Alf Ove Braseth

Information-Rich Design: A Concept for Large-Screen Display Graphics

Design Principles and Graphic Elements
for Real-World Complex Processes

Thesis for the degree of Doctor Philosophiae

Trondheim, January 2015

Norwegian University of Science and Technology
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Abstract

The objective in this thesis research is to mitigate two problems, which are typically experienced by control room operators monitoring large-scale processes in centralized control rooms: i) How to design for rapid perception of industrial-scale data sets? ii) How to avoid keyhole effects in complex processes? In this thesis, these problems are approached through research into Large-Screen Display (LSD) design; the contribution is a concept named Information-Rich Design (IRD). The concept is not domain specific, and it is useable typically for nuclear and petroleum industries. IRD can be used as a starting point for user-centred design, as opposed to approaching the problem from the technology end first. The thesis research is based on a broad perspective, through interaction design research methods: design exploration, design studies and design practice.

Design exploration was done on a small-scale early in the research process, and later through three complete LSD applications. The first two LSDs were implemented on full-scale nuclear simulators, and the most recent was implemented for an operational nuclear research reactor. Crews of certified control room operators have provided feedback for design in an iterative research process. Design studies were based on findings from basic, applied and clinical research: (1) human capabilities and characteristics, (2) principles for information visualization, (3) findings from human-computer interaction and (4) research from other related display concepts. Design practice from applying IRD commercially in Norwegian petroleum industry was fed back into the concept.

The thesis research suggests that LSDs should be designed from the ground-up, acting as a stable frame of reference for process monitoring, leaving details for desktop workstations. Research found that larger displays should support bottom-up data driven processes by presenting process data as simple visual patterns, suitable for rapid visual perception. Further, LSDs should support operators in top-down search for information, and aim to avoid keyhole effects through externalized graphics, which do not load limited visual memory resources. Graphics should reduce visual complexity by creating visual hierarchies, giving critical information the most prominent visual salience, while avoiding masking primary data from less important information. Based on this, the contribution for LSD designs, are design principles and accompanying graphics.

The IRD concept is theoretically validated, and externally validated through industrial applications and user tests. With a few concerns for inconsistency from using mathematical normalized scales in graphics, and readability of the grey-layered colours, the concept is generally found to be a reasonable approach on LSD design and the two research problems. The research contribution is not radical or revolutionary; rather it extends what others have found for computer graphics for smaller displays. It is positioned as applied research for LSD design, as a contribution to human-computer interaction. The innovative part of this thesis contribution is design-patented graphics for information presentation.

Further work should focus on providing more quantitative performance data, and on performing comparisons with other display concepts, particularly measuring Situation Awareness levels. Secondly, one should look at the question of consistency with other displays in the same setting. A natural extension of this thesis work would be to look at direct process interaction through LSDs.

Preface

The thesis is submitted for the degree dr.philos at the Norwegian University of Science and Technology in Trondheim (NTNU). The thesis research has been conducted at the Institute for Energy Technology (IFE) in Halden Norway. Research has partly been conducted with research colleagues at IFE, and with international research colleagues. IFE has been the main contributor in financing the thesis research work. A consortium of Scandinavian Nuclear Power Plants financed some of the research work in developing three Large-Screen Displays for research purposes. The Norwegian Research Foundation financed the first years of research work through a strategic institute programme (SIP).

List of corrections

The thesis was submitted in June 2014, some minor corrections are done for the final printed version of the thesis. Besides new page numbering and few typo-errors, the following corrections are done:

Appendix D is removed (personal declarations). The last paragraph on p. 41 is rephrased to include a reference to “perceived awareness” in paper 9 of this thesis. The caption for figure 10 on p. 45 is slightly rephrased.

Alf Ove Braseth, January 2015

Acknowledgements

Firstly, I am grateful to the Institute for Energy Technology (IFE) in Halden for supporting and funding this dr.philos research. I want to thank my research partner through the last three years, Trond Are Øritsland for encouraging me to write a thesis, and also for his insights and discussions through our research work. I am grateful for the support and help from the department of Product Design at the Norwegian University of Science and Technology in Trondheim. I also wish to thank my researcher colleagues IFE, in particular Morten Gustavsen, Steve Collier, Mike Louka and Alexandra Fernandes for high quality feedback, helping me to improve the quality of the thesis. My native English-speaking colleagues Steve Collier, Mike Louka and Claire Taylor have helped me a lot by proofreading this thesis text. Carl-Olof Fält has been very helpful by advising me how to format text and figures properly.

To my first two research partners, Øystein Veland and Robin Welch, you were there at the right moment in the early years when we struggled with prototyping graphics. Your effort made the design concept more than just a working prototype. Magnhild Kaarstad and Stine Strand, you contributed with high-quality contributions in user tests. Jari Laarni, thanks for your research effort, and helping me write better papers. Håkon Jokstad and Frank Sundal have helped me a lot by making graphics work in large-screen applications. Thanks to the group of Nordic Power Plants who founded research on Large-Screen Displays, and to operators participating in design and user-tests. I would like to express my greatest gratitude to expert operators at IFE, participating in large-screen detail design and evaluation, and particularly to Tommy Karlsson for your help in HAMMLAB. Robin Brooks, Remi Hansen and Unger Surfactants have been helpful by sharing their display designs for use in this thesis.

Thanks to Statoil for supporting the development of graphics, by using elements from Information-Rich Design as the foundation for Large-Screen Displays for offshore and onshore plants. I wish also to express my gratitude to industrial vendors for your high quality work in realizing the graphics through your software, particularly ABB, Siemens and Kongsberg Offshore. Thanks to the always helpful and service minded team at Sykehuset Østfold, which have kept me “ship-shape” physically for the challenge of writing the thesis. But most of all, thanks to my beautiful wife Iren. And to my kids, Jenny, Georg and Juni, putting things into perspective. To mom and dad, for your kind support.

Alf Ove Braseth, Halden 2014

Information-Rich Design: Summary of Contributions

This section presents the main contributions from this thesis research work. The contribution is the Information-Rich Design (IRD) concept for Large-Screen Display (LSD) design; the concept´s outcome is design principles and graphic elements. The IRD concept is designed for use in addition to desktop workstations in centralized control rooms for industry processes; the concept is not domain specific. The objective is to support rapid perception of industrial-scale data sets, while avoiding keyhole effects. Based on this research focus, design principles for LSD design are proposed, concepts from Ecological psychology are presented in *Italics*:

- Design for keyhole problems and limited visual memory resources through a flat externalized LSD layout rather than display hierarchy. Make graphics rich in perceived *affordances*. Avoid "out-of-the-loop" syndrome on automated systems, by explicitly visualizing automation data, rate-of-change cues, target values and alarm information.

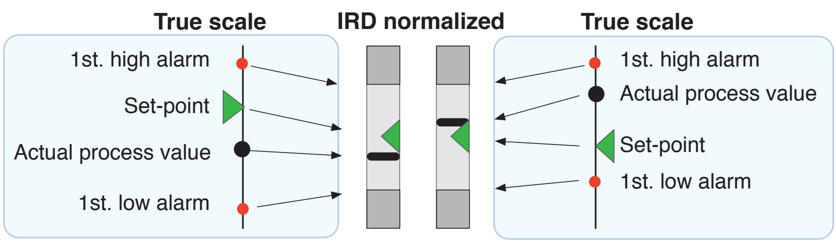
- Design for rapid visual perception; create visual patterns from process values and alarm limits. Qualitative indicators based on part-wise mathematical normalization is suitable. Reduce masking problems by limiting the number of different types of display objects. Design graphics for rapid *information pick-up*, using concepts from Ecological psychology as metaphors for design: through *substances*, *mediums*, and *surfaces*, as well as their *constraints*.

- Visualize a plant´s dynamic response through qualitative trended indicators; focus on visualizing dynamic data through a high data-ink ratio.

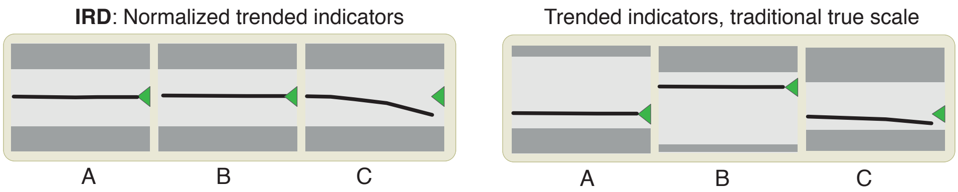
- Support top-down search awareness through lines, multi-scaled structuring elements, grouping, and open space.

- Support bottom-up data-driven awareness; data should be given lower level visual pop-out effects through a visual feature hierarchy, providing cognitive support through rapid eye movements achieved through graphics orientation, colour, size, and motion. Equally sized filled objects are better than frames for alarm pop out. Use a neutral background (such as grey) to facilitate pop-out effects, with the caveat that grey-scale graphics can cause readability problems in well-lit rooms using front-projected technology. Highlight new alarms through a gentle animation rather than flashing or blinking.

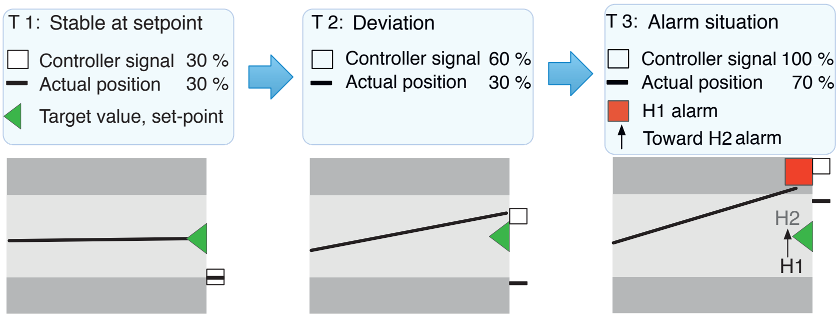
This thesis approaches rapid perception of process data by proposing normalized generic indicators for visualizing plant´s process variables such as: liquid level, pressure, temperature, flows etc. Mathematical normalization of variable´s measuring scale makes the IRD indicators suitable for rapid visual comparisons. The figure visually explains how two variables (true-scaled inside the blue box) are re-organized graphically through mathematical normalization for vertical axis graphics.



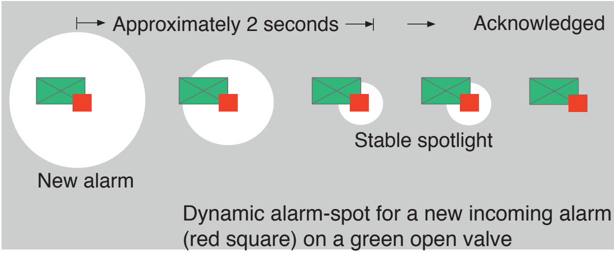
Mathematical normalization is calibrated from process variable´s first high and low alarm limits, and process variable´s set-point for normal stable operation. The indicators do not re-scale during plant operation. The IRD indicators reduce visual complexity for industrial-scale data sets through alignment and grouping. By this, the indicators can be arranged creating simple visual patterns of process values and alarm limits. The trended IRD indicator is suggested as better than the other IRD indicators for perception of plants dynamic response. The compressed and stretched scales in normalized graphics can, however, cause operators to build wrong models of the process. The figure visually explains how deviation is more easily spotted for variable C for IRD normalized mini-trend graphics, compared with a true-scaled representation (IRD in left group of three variables A, B, and C):



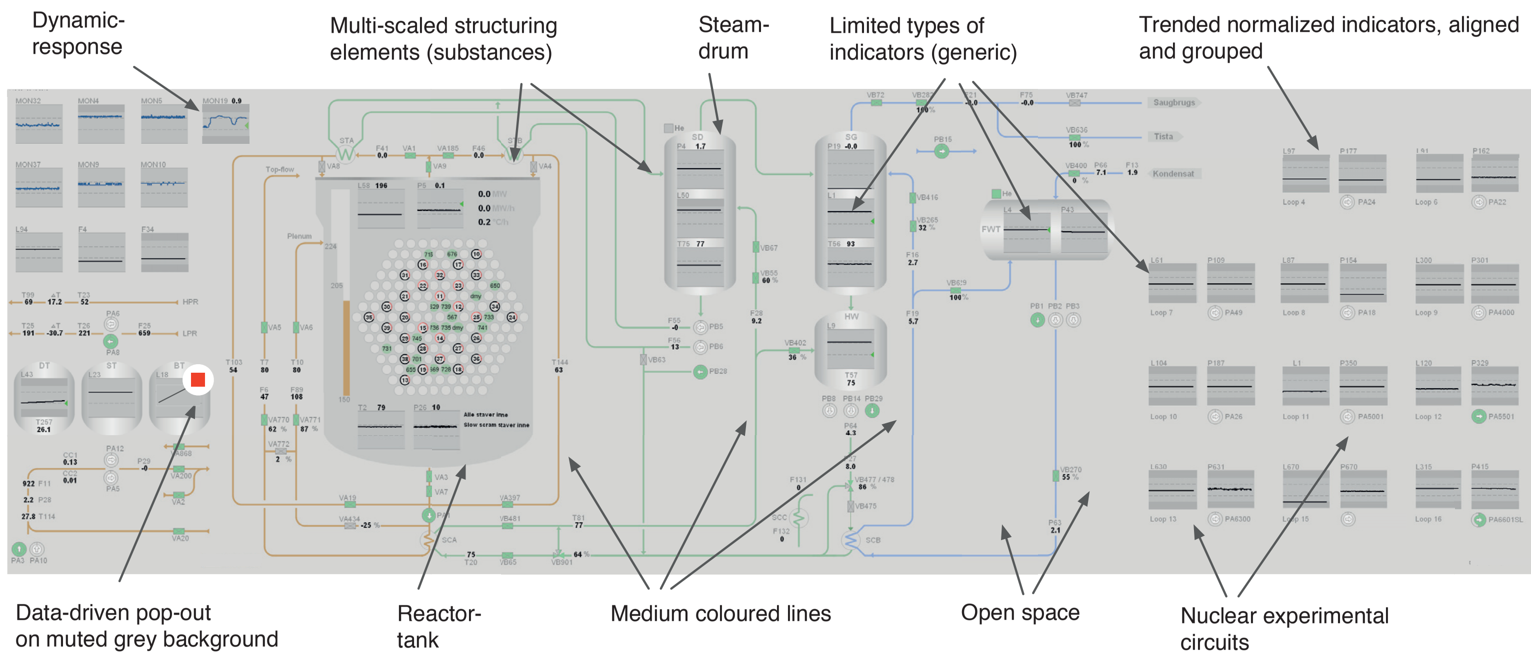
The thesis suggests compensating for limited capacity for visual memory, firstly through larger display surfaces (LSDs), showing externalized data without a display hierarchy, and secondly, through data-rich graphics, which integrate related data. The objective is to avoid the need to visit different parts of a display hierarchy to mentally construct a situation overview (keyhole). The following visually explains how graphics explicitly integrate: automation data, alarm data and rate-of-change cue (the arrow). The figure visually explains through a time series (T1, T2, T3) how IRD graphics work (explanation in blue box is not a part of LSD graphics).



A dynamic alarm spot for rapid awareness of data-driven incoming alarms is developed for use in LSDs. This gentler animated graphical component is an alternative to intrusive blinking/flashing effects. It is useable for alarms on IRD indicators, process equipment, valves, pumps, compressors etc.



The following LSD visually explains this thesis contribution.



The Halden Reactor LSD: 4,5 m

List of Original Publications

This thesis research work is presented in the main report, through papers 1-9, a magazine article (paper 10) and through design patented graphics. The following lists the papers and design patents:

List of papers:

Paper I:

Braseth A.O., Welch R., Veland Ø. (2003). A Building Block for Information Rich Displays. Paper at IFEA conference, Gardermoen, Norway.

Paper 2:

Braseth A.O., Veland Ø., Welch R. (2004). Information Rich Display Design, paper in Proceedings, Forth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Controls and Human-Machine Interface Technologies NPIC&HMIT, Columbus, Ohio, USA.

Paper 3:

Braseth A.O., Nurmilaukas V., Laarni J. (2009). Realizing the Information Rich Design for the Loviisa Nuclear Power Plant. Paper in Proceedings, Sixth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies NPIC&HMIT, Knoxville Tennessee, USA.

Paper 4:

J. Laarni, H. Koskinen, L. Salo, L. Norros, A.O. Braseth, V. Nurmilaukas (2009). Evaluation of the Fortum IRD Pilot. Paper in Proceedings, Sixth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies NPIC&HMIT, Knoxville Tennessee.

Paper 5:

Braseth A.O., Nihlwing C., Svengren H., Veland Ø., Hurlen L., Kvalem J. (2009). Lessons learned from Halden Project research on human system interfaces, Nuclear Engineering and Technology, An International Journal of the Korean Nuclear Society, Vol. 41, No. 3, pp. 215-224.

Paper 6:

Braseth A.O., Karlsson T., Jokstad H. (2010). Improving alarm visualization and consistency for a BWR large screen display using the Information Rich Concept. Paper in Proceedings, Seventh American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies NPIC&HMIT, Las Vegas.

Paper 7:

Braseth A.O., Øritsland T.A. (2013). Visualizing Complex Processes On Large Screen Displays: Design Principles Based On The Information Rich Design Concept, Elsevier Displays, No 34, pp. 215-222.

Paper 8:

Braseth A.O., Øritsland T.A. (2013). Seeing the Big Picture: Principles for dynamic process data visualization on Large Screen Displays, in Proceedings of Complexity, Cybernetics, and Informing Science and Engineering, Porto, Portugal, pp. 16-21.

Paper 9:

Braseth A.O. (2013). Evaluating usability of the Halden Reactor Large Screen Display: Is the Information Rich Design concept suitable for real-world installations? International Journal of Nuclear Safety and Simulation, Vol. 4, No. 2, pp. 160-169.

Magazine article

Paper 10:

Braseth A.O. (2014). Information-rich design for large-screen displays: A new approach to human-machine interfaces has produced a radically different design of control room displays. Nuclear Engineering International, special issue Instrumentation & control, February 2014, pp. 22-24.

Design patented graphics

The dynamic alarm spot registered on Alf Ove Braseth. Design patents and Design reg. In EU & Norway: No 001654765-0001, 082551.

The qualitative mathematical normalized indicators (mini-trend, polar-star and bar type) are registered on Alf Ove Braseth, Øystein Veland and Robin Welch. Design patents & Design reg. USA, EU & Norway: US D549, 870 S, No 000632740-0002, No 000633466-001, No 000633458-0001, No 000633458-0002, No 000633458-0003, 080686, 079695.

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Appendix A: A literature review of industrial Standards and Guidelines.

Appendix B: Declarations of co-authorship for the research papers of the thesis.

Appendix C: Declarations of co-authorship for design-patented graphics, and the author´s contribution in designing this thesis research-oriented Large-Screen Displays.

