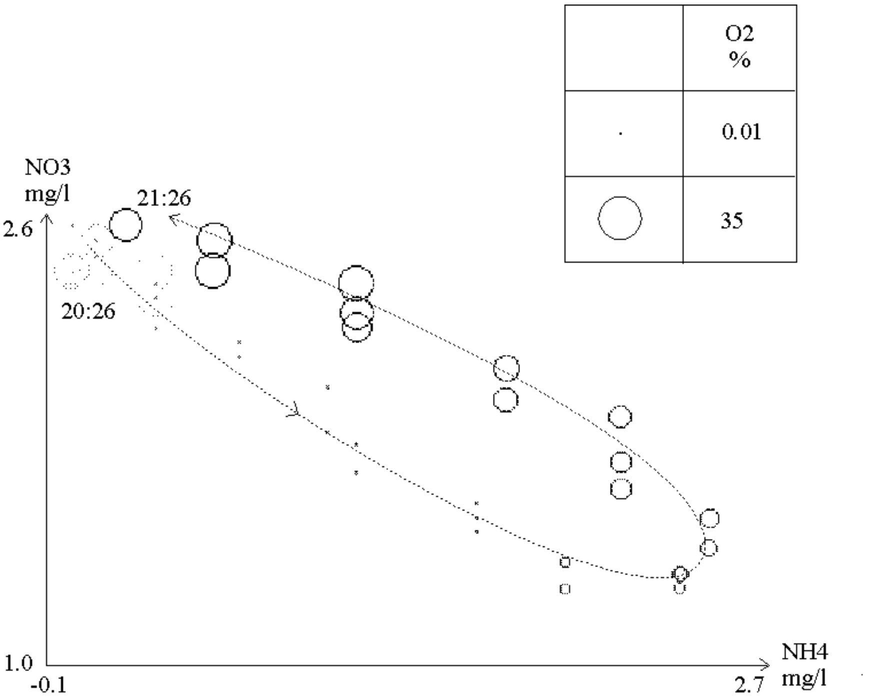


Fig. 4. The main variables nitrate (NO_3) and ammonium (NH_4) are plotted in a xy-plot over time. Colours (here grey scale) are used to visualise the time. The size of the circular markers visualises the amount of oxygen. The dotted line is here added to make the development of time plain.

Notice that the status of the rotor is not visualised, meaning that the control point is not visible to the production manager. Instead the focus is on the information which indicates the load of the plant. A higher load means higher nitrate and ammonium concentrations, which is visualised by the track moving toward the upper right corner of the graph. This is the situation shown in Fig. 4. The phase shift can be identified as “the turning point” for the track or by the size of the circular markers, where the size indicates the oxygen concentration. With this display it will be possible to indicate good operating areas and areas in which different actions must be taken.

Rings are used instead of filled circles, making it easier to see the markers when several measurements are nearly identical. The time is mapped into a colour-gradient fading from black (latest measurement) to white (oldest measurement) in Fig. 4. When measurements are similar it is difficult to distinguish new measurements from old, because of the colour coding. Therefore only 50 measurements (one denitrification and one nitrification phase) are shown in this graph.

In conclusion the embedding of secondary graphical types into primary graphical types (graphs in this present case), makes it possible to visualise several variables which will be percieved as one form. By choosing the right mapping between the variables (the information) and the visual dimensions, it might be possible to improve process displays. The question is how the right mappings are found. In the next section we will discuss some general principles involved in the mapping of information in visualisation.

3. INFORMATION MAPPING AND GRAPHICAL TAXONOMY

Scientific visualisation or visualisation in general is concerned with two levels of problems. At one level visualisation is a problem of modelling a working domain and choosing representations as part of a model of that domain. At another level, the level of information mapping, the model and its different data types has to be presented using combinations of modalities (cf. Fig. 1). Any model has several possible presentations, i.e. a model can always be presented using different combinations of graphical objects, relations and events.

The distinctions of modality and media has been suggested by several authors in an attempt to understand the invariant semantic types (modalities) that can be use for expressing information across different channels of communications (media) (Stenning & Inder 1995, May 1993, Bernsen 1994). Natural language (a modality) can be expressed in the accoustic media (speech) as well as in the graphical (text) or the haptic (braille text for the blind) media. Similarly, a flow chart (a modality inherited from conceptual diagrams) can be expressed in the graphical media and the haptic media (though in the haptic version, only simple charts can be expressed because of the imposed linear reading of the chart), but acoustic flow charts are not possible.

With a delimitation to the graphical media (excluding true multimedia presentations) for simplicity, a taxonomy of graphical modalities available for presentation of information is still needed. Graphical modalities cannot simply be classified as the objects known in different working domains, e.g. process control, because the used displays are complex combinations of modalities, when seen from a semiotic point of view (Bertin, 1983; May, 1993; May, 1998). In order to be able to analyse the different combinations of modalities and infer their properties with regard to information-mapping (their “potential” for presenting different types of information), it is necessary to consider each modality in isolation. It should be noted that most modalities are not useful individually, but must be combined with others.

A part of a taxonomy in the graphical media contains the following modalities: *images, maps, symbols, structural diagrams, graphs, conceptual diagrams and texts*.

Images as well as texts can be useful and informative individually, whereas maps, graphs and diagrams generally will have to be combined with other modalities to be useful.

It is beyond the scope of this article to present the taxonomy as a whole, but the basic principles is that each modality comes with different potentials for information mapping, and these properties are inherited when simple types are combined into multimodal presentations.

Before we return to the displays for the water treatment plant it is illustrated how modalities can be “reused” and combined in different ways in different working domains.