Part I: Main Report

1. INTRODUCTION

1.1 Personal role

The present author founded the Information-Rich Design (IRD) concept at the Norwegian Institute for Energy Technology (IFE) in the year 2000, and was later joined by fellow IFE scientists Øystein Veland and Robin Welch. Others have later participated in research activities, among them are: Jari Laarni from VTT (Finnish research institute), Ville Nurmilaukas from Fortum, and Trond Are Øritsland (University of Trondheim). Researcher colleagues from IFE have also contributed, among others are: Magnhild Kaarstad, Håkon Jokstad and Tommy Karlsson. My personal contribution in this thesis research papers and design-patented graphics is explained in Appendixes B and C.

1.2 The structure of this thesis

This thesis contribution is described through the following:

Part I Main report: The contribution of the main report is to provide the greater picture of this thesis research work, and it can be read as a standalone publication. It explains the purpose, methods, contribution and relevance of the research. The main report contains sections of new original and up-dated material, particularly for chapters: 3 Approaching challenges through Large-Screen Display design; 4 Research methods for Large-Screen Display design; 7 Discussion and 8. Conclusions, recommendations and further work.

Part II: Nine research papers (papers 1-9), which present research in a natural progression. They provide in-depth material for the thesis research activities. The research papers are a large part of this thesis contribution.

Part III: A magazine article (paper 10). The article is written for a broader audience with an interest in nuclear technology. The article summarizes previous research for this thesis concept, and adds a section describing a suitable design process.

Part IV: Design patented graphics developed through the research process; these graphical objects are a part of the thesis contribution, referring to US, EU and Norwegian design patents. The graphical objects are also explained in Part I of the main report, and in research papers.

Appendix A: A literature review on relevant industry Standards and Guidelines. This background material is used for discussing whether the thesis contribution is in conflict with industry practice (section 7.7). The following are examined: IEC 60964/61772 (2009); NUREG-0700 (2002); ISO 11064-5 (2008); ASM Consortium Guidelines Second Edition (2013) and ANSI/HFES 200 (2008).

Appendix B: Declarations of co-authorship for the research papers in this thesis.

Appendix C: Declarations of co-authorship for design-patented graphics, and author´s role in designing three large-screen displays for this thesis is described.

Part I: Main Report

The following gives an overview of Part I, the Main Report:

Chapter 2 – Problem description describes how modern industry operates complex processes from remote centralized control rooms, typically through desktop displays. Next, describing the research questions of this thesis: i) how to design for rapid perception of industrial-scale data sets? And ii) how to avoid keyhole effects in complex processes? This chapter builds on the material in the research papers.

Chapter 3 – Approaching challenges through Large-Screen Display design describes the research topic, how Large-Screen Display (LSD) design is a reasonable approach on research problems, and how this thesis approaches this through a broad research perspective. The scope, and topics of the research papers are presented chronologically at the end. This chapter extends the material of the research papers.

Chapter 4 – Research methods for Large-Screen Display design provides, first, background material on complexity. Next, describing how LSD design involves two complex systems, the process operators and the industrial plant. Based on this, the chapter positions the research problems and LSD design within the wicked-problems category. The chapter describes further how interaction design research methods are suitable for such problems, and how this thesis contribution to research is positioned as research for design. Lastly, the methods of the research papers are presented chronologically. Most of this chapter is new material.

Chapter 5 - Design studies for Large-Screen Display design provides background material for this thesis contribution, the LSD design concept. The material in this chapter is used for positioning the concept against state-of-the art concepts, and for validation of concept. This chapter builds on the material of the research papers.

Chapter 6 – Results for Large-Screen Display design presents first a summary of the design rationale for the proposed concept of this thesis, followed by thesis contribution: design principles and graphics for LSD design. Then follows the contributions of the research papers, chronologically presented. Sections, 6.1 - 6.4 of this chapter extend the material of the research papers, the last section 6.5 is based on research papers material.

Chapter 7 – Discussion validates the LSD concept implicitly from a theoretical position, and explicitly through user tests and industrial applications. Further, the IRD concept is positioned, and lastly, describes the contribution of the thesis. Most of this chapter is new material.

Chapter 8 – Conclusions, recommendations and further work first concludes this thesis research, and then provides recommendations for policymakers, operating companies and LSD designers. Lastly, outlining topics for further work. Most of this chapter is new material.

2. PROBLEM DESCRIPTION

Most of the material in this chapter builds further on the material describing challenges in perceiving industrial scale data sets from papers 1, 2, 5, 7 and 8. This chapter takes first a brief look at how modern industry operates complex processes from remote centralized control rooms, often through desktop displays. Next, referring to research and industry standards and guidelines, this chapter introduces two well-known problems, which this thesis mitigates through Large-Screen Display (LSD) design: unfortunate keyhole effects, and how industrial-scale data sets challenge human perception capacity.

2.1 Operating complex processes from centralized control room

In the past, industrial-scale processes were operated locally at machines, pumps, valves etc. However, technological advances in the last century made it possible to move from local control to centralized control room operation, by hard-wiring process data to analogue dials, knobs and buttons. The nuclear domain standard IEC 60964 (2009, p. 37) described how such control rooms represent whole integrated informing systems, consisting of: human-machine interfaces, control room staff (operators), operational procedures, training programmes, equipment and other facilities. For industrial processes, centralized control rooms play an important role, by informing operators of the plant´s operational state through interfaces. Such interfaces are used for monitoring and interaction purposes, used for spotting process variable deviations, for tuning process variables for product quality and production rates. For safety-concerned domains, as found in the nuclear and petroleum industries, the control room functions also as a barrier, preventing operation outside safe operational “envelopes”. Safety and integrity controlling systems inform operators through human-machine interfaces of the state of the plant, so proper measures can be taken.

Un-safe operation can have severe accident potential for explosion, loss of life, fire or release of toxic waste to the environment. The industrial standard IEC 60964 (2009, p. 16) wrote: “*A control room shall be designed to enable the nuclear power plant to be operated safely in all operational states and to bring it back to a safe state after the onset of accident conditions”.* In the aftermath of the Three Mile Island (President´s commission, 1979), and Chernobyl accidents (Wood, 2007), both human performance, training, organizational structure and human-machine interfaces have been identified to affect safety for such complex processes. However, the picture is complex and the root cause of those accidents was described as a combination of many factors (Meshkati, 1991).

In modern industrial control rooms, there have been considerable advances in technology; the larger analogue hard-wired panels have been replaced with computerized display interfaces. Such modern desktop workstations are used for process monitoring and interaction; this is illustrated in Figure 1. Operating process plants from desktop displays offers great flexibility and low-cost upgrade potential.

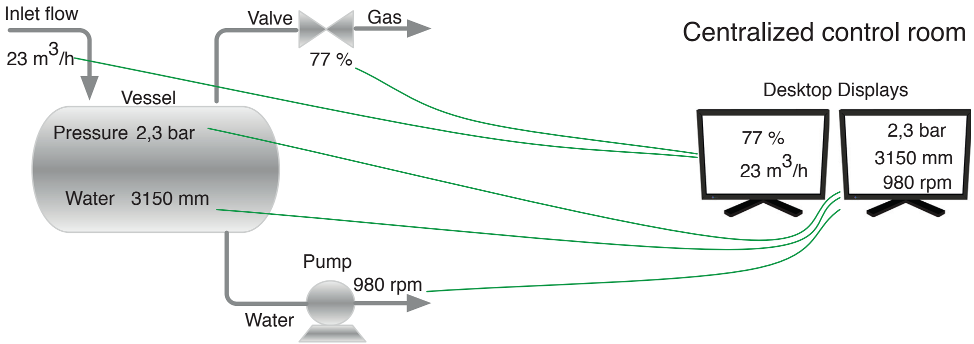


Fig. 1: A section of a process plant. Process data are monitored on desktop displays.

The review guidelines NUREG-0700 (2002, p.1) for nuclear control room human system interfaces explained how: "*Information is at the center of human performance in complex systems*". This pointed at the importance of looking at information selection, information presentation and human capabilities from a systems perspective. This is in line with other standards; IEC 61772 (2009, p. 11) described the following for control room visual display units (VDUs): "*The VDU system shall be designed so that operators can perform their tasks correctly and promptly*".

Human factors engineering has had a great influence on modern human-machine interfaces through task and work domain analysis methods, particularly highlighting the question: "what to display?" Which process variables should be represented in control room displays? A presentation for complex systems is found in Jamieson et al. (2007), for complex sociotechnical systems with case examples by Naikar (2013). Rosson and Carrol (2012) described more lightweight scenario-based methods. Specifying the display content relates in many ways to the first level of Situation Awareness (SA), perceiving critical factors in the environment, as described by Endsley (2013, p. 89), however, finding suitable display formats is also important, asking the question: "how to display process information?"

In an effort targeting the design of overview displays for petroleum processes, Reising and Bullemer (2008) focused their research on effective information presentation. They referred to several prominent industrial accidents that happened due to poorly designed control room displays, citing Texaco Pembroke, (Health & Safety Executive, 1997), and the BP Texas City disaster, (U.S. Chemical Safety and Hazard Investigation Board, 2007). This pointed to the importance of finding efficient graphics coding for industry plant´s data. And further, how process data in displays must provide the greater picture of plant´s state, easily perceivable in a wide range of operational situations. The next section explains why perceiving industrial-scale data sets through desktop displays are challenging.

2.2 Perceiving complex processes through desktop-displays is challenging

One challenge in perceiving industrial-scale data sets through desktop displays is described as the keyhole effect, Woods (1995). This problem stems from problems presenting a large data-space on a limited display surface; the desktop display is unable to present the greater picture in one single view. This is visually explained in Figure 2.

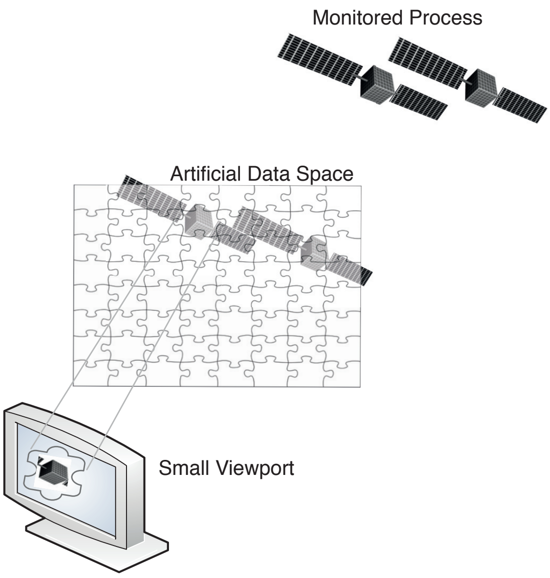


Fig. 2: The keyhole effect: Inspired by Woods (1995), redrawn by the author.

In the often-used approach of representing a plant´s data space on desktop display surfaces, details are visualized on the lower levels of a hierarchy, and key-data on top overview levels. Hollifield (2012), described how modern desktop display approaches typically use four hierarchy levels, see Figure 3.

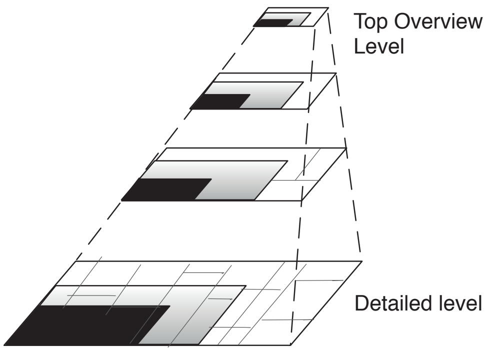


Fig. 3: Visualizing the data space through a display hierarchy, inspired by Pirus (2002), redrawn by the author.

Keyhole effects are unfortunate for several reasons. They challenge human capacity, fragmenting the greater picture of the plant´s situation, and introduce unfortunate time consuming navigation in display hierarchies. The transition from larger wall panels to modern desktop displays has contributed negatively to keyhole related problems. In a field study of older nuclear power plant control rooms, Vicente, Roth and Muaw (2001) described unfortunate effects by moving from larger analogue panels to desktop-displays. This was also found by a study on conventional and nuclear power plants by Salo et al. (2006). They concluded that it has become more difficult to get the instantaneous process state overview on desktop workstations, than through the old large analogue panels.

International standards and guidelines are also aware of the keyhole problem. Review guidelines for nuclear control rooms, NUREG-0700 (2002, p. 309), described how traditional control rooms (CRs) using analogue technology have evolved over many years, with designs contributing to crew performance, stating: "*Some of these positive characteristics of conventional CRs may be lost in CRs with computer-based workstations"*. They explained how it was difficult to maintain awareness of overall nuclear plant status through such displays with limited screen size, stating: "*This problem may be aggravated in computer-based CRs by the fact that only a portion of the total plant information is visible at one time through the limited viewing area of an information display screen"*. IEC 61772 (2009, p. 31) described how smaller displays don´t support human capabilities in spatial information coding and information "catching" to the same extent as the older large wall panels. They suggested that smaller displays have a disadvantage, since information will not always be present at the same location, referring to the keyhole effect.

In addition to unfortunate keyhole problems, the concept of information "catching", being able to perceive industrial-scale data sets rapid and intuitively is a challenge for operators monitoring and interacting with complex processes. An overview of how simultaneously dual tasks challenge human performance was described by Wickens (2002). He pointed particularly to unfortunate effects in dual tasks performance when both tasks are visual. Endsley (2013, p. 103) described how data overload is a challenge in building sufficient Situation Awareness (SA) levels, not only due to the scale of large data sets, but also due to ineffective data presentation. About data overload, she wrote: "*it often occurs because data are processed, stored, and presented ineffectively in many systems".* She described further how data acceptance rates could be increased if they were based on suitable interface information presentation formats.

The challenge of information processing was also described through Rasmussen´s (1983) influential Skills-Rules-Knowledge (SRK) taxonomy. The SRK model was used as guidance for assigning process data to efficient lower level cognitive control in the display concept named Ecological Interface Design (EID), see Vicente and Rasmussen (1992). Others have also described the advantage of designing graphics for lower level cognitive control for increased cognitive capacity; see Hoff and Hauser (2008), and Reising and Bullemer (2008). The importance of finding proper information coding was also raised by international standards on control room design for their VDU formats. IEC 61772 (2009, p. 11) wrote: "*As the information displayed on VDUs is a major information source and contributes to the total operator workload, the display design shall minimize the workload contribution from monitoring, operation and problem solving to avoid information overload".* This view is shared by NUREG-0700 (2002, p.1); the guidelines explained how information display systems should offer status at a glance (2002, p.11), to immediately assess plant status without performing interface management tasks.

The research objective of this thesis is to conduct research for how to support rapid perception of industrial-scale data sets, while avoiding keyhole effects. This is done through purpose-built graphics and design principles for LSDs. The research process has been shaped by the two following research questions:

2.3 Research question: how to design for rapid perception of industrial-scale data sets?

The first question is related to finding efficient information coding in line with human perception capacity, for enabling rapid pattern finding mechanisms. The information graphics must display process plant´s characteristics, such as process variables (pressure, liquid level, temperature, flow, etc.), automation and alarm information. The importance of finding suitable visual formats stems not only from the industrial-scale of these data sets, but also from the dynamic nature of such processes. They impose data-driven parallel processes; examples are multiple alarms, and/or simultaneously experienced disturbances. In addition to finding proper formats for process information, there is also a need to address the keyhole effect.

2.4 Research question: how to avoid keyhole effects in complex processes?

A reasonable approach to keyhole-related problems is to increase the display size, to move from desktop displays measuring inches, to larger display surfaces measuring meters, and advances in display technology have made this available for modern industrial control rooms. However, approaching keyhole related problems only from the technology end is not sufficient. Keyhole problems stem also from limited visual memory resources. For this reason, larger display surfaces should be designed for their purposes from the ground-up, where both LSDs graphics and components layout should be designed with keyhole effects in mind.

The two research questions are approached through a LSD concept, which focuses on rapid perception graphics, and externalized information presentation to avoid challenging limited visual memory resources. The next chapter describes why there is a need for such a LSD concept, and why LSD design should be done from the ground-up, based on a broad research perspective.

3. APPROACHING CHALLENGES THROUGH LARGE-SCREEN DISPLAY DESIGN

Most of this chapter´s material is new or rewritten, however, some parts build on material from papers 7, 8 and 10, describing why there is a need for LSD concepts based on a broad research perspective. The chapter first describes why there is a need for a concept for industrial processes; then how this thesis research is based on a broad perspective, and lastly, the scope is described.

3.1 There is a need for a Large-Screen Display concept

A reasonable approach to overcome keyhole problems might seem to be to just use larger displays, to scale up desktop workstation pictures, and minimize problems by displaying several of them on a large display surface. However, international industrial standards and guidelines rejected this approach. IEC 61772 (2009, p. 25) wrote*: "LSD pictures should not be copies of primary workstation pictures even if these workstations already have overview pictures available on them"*. They explained further how LSD pictures should be designed for their purpose, complimentary to existing workstation pictures. This view is also supported by other international standards; IEC 60964 (2009, p. 30) explains how displays should be selected for their intended purpose.

The view of LSDs as inherently different from smaller displays was supported through research, which explained how graphics traditionally have been developed for such display sizes. Endert et al. (2011) described how guidelines for graphic encodings (length, colour, size, slope, position), are developed for desktop displays. Although not intended specifically for complex process plants, their research for large, high-resolution, visualizations suggested that designers must consider key characteristics of each encoding for such larger display surfaces. Andrews et al. (2011) supported this, stating: "*Designing for these displays is thus not simply a matter of scaling up existing visualizations or displaying more data; instead, designers must adopt a more human-centric perspective".* Endert et al. (2012) pointed to important characteristics for LSD design, describing how human spatial memory is not strong, further, suggesting that if information is persistent in space, this can act as a form of efficient external memory.

With this in mind, this thesis argues that LSDs must be designed for their purpose from the ground-up, from a human-centric perspective, taking into account human capacity, where the large-screen should work complimentary to the control room´s other human-machine interfaces. Unfortunately, not many literature, research or display concepts are focused on LSD graphics. Standards and guidelines offer some insights; they are, however, more focused on reviewing than creating graphics designs. For this reason, the next section outlines this thesis approach, a research-oriented approach named Information-Rich Design (IRD), with an objective of mitigating the two research questions from a broad research perspective.

3.2 A broad research perspective on Large-Screen Display design

Even though there is a lack of LSD design concepts, industrial standards and guidelines offer insights on suitable theoretical foundations for efficient human-machine interfaces. ANSI/HFES 200 (2008, p. 371) from the Human Factors and Ergonomics Society wrote: "*Presentation of visual information should enable the user to perform perceptual tasks (e.g. searching for information on the screen) effectively, efficiently, and with satisfaction".* They described further, how it is necessary to have a broad understanding from several disciplines to achieve this, from: human physiology (the sensory system), psychology (mental workload), ergonomics (context of use), typography and graphical design. This view is in line with IEC 60964 (2009, p. 30), describing how display systems should consider human capabilities and characteristics.

Within cognitive engineering, user-centred design is described as an appropriate approach to handling complex processes (Endsley et al. 2003) and (Norman and Draper, 1986). In this approach, interfaces should be moulded around the capabilities and needs of the operator, rather than centred on the technologies that produce them. However, Hoff (2002) criticized such approaches. He suggested how they typically support an evolutionary process, building on former devices through iterative cycles, rather than revolutionary innovative processes based on fundamental facts of human behaviour and capacity.

There are, however, approaches to display design for complex processes that build on fundamental facts about the cognitive and perceptual apparatus for humans. Examples of such approaches are Tharanathan et al. (2012) for desktop overview displays, Hoff and Hauser (2008) for display interfaces of grid control in energy management systems, and Burns and Hajdukiewicz (2004), which outlined suitable graphical display objects for Ecological Interface Design (EID). These approaches are typically influenced by information presentation, which support lower level cognitive control. Although their work was originally not intended for computer graphics, the following author´s work has influenced such rapid perception graphics; Rasmussen's (1983) Skill-Rules and Knowledge (SRK) taxonomy, and Ecological psychology (Gibson, 1986) and the embodied-mind approach of Lakoff and Johnson (1999). The advantage of presenting information for rapid effortless perception in computer graphics is evident. As human perceptual apparatus is in general stable and strong across gender, age, race, and so on, such information presentation is suitable for a consistent and stable performance though a wide variety of operational situations.

In sum, this suggests how a broad research perspective is a reasonable approach to LSD design: considering human capabilities and limitations, building on the research of others for information visualization, and findings from comparable applications. Further, making the concept useable through design exploration and feedback from end users in realistic control room settings. This thesis contribution, the IRD concept is based on such broad research perspective, from basic theoretical concepts to industrial implementations.

3.3 Information-Rich Design: a research-oriented Large-Screen Display concept

The following section outlines IRD´s research foundation, referring to key research topics and references, where the objective is to support rapid perception of industrial-scale data sets, while avoiding keyhole effects. The research perspective is explained in Figure 4.

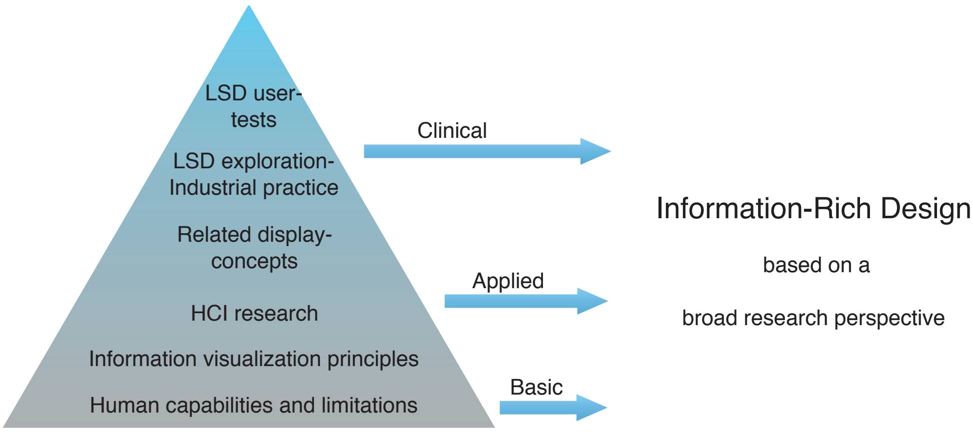


Fig. 4: A research oriented LSD concept: Information-Rich Design (IRD).

- **Human capabilities and limitations:** IRD uses Ecological and Gestalt psychology as a foundation for graphics supporting rapid visual perception of process data. Alignment and grouping of data is used to reduce the visual complexity of industrial-scale data sets. Rasmussen´s SRK model for cognitive control is used to scope the IRD concept, being useable for both self paced to tight "fire-fighter" operational situations.

- **Information visualization principles:** Applying well known rules-of-thumb for data visualization, among key figures used are Norman and Tufte. Based on this, IRD graphics use externalized data presentation to mitigate keyhole problems. Further, the concept focuses on information-richness, visual layering and a high data-ink ratio.

- **Human-computer interaction research:** On an applied level, the IRD concept is based on research for rapid awareness of process data through efficient top-down search, and bottom-up data driven events. Further, to avoid excessive load on limited visual memory (keyhole effects). The means used to achieve this is to build visual feature hierarchies with strong visual pop-out effects for key data, while avoid masking primary data by limiting the types of display objects. The key names used for this are Ware, Healey and Enns.

- **Related display concepts:** The concept uses findings from related display concepts, such as: Ecological Interface Design, overview displays research from the ASM Consortium, from Hoff and Hauser, the Parallel Coordinates concept, Function-Oriented Design, and concepts from industry leaders, such as ABB. Industrial standards and guidelines are examined for validation purposes, to see if IRD is in conflict with industry practice.

- **LSD exploration and practice:** On a clinical level, the LSD concept is user-tested on full-scale simulators and in real control room settings. This is used to improve IRD through an iterative research process. In addition, using knowledge from design practice from commercial applications as feedback for design.

The IRD concept is not domain specific, but aims to cover complex processes in general. The scope, deliverables and limitations are described in the following section.

3.4 Scope: Design Principles and graphics for Large-Screen Displays

The objective for the research is a LSD concept useable for real-world applications. The concept is intended for control room operators in the centralized control room, using the large-screen for monitoring industrial-scale data sets. For this reason, the IRD concept consists of display graphic objects and design principles, describing how to visualize process data, and how to organize the display layout. The graphics and design principles cover process plant characteristics, describing how to display process data, such as pressure, temperature, flow, liquid level, as well as graphics and principles for process automation and alarm visualization. However, each case of LSD design must further harmonize colors and graphics with a control room´s other display interfaces, and perform detailed design for plant-specific characteristics. In addition, other types of graphic visualization than those described in this thesis must be considered. Examples are: long-term trends for key-variables; displaying plant safety and integrity functions; visualization of a plant´s physical structures putting graphics in a familiar context; and CCTV-pictures for surveillance of hazardous areas.

Process plants are run in several operational conditions; the conditions supported by the IRD concept are typically:

- Normal “flat” stable production
- Running the process up and down.
- Detection of early disturbances and abnormalities.
- Detection of unacknowledged alarms, and key alarms.

There are other conditions not covered through the thesis LSD concept, which must be designed for in each case. Examples are: safety-critical operation, fire and gas, maintenance conditions etc. The scope is also limited to processes that are based on a continuous production, which is typically of energy production as found in nuclear and oil and gas based domains. Industrial batch type production is outside the scope of this thesis work. Display technology influences picture quality in control rooms: resolution, colour accuracy, brightness, contrast etc.

Which process data to display on human-machine interfaces is important, as this is necessary for ensuring the basic level of Situation Awareness (SA), described as perceiving critical factors in the environment (level 1 SA), see Endsley (2013, p. 89). The scope of this thesis LSD concept is, however, limited to: “how to visualize process data?” Not, “what to display?” The choice of creating a concept not only for research purposes, but also for real-world industry introduces, however, limitations. Most notably is the choice of basing the concept on traditional industrial instrumentation; often referred to as a Single-Sensor-Single-Indicator (SSSI) approach. IRD therefore visualizes instrumented characteristics: pressure, temperature flow, liquid level, automation and alarm data etc. Higher order variables (enthalpy, energy, entropy) are for this reason outside the scope of the concept. However, it should be noted that this is a limitation, higher variables are important for describing the plant´s behaviour and characteristics. Vicente and Rasmussen (1990) criticized such SSSI approaches, suggesting that higher order variables (global invariants) are important for informing operators of the plant´s state.

The importance of a suitable work process in developing control room applications is highlighted through industrial control room standards and guidelines (see ISO 11064-1, 2000, pp. 4, 7). It is also suggested by research-oriented display concepts. Burns and Hajdukiewicz (2004) described the process from work domain analysis to display graphics in Ecological interface Design. Although the author fully appreciates the importance of this, the IRD concept is not a work or design process; it is a concept describing graphics for larger display surfaces. Paper 10 (the magazine article), however, suggested briefly how IRD could be applied in a user-centred design process.

The IRD approach is not intended or developed for any specific technology, and for this reason, the technology aspects are outside the scope for this thesis research work.

3.5 The scope of the research papers

The LSD research in this thesis is performed over a period of approximately fourteen years (2000-2014). The research work is published in: nine research papers, an article, and design patents. Figure 5 visually explains the key research activities during the period.

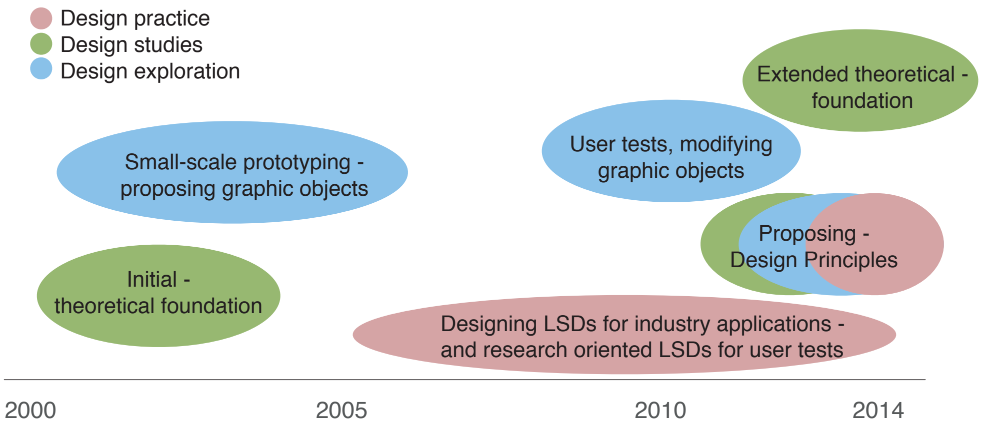


Fig. 5: The thesis research activities.

The following describes each paper´s issues and research questions. The early papers were less focused on specific research questions than more recent papers. Papers 1, 2, 3, 4, 6 and 8 are conference papers, papers 5, 7 and 9 are published in journals, and paper 10 is a magazine article.

Paper 1 (2003), “A Building Block for Information Rich Displays”: The paper brought up issues in monitoring and understanding large-scale processes: i) The keyhole problem by using small display-ports that only see a fraction of the process, and ii) The cost of concurrence, which reduces the operator’s mental capacity when operating several parallel processes. The papers discussed problems with current traditional design concepts, and asked: Can good design principles from other areas such as maps, statistics, and electronics be used?

Paper 2 (2004), “Information Rich Display Design”: The paper asked several questions: how to support the different roles of control room operators, from self-paced (researcher) to tight (fire fighter)? And how to free mental resources needed for problem solving in faster paced situations? Display concepts must focus on information presentation, rather than only identifying information content as per many other approaches.

Paper 3 (2009), “Realizing the Information Rich Design for the Loviisa Nuclear Power Plant”: Applying IRD for the first time to a large nuclear process, the paper focused on operational issues: How to provide a shared information space for operator cooperation, communication, coordination of tasks and increased awareness? And which plant operational states should this 1st generation LSD support?

Paper 4 (2009), “Evaluation of the Fortum IRD Pilot”: This first user evaluation focused on the following: What do the control room operators think of the usefulness of the IRD concept as realized through the Loviisa display? And how does it perform compared with a traditionally familiar overview display?

Paper 5 (2009), “Lessons Learned From Halden Project Research on Human System Interfaces”: The paper discussed and summarized results for control room displays where one of them was IRD. The paper focused on the following: the keyhole effect, interface management issues, visual patterns and teamwork transparency.

Paper 6 (2010), “Improving Alarm Vizualization and Consistency for a BWR Large Screen Display using the Information Rich Concept”: The paper described changes through the iterative research design process from 1st to 2nd generation LSD. How can the IRD concept be improved to address issues found in the 1st generation display to the 2nd generation LSD? Particular issues were alarm readability and visual consistency for graphics. How to differentiate unacknowledged alarms from old alarms?

Paper 7 (2013), “Visualizing Complex Processes On Large Screen Displays: Design Principles Based On The Information Rich Design Concept”: The paper raised three questions on LSD design: i) which type of process display objects is suitable? ii) How to visualize alarm information? And iii) what type of display layout is suitable? In addition, the second user-test of the IRD concept focused on: were modifications of the display concept from the 1st to the 2nd generation LSD successful? In addition: where do we position the IRD concept looking at related industrial approaches; is it in line with well-known design principles for such displays?

Paper 8 (2013), “Seeing the Big Picture: Principles for dynamic process data visualization on Large Screen Displays”: The paper asked two questions: i) which means are suitable to support rapid-search attention to dynamic data in LSDs? And ii) how should dynamic process plant behaviour be visualized in LSDs? In addition, the paper discussed the research contribution of IRD, and positions IRD by looking at other related scientific display approaches?

Paper 9 (2013), “Evaluating usability of the Halden Reactor Large Screen Display: Is the Information Rich Design concept suitable for real-world installations?” The paper explored two questions through the third user-test of the IRD concept: i) is usability of the IRD concept satisfying for real-life industrial installations? And ii) have the recently proposed IRD Design Principles improved perceived usability of the LSD concept?

Paper 10 (2014), “Information-rich design for large-screen displays: A new approach to human-machine interfaces has produced a radically different design of control room displays”. The paper asked: What is needed using IRD in a user/human-centered approach for industrial applications?

4. RESEARCH METHODS FOR LARGE-SCREEN DISPLAY DESIGN

This chapter describes the research methods of this thesis as a whole; the majority of the content of this chapter is new and not covered in the research papers. The chapter first provides background material on complexity theory (4,1), and how complexity can be approached. Next, it describes how LSD design involves two complex systems (4.1.1): the process plant and the control room operators. Based on this, LSD design and the research questions of this thesis are positioned within the wicked problem category (4.1.2). Section 4.2 describes background material on design-oriented research. The contribution, graphics and design principles are then positioned as applied research for LSD design. Section 4.3 positions the thesis research work within an interaction design research model proposed originally by Fallman (2008) and further explained by Fallman and Stolterman (2011). This is followed by the research approach of each paper, and lastly, a short discussion on limitations.

4.1 Background: complexity

Anderson (1999) described how complexity theory was developed from an interest in holism and Gestalt theories after World War I, to cybernetics and general systems theory after World War II, accelerated by the invention and use of modern computers. He described how complexity could be managed through simpler models, while other systems can be impossible to forecast through simpler models. Simon´s (1996, p. 1) work has been influential for complexity and complex systems. He wrote: "*The central task of a natural science is to make the wonderful commonplace: to show that complexity, correctly viewed, is only a mask for simplicity; to find pattern hidden in apparent chaos*". He described how complexity in computer programs to a large extent was the complexity of the environment the computer program was seeking to adapt (1996, p. 21). Looking at human beings from the same approach, Simon (1996, p. 80) described them as simple systems, and that the real complexity is within our environments: "*Human beings viewed as behaving systems, are quite simple. The apparent complexity of our behavior over time is largely a reflection of the complexity of the environment in which we find ourselves".*

More recently, Schroeder (2013) described how complexity is a characteristic of informing systems; however, contrary to Simon´s view, Schroeder described how both animals and humans are highly complex systems, much more so than mainframe computers. Gill (2012) described how complex tasks are fuzzy and difficult to categorize. He explained that those who try, even experts typically end up in logical inconsistencies. Gill suggested that task complexity consists of three different dimensions: unfamiliarity – where unfamiliarity is present, the task is perceived as difficult; complicatedness – the challenge of finding or describing a path from where we are, to where we want to go; and objective complexity – describing the end state or goal. Gill described this as the rugged terrain in complex problems; see also Gill and Hicks (2009). He described how altering one component alters the end state (the peak in the rugged landscape). The end state can be described though its fitness function; see also Frenken (2006). Gill (2012) suggested two extremes in objective complexity: decomposable, where the end state contributes to fitness independently; this is quite in line with the reductionist view of creating simpler models of understanding complexity (Simon´s view); and chaotic, where the fitness of the end state depends on the combination of other elements. The value of one specific combination of elements tells nothing about other combinations.

Frankel and Racine (2010) and Cross (1999) described how some leading design researchers in the early 1970s, including Christopher Alexander and John Chris Jones, began to reject the traditional analytical reductionist science approach; particularly following Rittel and Webber (1973), they characterised design and planning problems as wicked problems. In "*Wicked Problems in*

Design Thinking", Buchanan (1992) described design as an integrative discipline, and how they looked for alternatives to the traditional scientific linear step-by-step approach with distinct phases: problem definition and problem solution, particularly for ill-formulated complex problems. Schön (1983) described how skilled professionals approached ill-defined complex real-world problems through creative reflective practice. Cross (2001) described how this challenged the positivist doctrine of the earlier design science movement by Simon (1996) and others. Schön´s approach has had major influence on design theory, research, and in general how to approach complex problems. It is also embraced by modern interaction design as described by Löwgren and Stolterman (2004) in "*thoughtful interaction design*", and Fallman (2008), Fallman and Stolterman (2011).

4.1.1 Large-Screen Display design involves two complex systems

Process plants are often referred to as complex because of the large number of variables, interconnections and feedback loops, Anderson (1999). This physical system can, however, be described through simple thermodynamic laws and automation, hence not particularly chaotic, (Gill, 2012). The process plant´s behaviour can typically be simulated and verified through high fidelity computerized models, and for this reason it fits well into Simon´s (1996) view of a process suitable for decomposition.

The present author´s position is that the other system, the process operators, also represent a complex informing system, Schroeder (2013), not a simple system as described by Simon (1996). The position of this thesis is based on the assumption that human beings are unsuitable for reductionist decomposition. On the contrary, it involves knowledge of human perception, limitations and capacity. LSD design involves therefore knowledge and understanding of two systems: the process plant represented graphically on the LSD, and the process operator informed of the plant´s state through the LSD, this is illustrated in Figure 6.