A flow chart is basically a conceptual diagram based on an iconic presentation of potential movement, which is visualised as a path between points in the plane (May, 1998). Flow charts are as such a generic type, that can be used to present many different types of information in different working domains (flow of information, flow of fluids etc.). However, in order for a flow chart to be interpreted in any domain, it will at least have to be annotated with text, i.e. combined with another modality. In process control the flow chart is used together with other combinations of modalities than text. The nodes have been substituted by pictorial symbols (“icons”) representing valves, tanks etc.; that is the mimic diagram, which represents the topological layout of the plant. Although the mimic diagram usually is considered as one integral object, it is useful to consider it as a combination of modalities, resulting from substitution of one modality (pictorial symbols) into the parts of another (flow chart), in order to develop at taxonomy for information mapping. The process of substituting modalities is shown in Fig. 5.

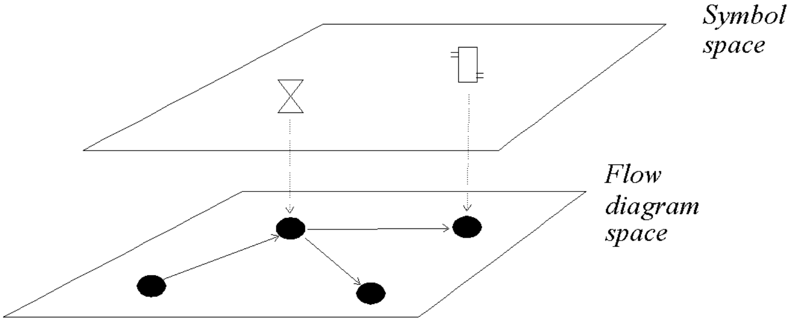


Fig. 5. "Iconic" flow charts, known as mimic diagrams in the domain of process control, as resulting from substitution instances of one modality into parts of another.

Returning to the displays for the water treatment plant the two parameters (NO_3 and NH_4 concentrations) in Fig. 3 are expressed as horizontal extension and vertical extension respectively yielding an elliptic shape. In Fig. 4 one parameter gives a circle.

These natural mappings of quantity to spatial extension are the basis of graphs based on co-ordinate systems in general, but in the display shown, the qualitative distribution of parameter values has been presented visually by interpreting the extensions as the axes of an elliptic object. In theory any number of axes could be used resulting in a rounded polygon shape or a star. The basic idea is that several parameters can be evaluated at the same time based on perception of shapes (Lindsay, 1990).

The polygon graphs are embedded in the parts of a presentation, that is itself a graph, see Fig. 6.

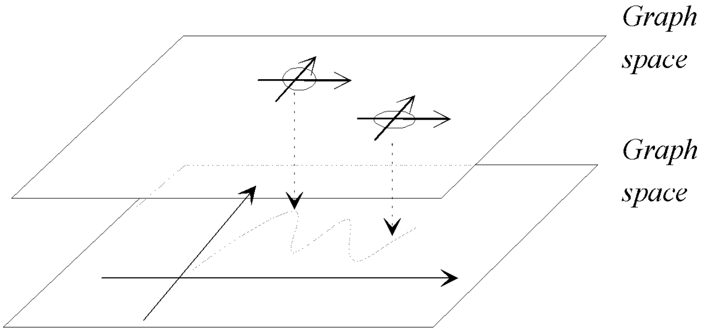


Fig. 6. Graph with embedded graphs as points of the graph (cf. the displays in Fig. 3 and Fig. 4).

The two graphs differs in the way they visualise their information, which in both cases are continuous ranges. In the primary graph the position of the marker is used to visualise the information, where as the shape is used in the secondary embedded graph.

Knowledge about human cognition and perception is needed to assess how many axes can be placed in the embedded graph. Moreover the form must be considered: should it be visualised as a star or as a rounded polygon ? (with two parameters as in the water treatment plant as a cross or as an ellipsis ?).

3.1. Cognitive and Perceptual Support for Visualisation

The mapping of information types into different presentations for visualisation purposes should follow a set of principles. The most fundamental of these is that any mapping should have "cognitive support". Cognitive support of information mapping can consist in one of several possible forms of support:

(1) a natural association (e.g. high temperature → red colour)

(2) a metonymic association (whole→ part, e.g. start process operation → push button)

(3) a metaphor (whole→ whole, e.g. desktop metaphor: office desk → workspace of screen)

(4) an "image schematic association "(Johnson 1997) (e.g. vertical schema: up is more, down is less in mapping of quantities)

(5) a symbolic convention (e.g. pictographic symbols in flow charts).

Perceptual support of visualisation should be based on this kind of primary cognitive support for the selected presentations. Perceptual support is found in the perceptual dimensions used to present a selected combination of modalities in a give media. In the graphical media important dimensions are shape, position, size, orientation, colour (hue), brightness, and texture (Bertin, 1981). Which one of these dimensions can be used for perceptual support of the presentation is however determined by the semantic type, i.e. the modality. In a graphical image for instance, the exact position and shape of objects are important dimensions for the communication of information whereas in a conceptual diagram - such as the flow chart – the position of objects are not informative. In the flow chart the connectivity (the topology) of objects carries the information and the positions of objects can be changed arbitrarily.

4. CONCLUSION

The separation of visualisation into to a problem of information mapping and into considerations of the cognitive and perceptual support seems to make it possible to develop taxonomies of graphical objects, which might be used in analytical assessment of visualisation. Several problems and aspects need to be solved and analysed, however, before such a taxonomy can be proposed.

By identifying the graphical modalities from existing displays it has been possible to state the capabilities of the modality to present specific types of information.

It has been possible to decompose the newly developed displays for a water treatment plant into the common graphical modalities listed in the paper, though it should be noted that other graphical modalities than the ones mentioned might exist.

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