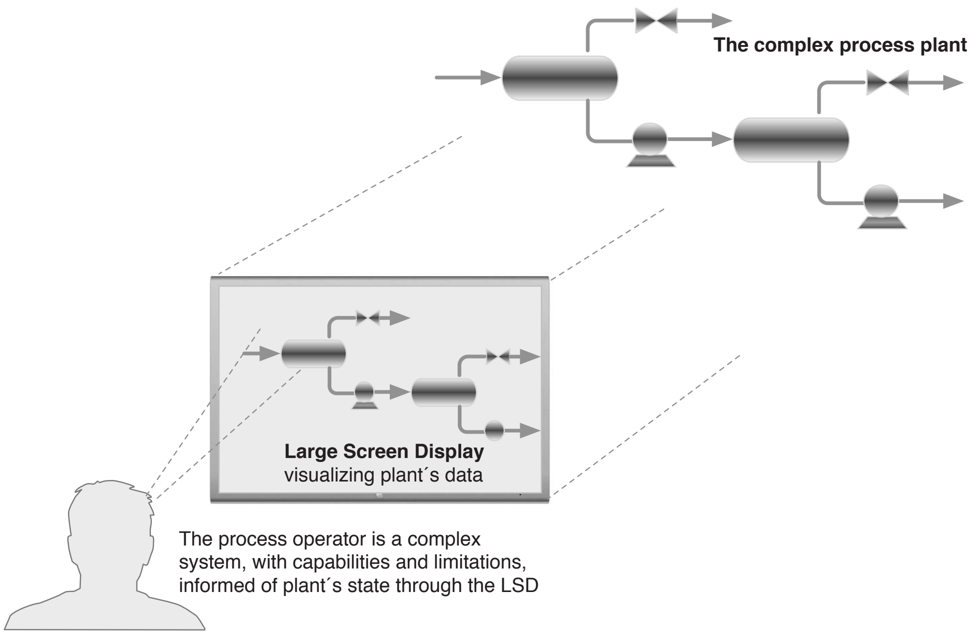


Fig.6: The general problem of designing LSDs involves two complex systems.

To summarize, LSD design involves two complex systems: i) the complex process plant that is suitable for decomposition described through, thermodynamics, fluid dynamics, automation and mechanical engineering, and ii) the process operator, which is not suitable for decomposition, informed by the plants state through the LSD. The research methods in creating a LSD concept must reflect the problem's position; this introduces the next section: categorizing LSD design as a wicked problem.

4.1.2 Large-Screen Display design is a wicked problem

Of the two systems involved in LSD design, the operator and process plant, particularly the operator represents the ill-defined part, not suitable for decomposition into simpler parts. This thesis approaches LSD design as an integrative discipline, in line with Schön´s (1983) view: approaching research through reflective-practice, combining many sources of information. Influential in this was the original wicked-problem description by Rittel and Webber (1973), later adopted for design thinking by Buchanan (1992). In the following, the original text describing some of the wicked problems properties in Buchanan´s paper is given in "*italics"*. Each property is commented for this thesis research for LSD design, for avoiding keyhole problems, while supporting rapid perception of industry data sets:

- *"Wicked problems have no definitive formulation, but every formulation of a wicked problem corresponds to the formulation of a solution"*. The formulation of the research questions of this thesis gives momentum and direction toward a solution, but other formulations could have been used, and that they would have directed the research work in other ways.
- *"Wicked problems have no stopping rules"*. This corresponds to Gill´s (2012) description of objective complexity: have we really found the end state, the best solution, described by the highest peak in the rugged fitness landscape? Probably not; there exists always a potential for improvement and better solutions.
- *"Solutions to wicked problems cannot be true or false, only good or bad"*. Industrial plants are operated on a daily basis using a wide variety of display designs, so there are undoubtedly many solutions that work, however, it is reasonable that some solutions are better than others.
- *"There is always more than one possible explanation, with explanations depending on the "Weltanchauung" of the designer"*. This points to the skills and position of the designer. It is apparent that for LSD graphics, the choice depends on the preferences of the person who is doing the actual work, their background, taste, skills etc.
- *"The wicked problem is a symptom of another, higher-level problem"*. The two research problems in this thesis point to limitations in human capacity, particularly to limited visual memory and information processing capacity for certain data formats.
- *"No formulation and solution of a wicked problem has a definitive test"*. Performance testing, and qualitative feedback from end users is valuable, but it has limited validity only for tested devices for tested scenarios. As suggested by others, a broad approach based on several activities is a reasonable choice.

The indeterminacy described in these selected problem properties corresponds to the general problem of creating a LSD concept, and also for the two research problems. Applying Gills (2012) categorization of complexity for LSD design, in particular complicatedness and objective complexity are high. It is therefore reasonable to categorize this thesis research within the wicked problems category. The next chapter outlines research methods suitable for such problems.

4.2 Background: research methods

The following section outlines background material for relevant LSD research methods: first design research, followed by interaction design, lastly more narrowly scoped Human-Computer Interaction (HCI) research.

4.2.1 Design research

The following section gives a brief overview of design research. Inspiration for this section was found from several research papers, amongst which was Frankel and Racine (2010): *The Complex Field of Research: for Design, through Design, and about Design.* Archer (1995) explained how Francis Bacon influenced science in the traditional western tradition, as being empirical, objective and inductive. However, he also explained that the Popperian revolution brought up new views, and that new scientific proposition may be the result of inspired guesswork rather than the result of inductive reasoning. Archer described how research in its most general sense, is to communicate a systematic enquiry, he described the following:

- It is systematic because it is pursued according to some plan;
- It is an enquiry because it seeks to find answers to questions;
- It is goal-directed because the objects of the enquiry are posed by the task description;
- It is knowledge-directed because the findings of the enquiry must go beyond providing mere information; and
- It is communicable because the findings must be intelligible to, and located within some framework of understanding for, an appropriate audience.

However, in contrast to traditional sciences, Archer described how the humanities approached research differently; comprising theology, philosophy, epistemology, ethics, aesthetics, language, literature, drama, art, music etc. Referring to the arts, he distinguished between: creating new works; performing (practice); knowing the content, history and categorization (scholarship); and research into, for the purposes of arts activities. Frayling (1993/4) suggested a quite similar description to Archer:

- Research for art and design: research where the end product is an artefact, the thinking is embodied in the artefact.
- Research through art and design: typically development work, action research and communicating the results through design activity.
- Research into art and design (about): historical, aesthetic and perceptual research, theoretical perspectives on art and design.

Cross (1999) described the development of design oriented research from the academic design scene in the 1970s, into a new research field, inspired amongst others by the earlier work of Archer. Cross´s taxonomy of design research falls into three categories: design epistemology (study of designerly ways of knowing); design praxiology (the practices and processes of design); and design phenomenology (form and configuration formats). Cross (1999) described further how good design research must be: purposive (identifying issue or problem; inquisitive (acquiring new knowledge); and informed (awareness of related research). Further, it must be methodical (planned and disciplined) and communicable (delivering results testable and accessible by others).

Friedman (2003) described design as a goal oriented process, meeting needs, improving situations, or creating something new or useful. He described design as an interdisciplinary, integrative discipline. Both Friedman and Buchanan (2001) identified three distinctive areas of design research:

- Basic research is directed toward fundamental problems, general principles explaining phenomena. Buchanan suggested that Galileo´s discovery of a theory of motion from observations and natural phenomena demonstrates basic research.
- Applied research is directed to a general class of problems, products or situations. Buchanan described how this could be principles or even rules-of-thumb, such as Edward Tufte´s (1990, 2001, 2006) approach on information design.
- Clinical research is directed toward specific cases, often important in design practice and education. Friedman described how clinical design could be used to test findings of basic and applied research.

Frankel and Racine (2010) argued that Frayling and Archers categories: research for design; research through design; and research about design, map closely with clinical, applied and basic research. Table 1 explains design research categories and typical activities based on Frankel and Racines (2010) literature review.

Archer - Frayling	Friedman - Buchanan	Research activities
Research for Design	Clinical Research individual cases	Construct something; action research, design practice, user-testing
Research through Design	Applied Research general cases	Provide explanation or theory within broader context, action reflection approach
Research about Design	Basic Research general principles	History of design, theory, defining and framing problems, how people design

Table 1: A brief overview of design research and typical activities, inspired from Frankel and Racine (2010).

This thesis contribution is research for design, for constructing LSDs graphics. Research from scholar theory, clinical cases of research-oriented LSDs, and industry practice are integrated to the general (apllied) class of LSDs as research for design. This research knowledge is communicated through design principles and graphics.

4.2.2 Interaction-Design research

Interaction design has a broad perspective; Fallman (2008) suggested its diverse origin, including disciplines such as: human computer interaction; computer science; industrial design; informatics; applied physics and electronics. Fallman (2008), Fallman and Stolterman (2011) proposed a model for interaction design research, inspired by, and extending earlier work from: Schön; Friedman; Archer; Cross and Buchanan. The model described three research activities: design studies; design exploration and design practice.

Fallman (2008) described design practice as the tacit knowledge and competence involved in hands-on creating real-life oriented products where the designer takes an active position in a design team, reflecting on research questions. He described how problem formulation is an important factor in design exploration through prototypes and complete dynamic gestalts: asking *what if*? This activity is described as creative, and can be used to challenge or provoke existing and traditional solutions. Design studies were described to be closely associated with traditional scholar disciplines, about design history, methods and philosophy. Fallman (2008) suggested, however, for interaction design research: "*we believe the most interesting and rewarding results in interaction design research come not from taking a specific position in the model, but rather from moving or drifting in between different positions".*

To summarize, it is reasonable to approach LSD research based on a broad perspective. Applying design studies, studying theory on human capacity and learning from other display approaches. Further, to perform design exploration both in small-scale and through whole LSDs, and to learn from industrial design practice where the LSD concept is explored through real-world installations.

4.2.3 Human-Computer Interaction research

Fallman (2011) described how Human-Computer Interaction (HCI) established itself as a discipline during the 80s; and how the first HCI wave was largely influenced by cognitive psychology and information processing models. Typical examples for system design from this era were user-centred system design, see Norman and Draper (1986) and Endsley et al. (2003). There was a focus on usability, design that was effective, efficient, consistent and easy to learn. This resulted in design guidelines, predicative models and systematic testing. Fallman described, however, how this first HCI wave experienced a theoretical crisis, and how a second wave moved from usability to user experience, adopting a less disembodied emphasis. One example was Gaver (1991); he adopted and suggested using the term affordances (originally from Gibson, 1986), analysing the link between perception and action in computer display designs. Nardi (1996) suggested using activity theory in HCI, inspired from a former Soviet psychology approach, describing complexity and real-life behaviour.

The concern for ill-structured wicked complex problems in favour of well-defined problems has influenced HCI research, moving from a strong belief in the value of empirically studying human behaviour and performance, toward a design oriented discipline. For HCI research, Fallman (2008b) made a distinction between design-oriented research and research-oriented design. He described design-oriented research, as when/where the produced artefact is the means to conduct research. Knowledge from studying the artefact is the main contribution from this type of research. In contrast, in research-oriented design, the artefact is the result; it is the primary outcome from the research process (for design). The primary outcome of this thesis research process is LSD graphics and design principles for designing the artefact LSD; a research-oriented design.

4.3 The research methods of this thesis

Based on the previous discussions, the model for interaction design research by Fallman (2008), further explained by Fallman and Stolterman (2011), is relevant for the ill-defined wicked problem of creating a LSD concept, for supporting rapid visual perception of industrial-scale data sets, and to mitigate keyhole problems. The contribution is scoped as applied HCI research for LSDs. Figure 7 positions the research work accordingly to the model. It should be noted that the research activities in this thesis matches quite well to “research for design” as described by Archer and Frayling, see table 1 in section 4.2.1.

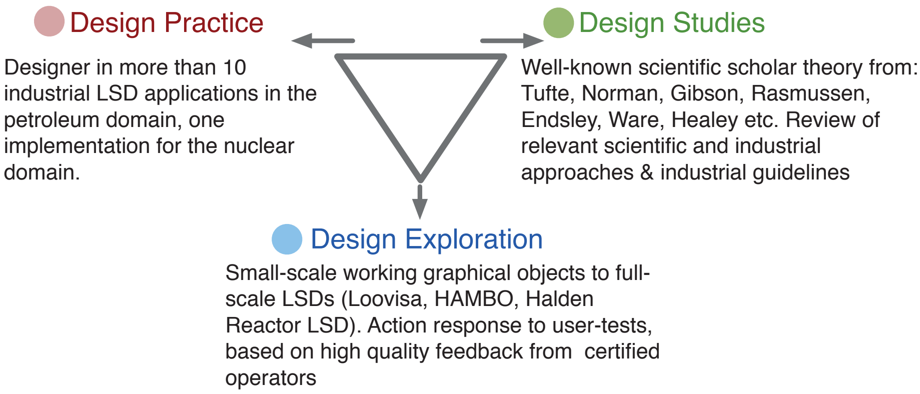


Fig. 7: The thesis research activities: based on Fallman (2008), redrawn by the author, see also figure 5.

It should be noted that author was made aware of this research model rather late in the research process. For this reason, research work was not originally planned taking the model into consideration.

Design practice from commercial projects has exposed the IRD concept for critique by end-users in real-world industrial plants. Design skills from these projects have been used in realizing the research-oriented LSDs: the Loviisa LSD; the HAMBO LSD; and the Halden Reactor LSD. Although the 3rd generation Halden Reactor LSD is installed and used in a live nuclear research reactor control room, the research project had greater flexibility to explore design changes than in ordinary commercial applications. For this reason, it is positioned both as design practice and as a design exploration concept.

4.3.1 The research approach for each paper

Initial design studies in papers 1 and 2 were necessary to understand control room operators problems, to see what is currently typical display design and to find inspiration for making a better alternative. Design studies were resumed later in papers 7 and 8, providing a foundation for design principles. Small-scale design exploration in form of suitable graphical objects is described in papers 1 and 2, in larger scale as LSDs in papers 3, 6 and 8. These displays are explored through user-tests in papers 4, 5, 7 and 9. The earlier user-tests in papers 4 and 7 were formative since user feedback was helpful for improving the design concept. The user-test in paper 9 was summative; since its purpose was to evaluate and position the usability of the design concept.

Papers 1-2: The papers introduced initial design studies for exploring and understanding the issues of keyhole effects, and workload problems by cognition of large-scale processes. Initial design exploration as graphical objects for displays were proposed and explored in a small-scale. Some informal comparisons were done against traditional design approaches for a separator design. The papers looked briefly at the well-known guideline, NUREG-0700, in the nuclear domain, for possible consistency problems.

Paper 3: The IRD concept was explored through a full-scale installation, the 1st generation Loviisa LSD. This represented a research-oriented design for a clinical case, where the IRD graphics were implemented on a high-fidelity nuclear simulator. The method represented typically design exploration, where the project was introduced to new challenges and problems: focusing on adapting graphics for a larger scale; finding a suitable design process; and design requirements.

New knowledge was shared through a work group of expert control room operators and a reference work group. Design skills were also improved through the complex product.

Paper 4: This paper evaluated the IRD concept through the first user-test; the Loviisa LSD was compared to a traditional overview display. Running scenarios on a full-scale nuclear simulator collected realistic performance data. Qualitative data for further improvement of the design concept were collected through interviews with control room operators.

Paper 5: The paper summarized research results from design exploration, and studies on display designs for the nuclear domain from the Halden Reactor Project. The results were presented within the context of typical challenges: keyhole effects, navigation issues, visual patterns and teamwork transparency. The wide angled approach summarized findings from: Information-Rich Design (IRD); Task-based Displays; Ecological Interface Design; and Function-Oriented Displays.

Paper 6: Issues and improvement potential from the 1st generation Loviisa display were mitigated through a new 2nd generation (HAMBO) display. This represented a clinical case of research-oriented design, applying both design exploration, using studies from previous design and improving design skills (practice). This resulted in upgraded and new graphical objects; these results were further integrated and used for the general class LSDs, as applied research findings.

Paper 7: The paper first expanded the theoretical framework for LSDs by performing design studies; it referred to other relevant studies on display design and other work on information visualization. This discussion was carried out in the context of Situation Awareness for complex processes. The second part of the paper evaluated the 2nd generation HAMBO display through the second user-test of the IRD concept. The paper´s research findings were summarized, and further proposed as design principles for LSD design. Possible problems for real-world installations were briefly looked at, by examining guidelines in the nuclear domain NUREG-0700.

Paper 8: The paper further expanded the theoretical foundation for the IRD concept by design studies, looking at other scientific approaches for complex processes, and relevant findings on visualization and perception on displays from HCI research, and research on human limitations and capabilities. These research findings were explored and demonstrated by designing the 3rd generation Halden Reactor LSD, a real-world control room installation. The paper´s research findings were summarized through design principles for the general class of LSD designs.

Paper 9: The paper´s research questions were explored through the third user-test of the 3rd generation Halden Reactor Display. The summative character of this study was chosen to find the level of completeness of the IRD concept at this stage. Comparisons were drawn to usability data for the replaced panels and the older 2nd generation HAMBO display.

Paper 10: The paper´s research question on user-centred design was explored by examining industrial standard ISO-9241-210 (2010) for human-centered design.

4.3.2 The audience for the papers

The IRD concept was from the beginning intended for use in real-world installations. For this reason, many of the papers are submitted to audiences with interest of applied technology. Much of the work in this thesis was related to the nuclear applications, and for this reason submitted at conferences or journals with specific interest in nuclear technology.

Paper 1: A Conference paper presented in Norway at IFEA; a conference focusing on industry, automation and control room technology.

Papers 2, 3, 4 and **6:** These are conference papers published for the nuclear domain for a conference series with broad interest of nuclear technology in USA: Nuclear Plant Instrumentation, Control, And Human-Machine Interface Technologies (NPIC & HMIT). The Human Factors, Instrumentation and Controls Division of the American Nuclear Society sponsor the conference series.

Paper 5: A journal article for Nuclear Engineering and Technology; this is an international journal of the Korean Nuclear Society. The journal focuses on original research for the Nuclear Domain.

Paper 7: A journal article for Elsevier Displays. The journal focuses on general research and application of technology and visual information in displays. The journal is not focused at specific domains.

Paper 8: A conference paper for an international Conference on: Complexity; Cybernetics and Informing Science and Engineering (CCISE). CCISE is not domain specific, but intended for scholars and professionals with interest of interdisciplinary problems.

Paper 9: A journal article for the International Journal of Nuclear Safety and Simulation, the journal promotes nuclear safety and related technologies for symbiosis of nuclear power with human, society and the environment.

Paper 10: A monthly magazine for the nuclear industry published for a broad audience with interest for nuclear technology; the IRD article was invited for special issue on instrumentation and control.

4.4 Limitations

There are limitations to the research approach, most notably by lack of performance data, including measurement of Situation Awareness levels. Since the IRD concepts graphical objects are designed to work in the context of LSDs, performance data should preferably be collected from whole functional LSDs, and not from individual graphical objects behaviour. Paper 4 presented, however, some initial performance data, but this is not enough; such data from the more matured designs is also needed. This is particularly valuable for safety-concerned domains such as nuclear power plants where the acceptance for new designs is likely to increase if performance benefits can be documented.

Endsley, Bolté and Jones (2003) described Situation Awareness (SA); "*Basically SA is being aware of what is happening around you and* understanding *what that information means to you now and in the future".* This is in many ways the objective of LSDs, a display that helps operators in understanding the whole picture of a plants operational state. Paper 7 discussed LSDs theoretically in the context of SA, and paper 9 measured perceived awareness. However, without data showing that IRD really help in increasing SA levels for complex processes. The IRD concept would benefit from measured SA level data, comparing the concept to other display approaches.

5. DESIGN STUDIES FOR LARGE-SCREEN DISPLAY DESIGN

This chapter presents material for the IRD theoretical framework, for positioning the concept, and for determining its contribution. The first section focuses on human capabilities and characteristics followed by general information visualization principles. Next is Human-Computer Interaction (HCI) research followed by state-of-the art display and a LSD concept. The text is accompanied with illustrations; some are redrawn with reference to the original work.

5.1 Human capabilities and characteristics

Material in this section is partly based on material from research papers 1, 2, 7, and 8. This section outlines the theoretical background for LSD design with a focus on human capacity for information processing. The material is chosen for the research questions of this thesis, to support rapid visual perception of data, while avoiding keyhole effects. The material is used as a basis for IRD´s theoretical framework. The relevance of the material for LSD design is described at the end of each section.

5.1.1 Reducing visual complexity with Gestalt principles

Among key figures, which influenced Gestalt psychology early in the 20th century, were Koffka, Wertheimer and Köhler. A digest of their original work was given in Ellis (1997). Wertheimer (in Ellis 1997, p. 2) described how European science was influenced by traditional scientific approaches, meaning breaking up complexes into elements, and then solving the problem by reassembling the individual pieces again. He explained how Gestalt theory was different, that the whole is other than its parts: “*There are wholes, the behaviour of which is not determined by that of their individual elements, but where the part-processes are themselves determined by the intrinsic nature of the wholes.”* Their works on human perception, how the mind organizes visual data, lead to several well-known Gestalt principles such as: proximity, similarity, prägnanz, symmetry, good continuation, common fate and closure. Figure 8 visually explains some principles.

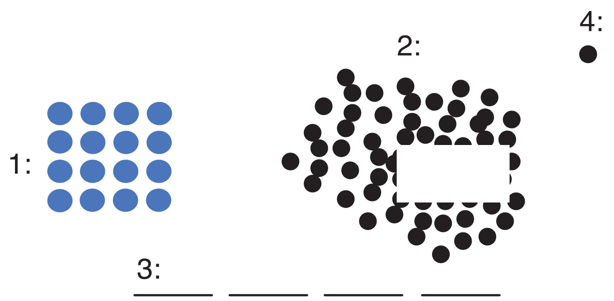


Fig. 8: Some Gestalt principles, the brain creates the simplest possible shape: 1:a square, 2: a square as whitespace, 3: a continuous line, 4: one dot is not grouped by proximity as other similar objects.

Gestalt principles have had great influence on psychology and human perception, among others are Arnheim (1974, pp. 4-5) and Gibson for Ecological psychology (1986, pp. 138-139), and through the embodied mind theory and use of basic level categories and metaphors as described by Lakoff and Johnson (1999, p. 28, 1980). More recently, Lidwell, Holden and Butler (2010) described how these principles could be used to reduce visual complexity, increase relatedness, and contribute to increased usability and better design. Tuck (2010) demonstrated how these principles were beneficial in web display design for computerized interfaces. Ware (2013, pp. 181-

197) suggested that Gestalt laws of pattern perception could be used for information display design.

Summarized, Gestalt principles are relevant for how to reduce visual complexity; they explain how to support rapid data perception. For this reason, this work is suitable for designing graphics for greater scaled displays. LSD graphics and layout should be designed for rapid perception, where data forms wholes rather than single elements to reduce complexity (closure), related data should be positioned for proximity perception, process data should be aligned for easy to spot deviations (good continuation) and related data should be grouped (similarity).

5.1.2 Ecological psychology: concepts for creating rapidly perceivable graphics

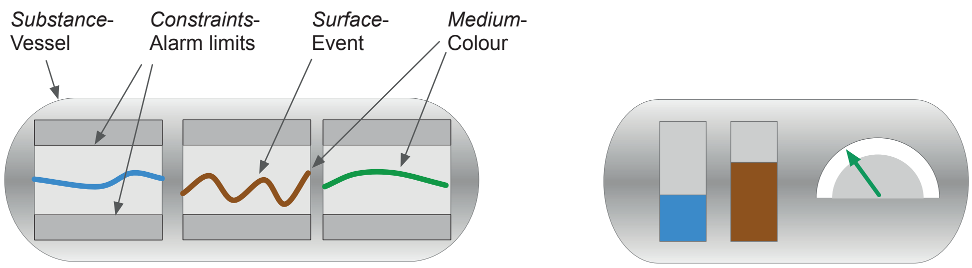
In the following section, concepts from Ecological psychology are presented in *Italics*. Gibson (1986) was one of the founders of Ecological psychology, and in this approach he saw humans and other animals from an organism-environment reciprocity perspective. Gibson described how the values and meaning of things in the physical environment are directly perceivable for humans and animals, contrary to a sensation-based perception triggered by stimuli, and approaches describing cognition through mental model processing. Gibson suggested terms for such instantaneous information perception: *information-pickup* (p. 238) and *direct perception*. This view on visual perception is of particular interest when looking into the possibility of having direct access to a large number of process variables through LSDs. It should be noted, however, that Gibson questioned *direct perception* of pictures (p. 10), (a display can be seen as a picture); he suggested that humans have a *direct perception* of the physical surface of a picture, but only indirect awareness of the virtual surfaces in pictures.

Smith (2009) described how the earlier Berlin School of Gestalt psychology, especially the work by Koffka and Lewin influenced Gibson. They sought to understand the relations between mental acts and external objects as participants in a larger complex of interactions between subjects and objects in a common physical and biological environment. Gibson later formalized this in Ecological psychology, where human and animal behaviour in the environment that surrounds us are complementary, to be considered a system. Gibson described how the world and it´s behavior gives immediate meaning for humans and other animals through: *substances*, *mediums*, *surfaces*, *events* and their *affordances*. Gibson (1986) suggested how *substance* (pp. 13, 23) is persistent to outer forces, and how bodies can move through *mediums* (p. 16), which are homogenous, without sharp transitions; examples are air and water. He described how *events* are changes in our environment as a result of shock or outer forces, shown as ripples on water, evaporation etc. (pp. 95). He suggested that *events* typically are observed on the *surfaces* that divide *substances* and *mediums*. *Affordances* (p. 127) were described as what the environment affords the animal or us, how the physical environment provides immediate actionable properties; examples are: walking on a floor, or sitting on a chair. *Constraints* describe their limitations. Gibson used the term *value-rich* for an environment providing several positive *affordances*.

The appropriate use of Gibson´s terms has been widely debated and discussed in the literature. One example was Stoffregen (2000). He argued that *events* in the environment might not be perceived. He suggested that only *affordances* are perceived. In a reply to this, Chemero (2003) argued that *affordances* are both real and perceivable, but not properties of either the environment or the animal. The term *affordance has* later been used also in man-made artifacts; Norman popularized its use in the well-known book, *The Psychology of Everyday Things,* republished as *The Design of Everyday Things* (2002). He later (2004) suggested using *perceived affordance* when applied to screen-based interfaces. Hartson (2003) extended this further for interaction design and evaluation, and proposed more specific use of the term through: *cognitive affordance,* *physical affordance, sensory affordance*, and *functional affordance*. Thompson et al. (2011, pp. 356-367) discussed *affordances* from a computer graphics perspective, looking particularly at theoretical views about whether actions are informed by different visual systems than perception, whether they can be separated, or whether they are grounded in an integrated embodied system. They suggested how direct actions might not make sense cognitively in screen-based displays. Inspired by Russian activity theory, Bærentsen and Trettvik (2002) revisited the use of *affordance* for human-machine interaction. They proposed that *affordances* in design not only necessitate exploring characteristics of the interface, but also how the user operates the system.

Ecological psychology as a theoretical framework has greatly influenced approaches to human-machine interface research for complex systems, the foremost of which is possibly Ecological Interface Design (EID) founded in the late 80s and early 90s (described detailed later in this chapter). Flach (in Flach et al., 1995, pp. 1-3) described how Gibson's theories about behavior influenced human-factors approach on *Ecology of Human-Machine systems*. Flach (pp. 8-10) described *affordances* as important in capturing the functional properties of the *environment* (system), and creating a display design that maps functional properties of the work domain through *direct perception*. Although Ecological psychology aimed to address human behaviour in the complex, multisensory, dynamic, physical world, and not for abstract LSDs, it offered several useful concepts when considering the process control operator as an integral, mutual, part of a complex process plant. Most notably, it enabled exploring *direct perception* of a complex domain. *Direct perception* suggested information presented in a manner appropriate for rapid visual perception, for *information pick-up*, rather than information processing mechanisms (mental models).

Summarized, Ecological psychology is interesting for creating rapidly perceivable graphics, presenting industrial-scale data sets in LSDs in a way that is directly perceivable. One way of doing this, as suggested in this thesis, is to use Ecological concepts as metaphors for graphics, creating graphics along principles in line with the concepts: *substances*, *mediums*, *surfaces*, *events* and *affordances*. Based on this, LSDs should be rich in *perceived affordances*, providing many clues to the complex process plant, enabling the operator to detect and see the big picture with enough detail to comprehend the whole situation. Dynamic process disturbances could be described through *events*, directly perceived through trended *surfaces* and their *constraints*. Physical vessels and structures in the process plant could be visualized as *substances*. Figure 9 visually explains how IRD graphics are inspired from Ecological psychology.



Direct perception of plant´s dynamic response-
as used in IRD Large-Screen Displays.

Only immediate description
of process value

Fig. 9: IRD on the left side: concepts from Ecological psychology used as metaphors for rapid perceivable graphics. On the right side: the design supports rapid perception of process data, but the graphic elements does not visualize the plant´s dynamic response.

5.1.3 The Skills-Rules-Knowledge model for cognitive information processing

The Skills Rules-Knowledge (SRK) model proposed by Rasmussen (1983) has been influential as a theoretical background for display design; it is closely related to the EID theoretical framework in assigning data efficiently in display design. The SRK model described cognitive capacity in relation to human behaviour in everyday situations. In display design, the model was used with an objective to not force cognitive control to a higher level than the task requires (Vicente and Rasmussen, 1992). They described typical information processing characteristics from this model:

- Skills based information processing: rapid, effortless using parallel capacity.
- Rule based information processing: a “normal” response to familiar recognizable situations. This required previous experience from familiar situations in an environment that has allowed us to learn to recognize complex patterns that can serve as cues. Rule based behaviour was described to have some parallel capacity.
- Knowledge based information processing: a complex process, integrating information from a wide variety of sources, and planning and executing a proper response. Mentally demanding and requiring full attention, the response is slow, error prone and has poor parallel capacity.

Others have also found inspiration from the SRK model; Hoff and Hauser (2008) revisited the SRK model for efficient display design for energy management systems. They supported the view from EID that efficient display design must support both Skills- and Rules based behaviour as well as Knowledge based reasoning.

Summarized, the SRK model is relevant for LSD design; it explains how displays should inform and support control room operators in a wide range of roles. This is qualitatively illustrated in Figure 10. The figure illustrates how the maximum information load threshold line shrinks in faster paced situations, and that LSD design must support lower level cognitive control in such situations, hence rapid perception of process data in stressful situations. This suggested how LSDs must support the plant´s different operational states: high accuracy numbers for self paced situations; and qualitative graphics for rapid visual perception in tighter paced situations.

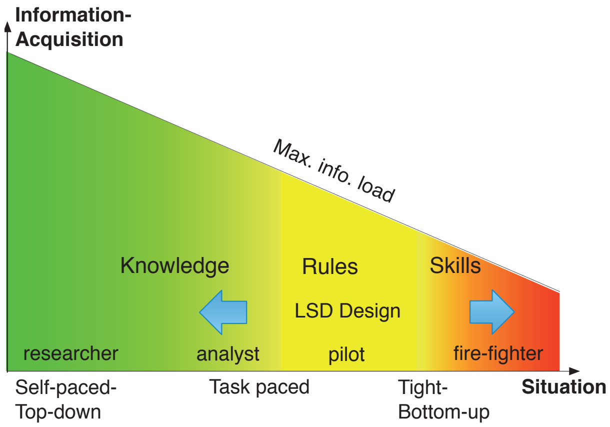


Fig. 10: The SRK-model (from paper 8) describing the control room operators’ roles. It is used as an inspiration for LSD design.

5.1.4 Metaphors and the Embodied Mind theory for rapid perception

Lakoff and Johnson (1999) did not see the human brain as computer software, manipulating meaningless symbols as input, manipulating them by rule for output in a computer-like process. Their view on human cognition was that it is largely unconscious and operating too quickly to be focused on, and that that our abstract concepts are largely metaphorical; also described in Lakoff and Johnson (1980). This is quite in line with direct perception as described by Gibson, and interesting from the view of designing LSDs. It supports the idea of rapid perception of process data. Lakoff and Johnson described the concept of information categorization as a process done by humans and animals in order to simplify the environment that surrounds us, where categorization was described as for the most an unconscious process, naturally evolved through our embodiment. The concept of categorization seems to be quite similar to nesting, described by Gibson (1986, p. 9).

They described further how people conceptualize categories into different concepts. Basic-level categories are where people optimally interact with their environment. Examples of basic-level categories are: air, water and floor. On the level above are the corresponding superordinate categories: medium, substance and surface. Lakoff and Johnson described how evolution has not required people to be as accurate on levels above (superordinate) or below the basic-level categories. It is interesting to note that Gibson used basic-level categories in his description of the natural environment that people directly perceive: seat in general (superordinate), or stool, bench (basic level). This suggests that using basic level categories for graphical objects in displays could be advantageous for rapid perception. Some typical software application icons represent basic-level categories: disc icon- save, printer icon- printing paper etc.

Hoff and Ødegård (2008) were inspired from Ecological psychology, and what they described as second-generation cognitive psychology from Lakoff and Johnson; they developed a new approach on human-machine interfaces, named Ecological Interaction Properties (EIP). They argued that this type of framework offered a description of the directness of a human-machine system. Norman (2004) maintained, however, a quite cautious use of metaphors for display design. In an essay on Affordances and Design, he stated: "*Metaphor is both useful and harmful. I personally believe that metaphors are more harmful than useful, but this is a different topic for a different day*."

Summarized; the embodied mind approach and metaphors are relevant for LSD graphics, for creating intuitive designs. IRD use concepts from Ecological psychology as metaphors for display graphics. Further, metaphors can be useful for making LSD intuitive (directedness). For this reason, LSD design should not be in conflict with common use of metaphors; graphics should follow expected conventions; more should be "up", less should be "down", "green" is safe, red is "alarm" etc. This is illustrated by an example of visualization of alarm priority in Figure 11.

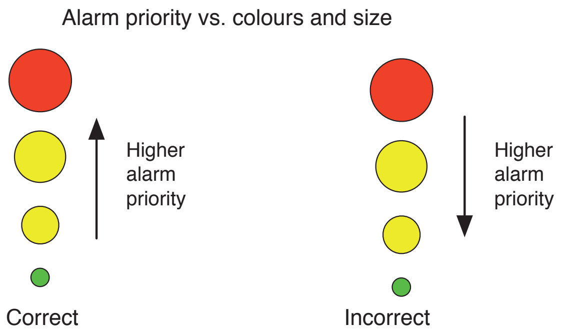


Fig. 11: Explaining the use of metaphors for alarm priority: intuitive use of metaphors on left side, incorrect on right side.

5.1.5 Situation Awareness: seeing the picture

Endsley (2013, p. 88) explained how Situation Awareness (SA) is a central concept for human decision-making in complex domains. She stated: "*Situation awareness can be thought of as an internalized mental model of the current state of the operator´s environment*." She suggested the following widely applicable SA definition (p. 89): "*the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future*." She suggested three SA levels (p. 89): perception of the elements in the environment (Level 1); comprehension of the current situation (Level 2); and projection of future status (Level 3). SA is a widely used concept in understanding complex processes; Durso et al. (2007) found problems with SA to be a factor in both aviation and industrial accidents. Reising and Bullemer (2008) used SA as motivation for developing overview displays for the hydrocarbon processing industry. Tharanathan et al. (2012) measured and compared SA levels for different overview displays.

Endsley et al. (2003, p. 21) described how limitations in working memory and parallel processing challenge building sufficient SA. They also explained how long time memory structures named schema and mental models play an important role in gaining high levels of SA. Further, how people must be able to quickly switch between goal-driven (top-down) and data-driven processing for building high SA levels. Endsley (2013) named several SA challenges (demons): attentional tunneling; requisite memory trap; workload and others stressors; data overload; misplaced salience; complexity creep; errant mental models and "out-of-the-loop" syndrome.

To summarize; SA is relevant for LSD design. It captures in many ways the purpose of larger displays: *"seeing the picture"*. Among SA´s concepts, the following topics are of particular interest for developing LSD graphics: being goal directed (display target data); avoiding the "out-of-the-loop" syndrome (inform of automation and alarm data); and predicting future status (visualizing rate-of-change cues). Endsley´s work confirmed further the importance of designing graphics for both top-down search, and bottom-up data driven processes, which were also suggested by Ware (2008, 2013) and Healy and Enns (2012). The SA challenge (demon) data overload is closely related to this thesis first research question: how to design for rapid perception of industrial-scale data sets? The SA challenges (demons) named attentional tunnelling and the requisite memory trap, are closely related to this thesis second research problem: how to avoid keyhole effects in complex processes? This is further discussed in chapter 7.3.

5.2 Information visualization principles

The material in the following section is partly from research papers 1, 2, 7, 8, and 9. This section focuses on rules-of-thumb for information visualization; the content is based on, and in some parts extends the work from the individual papers. It should be noted that most of the following work was not intended for computerized graphics. However, these well-known principles are relevant for LSD graphics since they offer general insights on how to organize and visualize information in accordance with human cognitive capacity.

5.2.1 High visibility, affordances, natural mapping and conceptual models

Norman is a prominent figure in cognitive engineering and user-centred system design. He proposed principles for system design (1986, pp. 59-61), stating: "*Do user-centered design: Start with the needs of the user".* By this approach, Norman focused on the purpose of the system, to serve the user, and not to apply or use a specific technology; this is in accordance with the view of Endsley et al. (2003). Norman´s *The Design of Everyday Things* (2002), looked at how and why products and man-machine interfaces satisfied customers, while other products were frustrating. He introduced important concepts for design. Among others, the following are interesting from the point of making intuitive LSD design in line with human capacity (2002, pp. 4-5, 9-10, 12-13, 55):

- He described how good design must afford a high degree of visibility, how correct parts must be visible and convey a correct signal or message to the user. He suggested that these signals must offer a natural mapping to actions, without the need for conscious operations. Norman used the term, natural design for this.
- He suggested that the actual and perceived properties of things must be clearly presented, using the term affordances. He described how the user instantaneously knows what to do if the design takes advantage of affordances. If used wrongly; they might lead to false causality. As described earlier in this chapter, Norman thought later (2004) that designers have misused affordance for display design, suggesting instead the term perceived affordance for this.
- He described how people form a conceptual model of how devices operate and work from their visible structure, further how clues can come from affordances, constraints and mappings. Norman suggested that products should provide a good conceptual model of how they work, and an intuitive prediction of the effect of actions.
- Norman described how much of the information that people need, can be presented as externalized available knowledge (in the world). The opposite is described as memory-challenging knowledge (in the head). He explained how great precision often is not required for correct behaviour.

Norman (2011) has worked more recently on how to cope with complexity through good design. His view was that the real world and how it works is complex, and tools must match this complexity, however, that they can be made understandable. He extended on his earlier work and described the following for coping with complexity through design. Design should take advantage of clear use of signifiers, and to avoid external complexity, it can be hidden inside as internal complexity, referring to Tesler´s law: complexity is constant (2011, t: 26 min). Further how to take advantage of good conceptual models (2011, t: 43 min) and avoiding isolated devices. He suggested using a systems approach for complex products (2011, t: 44 min).

Norman (2011) explained how there is a "sweet spot" in acceptance of complexity; too simple, and it is perceived as uninteresting, boring and dull. Too complex, and products are perceived as confusing and frustrating. He described the sweet spot as movable; as you move from novice to expert, the acceptance for complexity increases. This is visually explained in Figure 12. Endsley (2013, p. 96) described also how novices have problems in building sufficient levels of Situation Awareness, she stated: *"They will be severely hampered in their efforts by both limited attention and limited working memory."*

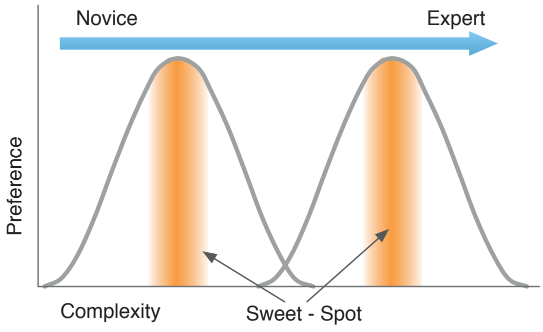


Fig. 12: Acceptance for complexity in product design, adapted from Norman (2011, t: 21 min), redrawn by the author.

For the purpose of designing LSDs, Norman´s approach of starting with the user rather than technology is relevant; this is in line with Endsley´s approach on user-centred design. This pointed to several issues: using graphics for externalized available knowledge (in the world) rather than internal (in the head) for avoiding keyhole effects. Further, using a system approach through integration of functionality rather than separation into many standalone display elements for reducing visual complexity. High visibility and natural mapping points to the necessity of highlighting dynamic and safety related data, presenting them in an easy understandable context.

5.2.2 High data-ink ratio, information layering and sparklines

Tufte is a well-known and prominent figure in information visualization; although his work is not developed for use on complex process plants, the work is relevant for visualization of complex data sets. Most of his work is for printed-paper, some recent work is, however, developed for information visualization on displays. One of Tufte´s (2001, pp. 91-105) principles was a focus on using a high data-ink ratio (data-ink divided to total ink used to print the graphics). He suggested further how ornaments and redundant ink often could be removed from information presentations, using clever design instead, were the real data itself provides context. He stated (p. 91): "*Data graphics should draw the viewer´s attention to the sense and substance of data, not to something else"*. Tufte (2001, p. 174) demonstrated also how larger data sets could be made easily perceivable through alignment and grouping. He referred to the work by masters Newton and da Vinci describing how they integrated text and figures (2001, pp. 180-182). Tufte advocated the necessity to avoid fragmented visualizations, and instead integrate words, numbers and pictures naturally in information visualization.

Tufte (1990, pp. 53-65) wrote: "*Confusion and clutter are failures of design, not attributes of information"*, describing how display elements can create unfortunate 1 + 1 = 3 effects. He suggested instead how careful use of colour layering and lines help focus on the real data. This is visually explained in Figure 13.

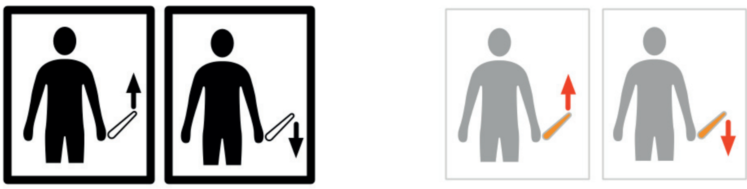


Fig. 13: Clutter and 1+1=3 effects in left figures, colour layering and separation in right figure. Based on Tufte (1990, p. 63), redrawn by the author.

Tufte (2006, p. 47) proposed the use of small trends in computer graphics, which he named "sparklines". These graphics included number, text and a small trend with a normal operating range. It offered high-density graphics, and visual comparisons of data sets. This is visually explained in Figure 14.

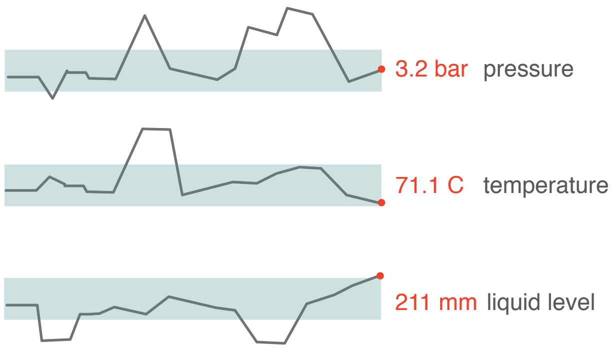


Fig. 14: Three sparklines, based on Tufte (2006, p. 47), redrawn and modified by the author.

Gillan and Sorensen (2009) applied Tufte´s concepts of high data-ink ratio in computer displays, examining the effect of graph backgrounds on visual search. Their empirical results suggested that indicators and backgrounds should be given distinct different visual features. Van Laar (2001) suggested using colour layering in computer graphics. Van Laar and Deshe (2001) demonstrated faster search times with these displays than with monochrome or non-layered colour displays.

Summarized for LSD graphics; follow Tufte´s rule-of-thumb principles: use a high data-ink ratio; use colour layering focusing on dynamic data; trended graphic is suitable.

5.3 Human-Computer Interaction research

Material for the following section is partly based on research papers 7 and 8. The following section provides material for rapid visual perception for computer graphics; however, the work was not specifically developed for LSD applications. The following work is mostly based on the following publications: Ware (2013): *Information Visualization Perception For Design*; Ware (2008): *Visual Thinking for Design;* and Healey and Enns (2012): *Attention and Visual Memory in Visualization and Computer Graphics*. In addition to their own work, Ware´s, and Healey´s and Enns´s publications are based on other research, among which are: Gibson (1986) for perception; Treisman (1991); Treisman and Gormican (1988) on low level features and preattentive processing; Quinland and Humphreys (1987) and Duncan and Humphreys (1989) on search speed and masking problems; and Wolfe (1994) on attention guided search as bottom-up and top-down processes.

5.3.1 Affordances and direct perception revisited

Ware (2013, pp. 7-9) discussed the question of pictorial representations. He referred to several studies which showed that lifelike pictorial representations could offer direct meaning to untrained children and users from remote areas in the world, suggesting that well presented, artificial graphics can take advantage of human cognitive abilities for rapid intuitive perception of data. This is not necessarily the same as Gibson´s concept of direct perception of our natural environment. To the contrary, Ware (2013, pp. 17-20) described how Gibson´s directly perceivable *affordances* posed challenges for use in computer graphics, which presents data indirectly, affording no physical actionable properties. He (2013, p. 20) explained how Gibson´s theories more loosely construed could be used as a foundation for display design, borrowing power for our ability to see pictures and physical environments as inspiration for computer graphics, also referring to the influential earlier work by Norman (*The Psychology of Everyday Things)*.

Ware´s guidelines for design are based on the assumption of models of perceptual mechanisms (2013, p. 19). These are based on many years of experiments describing mechanisms for colour perception, how we build patterns, working memory etc. Gibson and later work by Lakoff and Johnson, however, rejected such reductionist approaches, where humans and other animals were divided into separate systems (models). To the contrary, instead of looking at the individual mechanisms, they described how people and other animals perceive the world directly through the whole embodied system.

The author finds direct perception as described by the embodied mind approach and by Gibson relevant for the purpose of creating rapid perception graphics. It is, however, reasonable to also include findings from modern HCI research, even if they base their findings on models for cognitive processing mechanisms. Furthermore, accordingly to Ware, it is interesting to also "loosely" use Gibson´s concepts. In this thesis they are used as metaphors for easy perceivable LSD graphics through: *substances*, *mediums*, *surfaces*, *events* and *affordances*.

5.3.2 Limited visual memory

Healey and Enns (2012) asked the following question: "*What do we remember about an object or a scene when we stop attending to it and look at something else?"* Referring to studies in psychophysics, they explained how people do not construct and remember high-resolution images; they described how our visual system does not resemble that of photography. Instead, they suggested that vision is constructed from a dynamic cycle, which builds: "*short-lived models of the external world that are specifically designed for the current visually guided task of the viewer"*. Ware (2008, p. 11) explained how we have a small capacity of visual working memory, and how a low capacity in our conscious awareness is compensated through unconscious rapid visual mechanisms. From this, he suggested how limited visual memory is a challenge, and must be taken into consideration. Healey and Enns referred further to several studies suggesting that the viewer´s current state of mind plays an important role in what can be detected in a given moment (expectation, attention guiding, prediction). They explained how designing efficient visualizations must consider this, taking into consideration how we think, remember and expect.

In summary, this has implications for LSD design. Design should avoid problems related to limited visual memory; instead enabling visual processing mechanisms, directing visual attention in a proper way. Figure 15 visually explains this; the left side has all the information in one display, making it suitable for visual perception. The right side has the same information in a display hierarchy, which puts excessive load on visual memory.

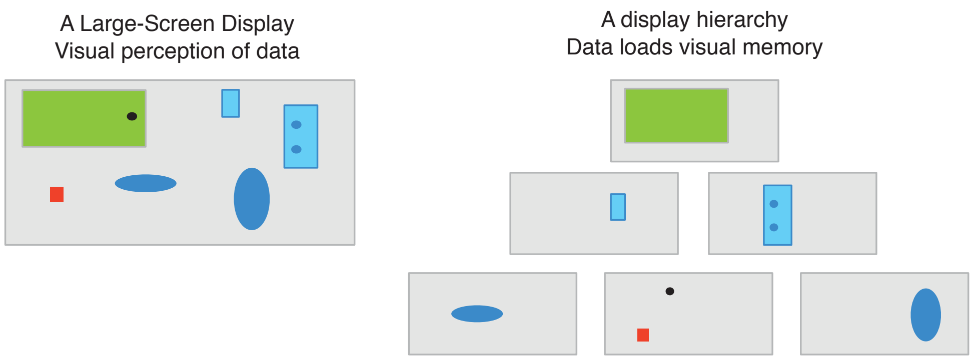


Fig. 15: Right side: a display hierarchy puts excessive load on limited visual memory resources.

5.3.3 Rapid preattentive processing, active vision

Healey and Enns and Ware described how a rapid unconscious visual perception process compensates for limited conscious visual working memory. Ware (2008, p. 2) described how this process is misleading us to think: "*we think we have all of it at once in our conscious experience*". Ware (p. 3) used the term visual thinking of this perception process that guides attention, tuning our pattern-finding circuits and eye movements. Healey and Enns used the term preattentive processing to refer to how human vision rapidly and automatically categorize visual images.

Both Ware (2008, pp. 8-9) and Healey and Enns described how seeing is done through a dynamic fixation-saccade cycle, where only a limited number of visual features can be detected within a single glance in a saccade cycle. Both Ware, and Healy and Enns describe this act of perception through bottom-up information collection from each fixation, and how our mental state guides in top-down search for information. Figure 16 illustrates how a person scans the display through a trajectory (line), having a limited focus area from our perceptual apparatus, and only memorizing a limited number of graphical objects in conscious visual memory.

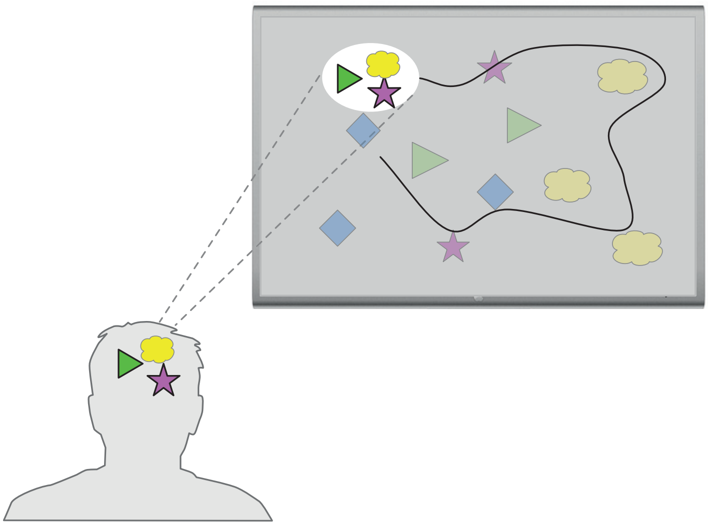


Fig. 16: The dynamic visual perception process: fast scanning through a saccade cycle (line), fixating only at a small area, the brain has limited visual memory resources.

Ware (2008, p. 11, preface) explained how the limited capacity of visual working memory has implications for human behaviour, that it is better to redo cognitive operations than to remember them. He explained how computer graphics could be seen as cognitive tools, as an extension of our brains, using the term "active vision" for this.

It is reasonable to approach LSD graphics based on the following: supporting fast visual scan strategies through alignment and functional grouping of data; arranging graphics for use as extension and support for limited visual memory.

5.3.4 Top-down search, bottom-up features, masking problems and change blindness

Referring to the earlier work of Gestalt psychology, and other studies, Ware (2008, p.10) explained how certain features trigger rapid preattentive processing. He described the strongest visual pop-out triggers or features to be: color, orientation, size and motion (omitting depth here). He suggested as a rule-of-thumb that the most important, and common queries in displays should be given the most weight: “*if all the world is grey, a patch of vivid color pops out”* (2008, p. 74).

Ware (p. 37) described how motion in particular creates strong pop-out responses, however, that extensive use of blinking and other high-frequency motion in displays is problematic, creating visual noise. Figure 17 illustrates some basic pop-out features; a more extensive presentation is given both by Healey and Enns (2012), and on Healey´s webpage (2014).

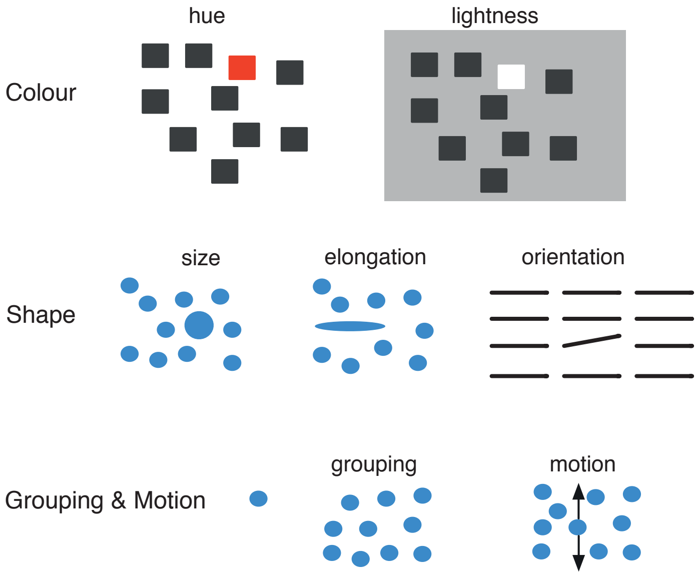


Fig. 17: Features that triggers primitive basic pop-out channels, inspired from Ware (2008, p. 41), redrawn by the author.

Healey and Enns described how display design should take advantage of our built-in apparatus for pattern finding mechanisms, using perceptual salience for direction attention in computer graphics. They described how: ”*Feature hierarchies suggest the most important data attributes should be displayed with the most salient visual features, to avoid situations where secondary data values mask the information the viewer want to see”*. The problems of unfortunate masking from secondary data can be minimized by reserving strong visual pop-out effects for a few objects, being the only object in a display that triggers a particular feature channel, or making symbols maximally distinctive, Ware (2013, pp. 157, 159).

Foreground signal colours and information can also be masked by the background colour. Some masking effects are visually explained in Figure 18.

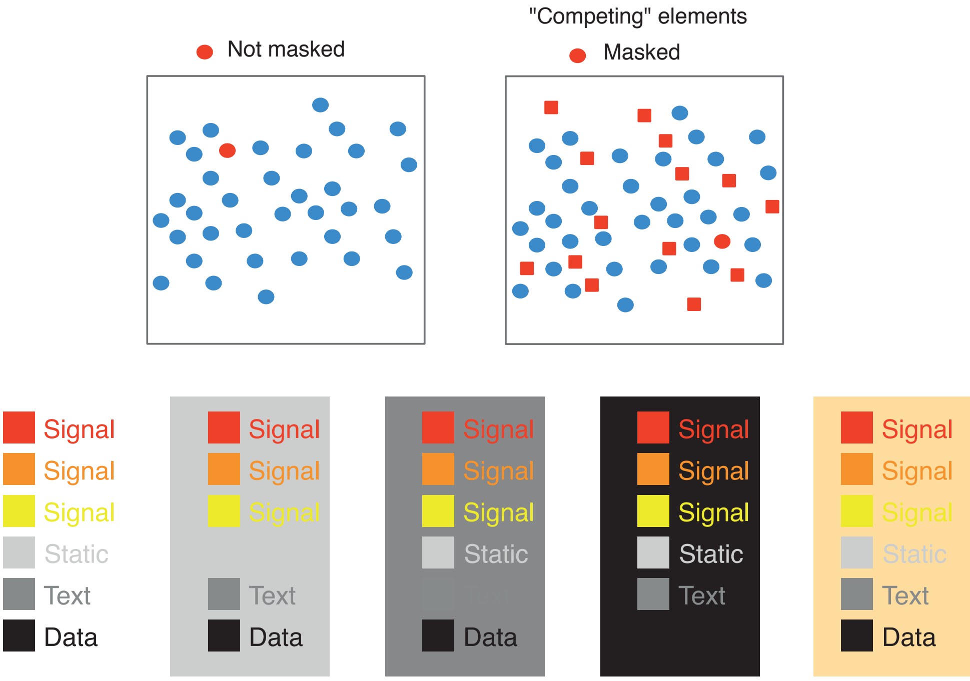


Fig. 18: Top figures: masking effect on right side from visually "competing" elements. Bottom figures: the background colour can mask the foreground information and signals (inspiration from ASM Consortium Guidelines, 2013, p. 93).

Attention and bias is closely linked to top-down search; see Ware (2008, pp. 12-13). Referring to research studies, he suggested this as a process of tuning feature receptors, so that the goal (target) sends stronger signals than other features. Healey and Enns suggested particularly how larger format displays could make change blindness (being unaware of changes) worse than for smaller displays, since users on such displays are encouraged to look around for information. Ware (2008, p. 40) suggested visualizing large and small-scale structures to support efficient visual top-down search. He described further how a relationship between concepts could be established through: proximity grouping; enclosing contour; common colour region; alignment and lines and connectors (p. 58).

Summarized; the research suggests how LSDs should support top-down search through Ware´s suggestions, and bottom-up driven processes through feature hierarchies. Endsley (2013) described also importance of supporting top-down search and bottom-up processes; she found it important for building sufficient SA levels. Further, LSD graphics should avoid masking primary data from "competing" elements and background, a greater problem in LSDs measuring meters than in desktop displays measuring inches.

5.4 State-of-the-art display concepts

Material for this section is partly from research papers 7 and 8. This section looks at display concepts for complex processes regarded as state-of-the-art; these are used as inspiration for graphics and design principles, and for later in the position and determination of IRD´s research contribution. The section presents first research-oriented design concepts inspired from Ecological psychology, next is the Parallel Coordinates concept which excels in data density, and the Function-Oriented Design (FOD) concept, which reduces complexity through a display hierarchy. Then there follows a typical modern industrial approach. Unfortunately, there are not many research-oriented LSD concepts designed for industrial use, but a typical representation of a modern advanced LSD design is presented at the end of the section.

5.4.1 Concepts inspired from Ecological psychology

Vicente and Rasmussen (1992) founded Ecological Interface Design (EID) in the late 1980´s and beginning of the 1990´s. Vicente and Rasmussen (1990) positioned the concept as a cognitive engineering approach on interface design for complex processes, drawing parallels between cognitive engineering and Ecological theory. They focused particularly on the operator-system analysis, how a multi level work domain analysis of the complex system was beneficial in describing the fundamentals (*constraints*) of the complex process (*environment*), not forcing users to operate at a higher level of cognitive control than the task required (SRK-model).

Vicente and Rasmussen (1990) suggested that the human-machine design problem was quite similar to the structure of organism environment reciprocity studied in Ecological psychology. Vicente (In Flach et al. 1995) described how the EID abstraction hierarchy can be seen as the nested set of *affordances* in a work environment, and how traditional task analysis approaches were not able to capture the *richness* of behavior in complex systems. Vicente and Rasmussen (1990) referred to Gibson´s direct perception, stating: "*the designer should use computer technology to make the previously identified affordances available to the organism in a form that "vision is ready to pick up""*. Vicente and Rasmussen (1990) described how the Ecological concept *constraints* were exploited through the means-ends hierarchy, dividing them into several classes: global constraints for which the system was designed for, and local constraints representing boundary conditions for instrumented process variables. From this, it is clear how EID´s relation to Ecological psychology was a quite abstract concept for display design.

Through this theoretical framework for display design for complex processes, Vicente and Rasmussen (1992) described how EID created a robust system coping with familiar, unfamiliar and in particular, unanticipated events. They criticized traditional approaches using Single-Sensor-Single-Indicator (SSSI), and stated that such approaches had major drawbacks to controllability. Burns and Hajdukiewicz (2004, pp. 47-84) suggested several easy perceivable qualitative indicators for use in EID, such as dials, bars, trends and charts. Jamieson (2007) found encouraging empirical results for an Ecological interface for petrochemical process control. It demonstrated better performance than a more traditional familiar display type using experienced operators. Lau et al. (2008) applied EID to a full-scale nuclear simulator, and the empirical results suggested that EID displays supported operators better than other displays for monitoring unanticipated events. However, the EID design did not support operator performance differently for other types of tasks.

Hoff and Hauser (2008) presented an approach to improve display interfaces of grid control in energy management systems. They argued that traditional display approaches were not tuned to our natural Ecological perceptual system. They suggested an approach that supports rapid information pick-up in line with Ecological psychology and Rasmussen´s SRK model. They offered some display examples of easy to perceive analogue diagrams. It should be noted that these design approaches (the EID and the one from Hoff and Hauser) were not LSD design concepts.

Summarized for LSD design, research-oriented display concepts inspired from Ecological psychology were not designed for LSDs. They show, however, that Ecological psychology is a relevant foundation for rapid perception graphics, in accordance with human perception capacity. Although no unified indicators are developed for this type of graphic, most concepts use variants of analogue indicators.

5.4.2 The Parallel Coordinates concept

The Parallel Coordinates concept is typically used to visualize large-scale data sets in one single display, it transforms the information space into a two dimensional visual pattern. Lines are drawn as patterns of values for variables at different instances of time, where deviation from normal plant modes can be spotted as lines falling outside earlier clusters of lines. The concept particularly excels in high-density graphics for displays. The Parallel Coordinates concept was not LSD design concept.

Inselberg (1985) popularized the concept; a later paper by Wegman (1990) initiated computerized applications of parallel coordinates. The concept is used in industrial applications in several domains, also for complex process industry as demonstrated by Brooks et al. (2004). One example from a display is shown in Figure 19.

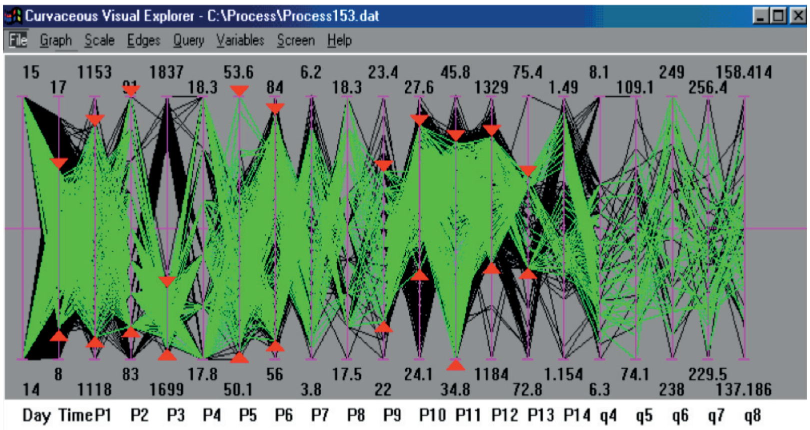


Figure 19: Example of the Parallel Coordinates concept, data from PPCL software. Permission and figure by R. Brooks (pers. communication 2012).

Each vertical axis in Figure 19 relates to one process variable´s measuring scale. For each instance of time, a line (green) is drawn through each process variables value range creating a continuous polyline. The red triangles are upper and lower constraints (alarm limits). The concept is particularly well suited for tuning in alarm limits (red triangles) to the process plant´s operating conditions, and it is for this reason more oriented toward process optimization than process monitoring.

Brooks et al. (2012) described how alarms are the first line of defense in large processes, and how the use of parallel coordinates can contribute in describing a well-defined operating envelope. Comfort et al. (2011) performed a case study determining the effectiveness of parallel coordinates for supporting operators in mitigating hazard events through historical process data. They found the concept excellent for general explorative data analysis.

Summarized; the Parallel Coordinates concept suggests how creating a simple visual pattern of process variables and alarm limits is beneficial in perceiving larger scale data sets.

5.4.3 The Function-Oriented Design concept

Thew Function-Oriented Design (FOD) concept originated from the work by Pirus (2002) and his colleagues at Electricité de France. It was an innovative approach to human-system interfaces, intended for use in large complex nuclear systems on a display system named FITNESS, it should be noted that this approach was not developed for LSDs. Pirus described the objective of FOD as to: "*control the complexity of the plants and their operation by introducing structuring elements"*. FOD reduced plant complexity by applying a hierarchical display structure as illustrated in Figure 20. Each layer in the display structure described the status of lower layer functions through easily perceivable signals. By this, each layer was visually quite simple and easy to perceive.

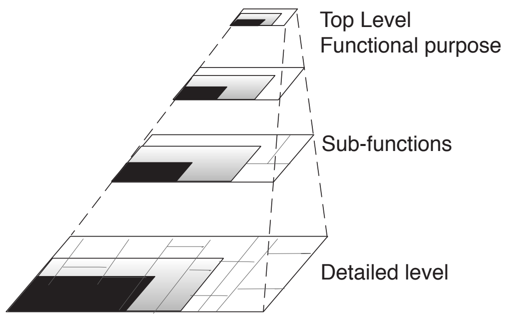


Figure 20: FOD reduces visual complexity through a display hierarchy, based on Pirus (2002), redrawn by the author.

Andresen (in Skjerve and Bye, 2011) described how status/alarm information could be accessed in terms of its impact at the highest and lowest plant levels and by this could help operators to prioritize in complex situations. This was described to mitigate keyhole related problems. Andresen et al. (2005) tested the FOD concept on a full-scale nuclear simulator; it was given positive feedback by the test subjects on process-overview, disturbances, and alarm visualization. On the negative side, there was an extensive need for button pushing and navigation in the display hierarchy.

Summarized; the FOD concept is relevant for LSD design; it demonstrates a way to reduce visual complexity. However, the use of "deep" hierarchies can give extensive need for navigation and button pushing.

5.4.4 Industrial desktop display approaches

In an effort to provide guidance on desktop overview displays by the Abnormal Situation Management (ASM) Consortium for hydrocarbon processing industries, Reising and Bullemer (2008) suggested how direct perception indicators were suitable for overview at-a-glance in desktop overview display design. Through a discussion based on Situation Awareness (SA), they identified the following failure modes relevant for such overview displays: inaccurate mental models; cognitive tunnel vision; and data overload. Following this, they proposed a practice oriented design process, suitable display objects and a suitable graphics layout. They suggested how process data could be displayed through several generic qualitative indicators, combining dials, and vertical and horizontal bars.

Figure 21 shows some of the qualitative display shapes proposed for ASM Consortium overview displays, they are redrawn from an ASM Webinar series describing rationale and graphical design (Laberge and Bullemer, 2010):

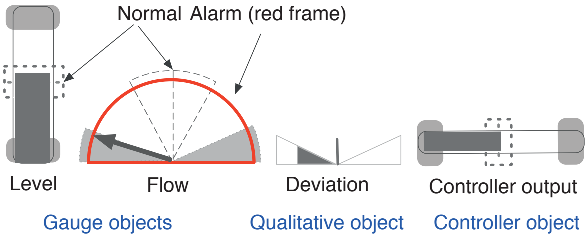


Fig. 21: Qualitative indicators for overview displays, based on Laberge and Bullemer (2010, Webinar), redrawn by the author.

Reising and Bullemer (2008) suggested how these indicators resembled some of the at-a-glance monitoring possibilities seen in the earlier analogue technology. They suggested the following for their functionality: “*eliminating the need to make mental comparisons an calculations*”.. Tharanathan et al. (2012) found an overview display based on the ASM Consortium design approach more effective in supporting SA than ordinary schematic displays with traditional data coding. The results suggested that a transition to a functional display organization was not overly problematic.

In an ASM sponsored paper, Bullemer et al. (2011) discussed the advantage of new display technologies, which were not restricted by colour limitations as in the past. Considering: SA; alertness; eyestrain; and fatigue, they recommended using a grey background. Hollifield (2012) described how modern desktop displays for industrial complex processes can take advantage of both colour layering and qualitative indicators, sometimes referred to as direct-perception indicators. Traditional industrial vendors have for some time used such qualitative indicators and colour layering with grey backgrounds (see Figure 18 for background colours). A typical example of a modern desktop display by ABB is shown in Figure 22.

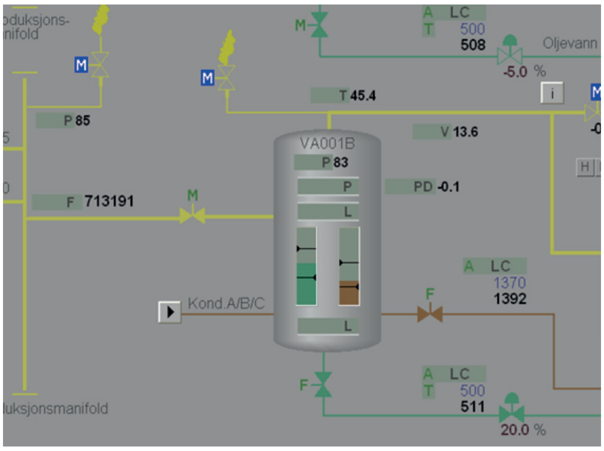


Fig. 22: A modern industrial desktop display approach by ABB 800xa: combining qualitative indicators (bars), digital numbers and colour layering on grey background, mimic style layout. Permission and figure by R. Hansen ABB (pers. communication 2012).

Industrial vendor approaches use a traditional schematic layout where process lines are used to connect process equipment; this is sometimes referred to as mimic style layout. Tharanathan et al. (2012) suggested using a more condensed functional layout, where display objects are organized on the basis of functional relations. One motivation for this approach is a stronger focus on dynamic data, and to reduce visual clutter.

Control room operators at Unger Surfactants (chemical industry) developed a desktop display approach, which focused particularly on alarm visualization, see Figure 23. A strong visual pop-out effect was developed for process alarms by using red filled dots for alarms. The visual effect was particularly strong since signal colours were reserved for alarms.

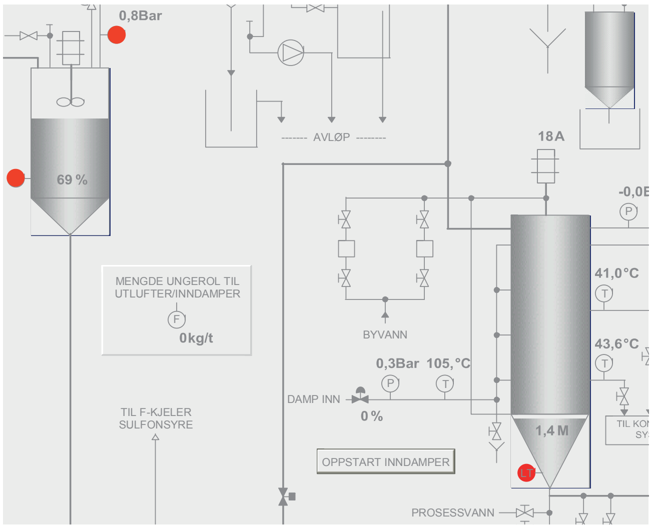


Fig. 23: An industrial desktop display approach developed by Unger Surfactants for use in chemical industry. Alarms (red dots) create strong visual pop-out effects. Masking effects are avoided by reserving the red signal colour for alarms. Permission and figure by Unger Surfactants (pers. communication 2014).

A more radical display approach is the HawkEye process automation interface developed by ABB Strategic R&D for Oil, Gas & Petrochemicals in Oslo. Husøy and Enkerud (2010) described how cumbersome navigation issues from keyhole problems, were mitigated through a non-paged zoomable virtual surface. On the top level, the whole plant can be viewed. The level of detail increases as the user zooms through different levels, using vector graphics. HawkEye was designed for overview purposes and to support detailed views, it is not positioned as a LSD concept.

Summarized, although these industry approaches were meant for smaller displays, they suggest that colour layering is suitable for display design using a muted grey background, and to reserve signal colours for alarms. Filled objects give particular strong visual pop-out effects. Further, they show how qualitative direct-perception indicators are suitable for rapid perception of plant´s process characteristics. The Hawkeye approach demonstrates a way to reduce visual clutter, however, with the downside of challenging visual memory (missing the larger picture) when zooming in on details.

5.4.5 A modern Large-Screen Display design

The Norwegian Institute for Energy Technology (IFE) in Halden has developed several LSDs for research purposes. Berg et al. (in Skjerve & Bye, 2011) described a typical representative of a modern LSD approach. The LSD was implemented and used for monitoring purposes of a full-scale nuclear reactor simulator. It used flow-lines to connect process equipment, which is typical of mimic-style layouts. It used colour layering with a muted beige coloured background. The LSD used both digital numbers, and more advanced features such as small trends, and integrated bar graphs to represent process values, see Figure 24. The LSD was found particularly useful when used as an integral part of a larger alarm system (Kaarstad, 2004).

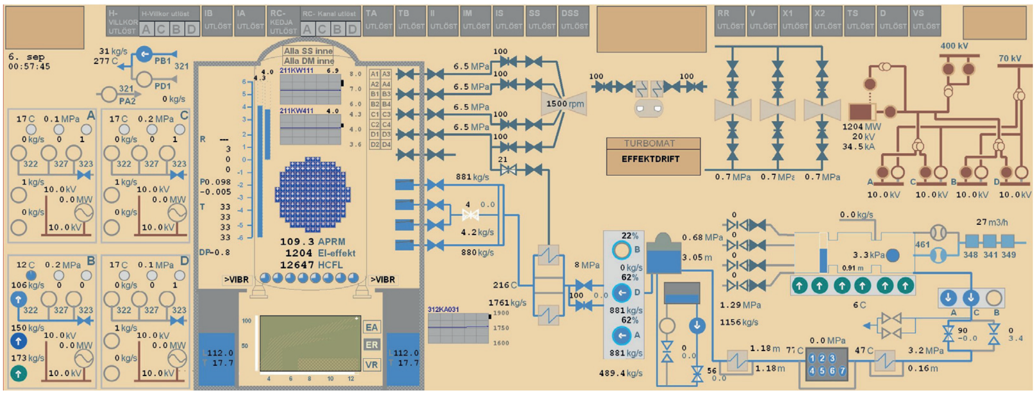


Fig. 24: A typical modern LSD approach, 4 x 1.5 m from IFE Halden: a traditional schematic layout; colour layering; digital values and qualitative indicators. Description and figure by Berg et al. (in Skjerve and Bye (eds. 2011, p. 162).

To summarize; the LSD design demonstrated the usefulness of colour layering with a muted background, however, the use of a beige background could mask yellow or red alarms. The LSD showed the usefulness of analogue rapid perception graphics. Unlike the Hawkeye or FOD display approaches, which used zooming or display hierarchies, the LSD was designed for process monitoring, while details were left for desktop workstations. This showed that it is reasonable to use the LSD as a stable frame of reference, which can provide the big picture. The LSD does not create simpler visual patterns of process variables and alarm limits for rapid-perception like the Parallel Coordinates concept.

6. RESULTS FOR LARGE-SCREEN DISPLAY DESIGN

This chapter outlines the thesis research contribution: graphics and design principles for LSD design. The chapter is organized as follows: first a section summarizing the design rationale, then a presentation of the main outcome followed by each paper´s contribution. Section 6.1 is new, 6.2, 6,3 and 6,4 are based on papers 7, 8, 9 and 10. Each paper´s (1-10) contribution to LSD design is presented chronologically in chapter 6.5. Note that graphical objects are for illustrative purposes and are not reproductions of registered design patents.

6.1 Summary of design rationale

This section summarizes the rationale for the thesis contribution. This summary is based on the research process, which was explained in Figures 4, 5 and 7; a few key references are cited in the following section.

Human capabilities and limitations (basic research):

Ecological psychology, Gestalt psychology and the SRK-model are the basic theoretical frameworks underlying IRD. Gestalt principles are applied to reduce visual complexity, and to explain how to arrange graphics for rapid visual perception. Thus, LSD graphics and layout form wholes rather than single elements for reduced visual complexity (closure), and related data are positioned for proximity perception; process values and alarm limits are aligned for easy-to-spot deviations (good continuation). This is the basis for applying part-wise mathematical normalized graphics in IRD, where process values and alarm limits create simpler low-level visual patterns.

Concepts from Ecological psychology (Gibson, 1986) are used as metaphors for rapid visual perception of dynamic process data. Based on this approach, IRD is rich in *perceived affordances*, providing many clues to the plant´s data space (process data, target values, automation data, rate-of-change cues, alarm information), enabling the operator to perceive the big picture with enough detail to comprehend the whole situation. Further, dynamic process disturbances are described through *events*, which are directly perceived through trended *surfaces* within their *constraints* (alarm limits). Physical vessels and structures in the process plant are visualized as *substances*; which are used as a familiar context for process data.

IRD´s scope is from Rasmussen´s Skills-Rules-Knowledge model (Rasmussen, 1983): to inform and support control room operators in a wide range of roles, even in faster paced situations. From this, LSD design is based on supporting lower level cognitive control through qualitative graphics for rapid visual perception. High accuracy perception of data for slower paced situations can be achieved through digital numbers.

Metaphors and the embodied mind approach (Lakoff and Johnson, 1999) have less influence on IRD. However, metaphors are useful for making LSD intuitive (directedness). From this, IRD graphics follow expected conventions: more should be up; less should be down; green is safe; red is alarm etc. Endsley´s (2013) work on Situation Awareness (SA), is used for: displaying goals (target data, goal centred); avoiding the out-of-the-loop syndrome on automated systems by explicitly visualizing automation and alarm data; and predicting future status by visualizing a rate-of-change cue.

Information visualization principles (applied research, rules-of-thumb):

IRD applies Norman´s (2002, 1986) and Endsley et al. (2003) approach of starting with the user rather than technology in user-centred design. From this, using graphics for externalized awareness in the world rather than in the head (keyhole). Further, IRD applies a system approach through integration of related process information rather than separation into many standalone display elements for reduced visual complexity, and reducing the need for operators to mentally construct a situation overview. Inspired by high visibility and natural mapping, IRD highlights dynamic and safety related data, presenting them in an easily understandable context of physical structures. IRD applies Tufte´s (1990, 2001, 2006) principles, through a high data-ink ratio; colour layering; and a focus on dynamic data and trended graphics.

Human Computer Interaction research (applied research, for display design in general):

Ware (2008, 2013), Healey and Enns (2012) contributed with the rationale for designing graphics for rapid visual scanning strategies rather than challenging limited visual memory. According to this, IRD supports efficient top-down search for information, and bottom-up data driven processes (also described by Endsley, 2013).

Display approaches (applied research, for process displays):

Research oriented designs (chapter 5.4) inspired from Ecological psychology, the Parallel Coordinates concept, the ASM Consortium concept and industry-applied designs explained how qualitative direct perception indicators are suitable for displaying process data. Further, that colour layering and a muted grey background colour are suitable, reserving signal colours for alarms. The Function-Oriented Design concept showed however how deep hierarchies can give extensive need for navigation and button pushing. The typical modern LSD approach in Figure 24 was designed from a systems perspective, leaving details for desktop workstation. This suggests that LSDs can act as a stable frame of reference for process monitoring.

IRD design exploration and practice (clinical research, for LSDs):

Research and industrial practice shows that pattern recognition of IRD mathematical normalized graphics is understood, and has promising initial performance; the same applies for user feedback for the dynamic alarm-spot. The trended indicator is better than other IRD indicators; particularly for visualizing plant´s dynamic response in a natural way. Equally sized filled objects are better than frames for strong visual pop out. The grey colour-layering concept is, however, problematic, resulting in poor readability in well-lit control rooms using video projectors. Commercial applications showed that simpler graphics work better than complex, and, how IRD graphics are implementable and usable in industrial systems in several domains.

6.2 Contribution: Design Principles for Large-Screen Displays

The following list outlines IRD principles for LSDs; concepts from Ecological psychology are presented in *Italics*:

- Design for keyhole problems and limited visual memory resources through a flat externalized LSD layout rather than display hierarchy. Make graphics rich in *perceived affordances*. Avoid the out-of-the-loop syndrome on automated systems, by explicitly visualizing automation data, rate-of-change cues, target values and alarm information.

- Design for rapid visual perception; create visual patterns from process values and alarm limits. Qualitative indicators based on part-wise mathematical normalization is suitable. Reduce masking problems by limiting the number of different types of display objects. Design graphics for rapid *information pick-up*, using concepts from Ecological psychology as metaphors for design: through *substances*, *mediums*, and *surfaces*, as well as their *constraints*.

- Visualize a plant´s dynamic response through qualitative trended indicators; focus on visualizing dynamic data through high data-ink ratio.
- Support top-down search awareness through lines, multi-scaled structuring elements, grouping, and open space.
- Support bottom-up data-driven awareness; data should be given lower level visual pop-out effects through a visual feature hierarchy, providing cognitive support through rapid eye movements achieved through graphics orientation, colour, size, and motion. Equally sized filled objects are better than frames for alarm pop out. Use a neutral background (such as grey) to facilitate pop-out effects, with the caveat that grey-scale graphics can cause readability problems in well-lit rooms using front-projected technology. Highlight new alarms through a gentle animation rather than flashing or blinking.

6.3 Design Principles: re-organized for practical design

The following section reformulates the design principles for use in practical LSD design. A small section “design process” is added, briefly explaining how to approach LSD design from a user-centred perspective:

Graphic components:

- Display graphics should be rich in *perceived affordances*, visualizing *substances*, *mediums*, *surfaces*, as well as their *constraints*, focusing on high data-ink ratio and dynamic data.
- Use qualitative direct perception normalized indicators to display process data, such as: pressure; temperature; liquid level and flow. The trended indicator is best for displaying plants´ dynamic response. Integrate: target values; alarm information; rate-of-change cue; and inform of automated functions through explicit visualization of automation data.
- Data should be given lower level visual pop-out effects through a visual feature hierarchy, providing cognitive support through rapid eye movements, achieved through: graphics orientation; colour; size; and motion. Equally sized filled objects are better than frames for alarm visualization. A gentle animation is a preferred alternative to intrusive flashing or blinking in LSDs to highlight new alarms.

Components layout:

- Reduce visual complexity through alignment and grouping. To avoid masking problems, limit the number of different types of display objects.
- Support rapid top-down visual search in displays. Suitable means are lines, multi-scaled structuring elements, grouping, and open space.
- A flat, externalized display layout is suitable (externalized visible elements).

Colours:

- Colour layering is appropriate, reserve signal colours (red, yellow) for alarms; use a muted grey background colour. However, the grey-scale has given readability problems in well-lit rooms using front-projected technology.

Design Process:

- A user-centred design process is appropriate for industrial LSD design: design from a systems perspective; harmonize graphics with the control room´s other human-machine interfaces; form a design team with a broad skills profile; use an iterative design process and base LSD information content on work domain analysis findings. If appropriate, include long-term trends for key-variables, and visualize plant´s safety and integrity functions.

6.4 Contribution: graphic elements for Large-Screen Displays

This section presents the graphical objects developed for LSD design; they are presented chronologically in the order they were developed. The objective is to support rapid visual perception and comparison of data trough mathematical normalized generic indicators for process data, for liquid level, pressure, temperature, flow etc. Figure 25 visually explains how two variables (true-scaled inside the blue box) are re-organized graphically through mathematical normalization for vertical axis graphics.

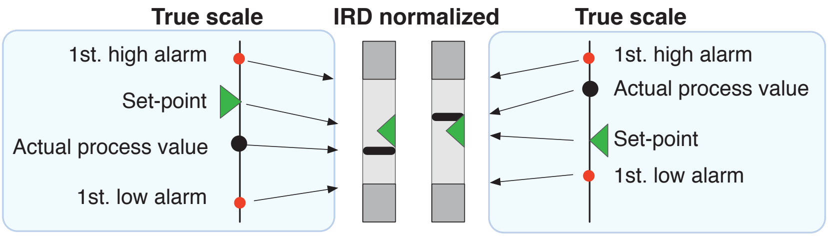


Fig. 25: Re-organizing graphics through part-wise mathematical normalization of process variable´s measuring scale. IRD indicators are calibrated from alarm limits and the set-point.

Mathematical normalization is calibrated from the first high and low alarm limits, and the process variable´s set-point for normal stable operation. The indicators do not re-scale during plant operation. The first graphics contribution covered by this thesis was the original IRD indicators; they are illustrated in Figure 26. The indicators create visual patterns of process values and alarm limits, aligning into horizontal bands for vertical axis graphics, or a circle for the polar star with radial axis representation. The typical time scale for the trended element is 10 minutes.

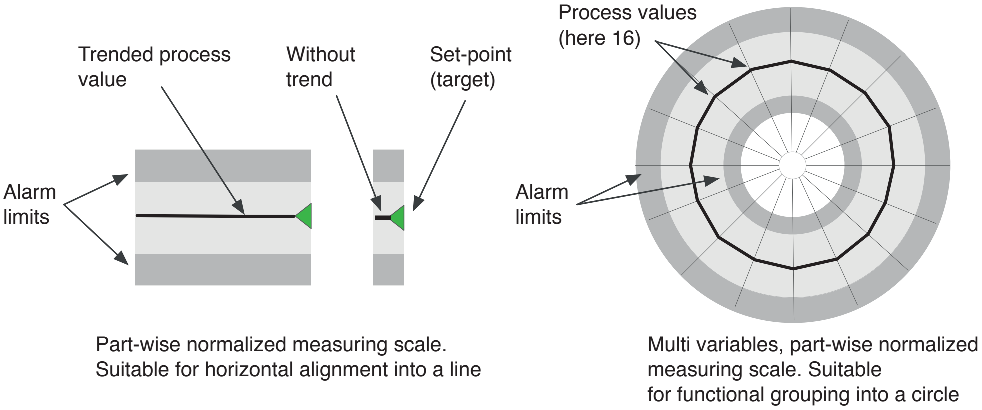


Fig. 26: The original IRD generic graphical elements for visualization of process variables: creating visual patterns in LSDs of process values and alarm limits.

Figure 27 visually explains how a deviation is more easily spotted for variable C, for a group of IRD normalized mini-trend graphics (left group of three variables A, B, and C). The compressed and stretched scales in normalized graphics can, however, potentially result in operators building wrong mental models.

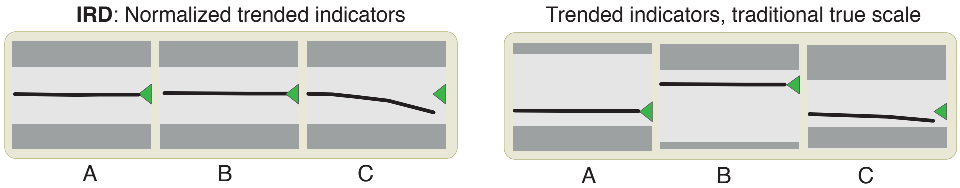


Fig. 27: Deviation is more easily spotted in normalized IRD graphics for left group (variable C).

Unfortunate keyhole effects and limited capacity for visual memory are compensated for, firstly, through larger display surfaces (LSDs) showing externalized data without a display hierarchy, and secondly, through data-rich graphics integrating related data. The objective of this approach is to avoid the need to visit different parts of a display hierarchy to mentally construct a situation overview (keyhole). Figure 28 explains how automation data was integrated for the IRD concept.

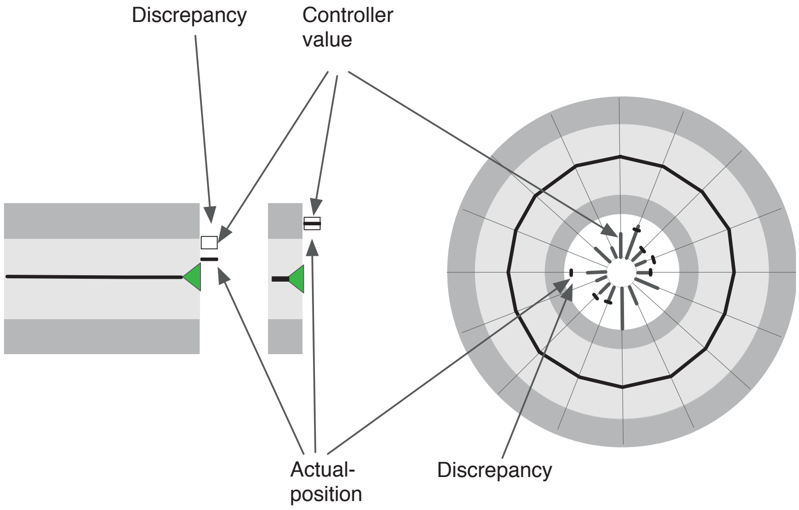


Fig. 28: Adding qualitatively automation data in IRD graphics.

Figure 29 visually explains through a time series how graphics explicitly integrate: automation data; alarm data; and a rate-of-change cue (explanation in the blue box is not a part of LSD graphics). The figure shows how automation discrepancies can be spotted when controller output and position (valve) are misaligned:

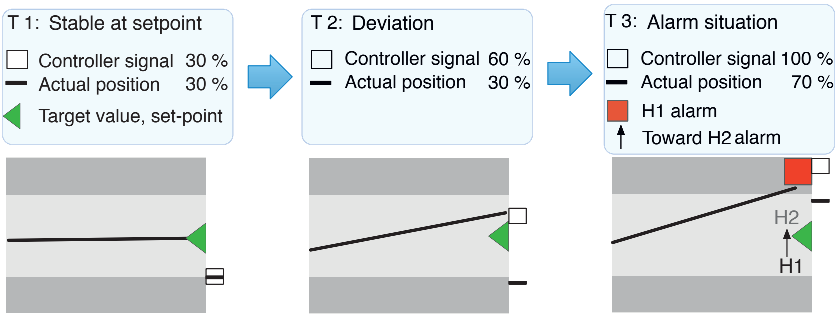


Fig. 29: Time variance, explanations in blue box: integrating explicitly related data for increased information richness.

Rapid perception of plants dynamic response is approached through trended graphics; this is visually explained in Figure 30. In addition, the figure shows how concepts from Ecological psychology are used as metaphors for LSD graphics.

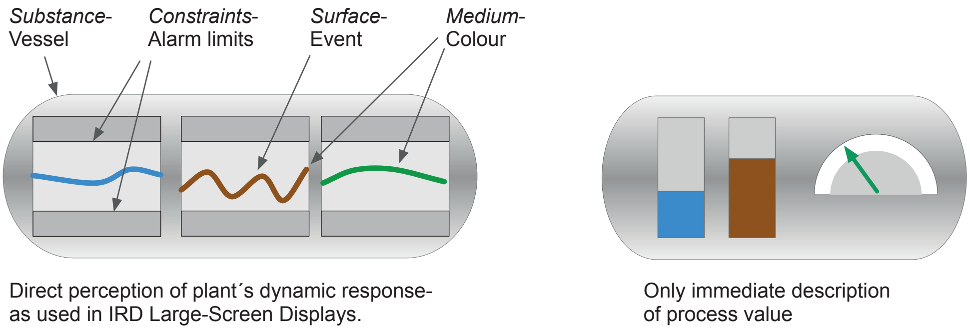


Fig. 30: IRD on left side: using concepts from Ecological psychology as metaphors for LSD graphics.

Figure 31 explains IRD graphics for rapid awareness of data-driven, incoming alarms. The dynamic alarm-spot was developed as an alternative to intrusive blinking/flashing effects. It is useable for alarms on IRD indicators, and process equipment such as valves, pumps, compressors, etc.

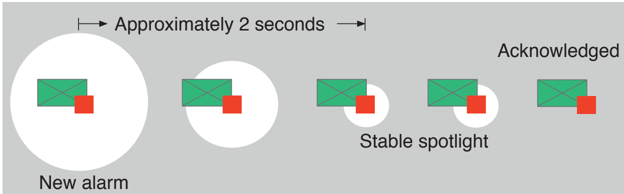


Fig. 31: Dynamic alarm-spot, visualizing incoming alarms in LSDs.

Figure 32 demonstrates this thesis design principles and graphics applied for LSD design.

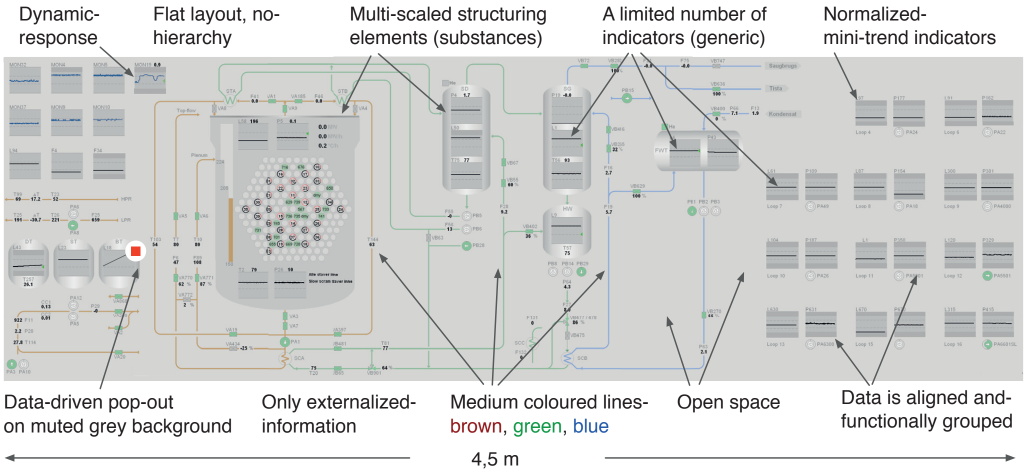


Fig. 32: Applying IRD design principles and graphics for an operational research reactor LSD.

6.5 The contributions of the research papers

This section summarizes each paper´s research findings chronologically. The text in *Italics* gives a short introduction to each paper, briefly describing it´s purpose and the research position at the time. Key references to background material are provided, however, please examine the research papers for more details.

6.5.1 Challenges in perceiving complex processes, proposing graphical objects

This section summarizes the contribution from papers 1 and 2: "A Building Block for Information Rich Displays", and "Information Rich Display Design". These papers were written together with research colleagues Veland and Welch at IFE. After approximately three years work, the objectives of the concept began to be clarified, as a concept supporting operators in rapid visual perception of process data, using a high data-ink ratio graphics. It was suggested that the IRD concept could be used to supplement and/or compliment other design concepts such as Ecological Interface Design or Function-Oriented Design. In this earlier work, the concept was focused on petroleum processes. The concept was explored in small scale on desktop displays. The dullscreen colour-layering concept earlier developed by Veland, Haukenes and Seim was adopted for IRD displays.

Paper 1 discussed how complex processes were causing a high cognitive strain on control room operators through parallel processes, referred to as the cost of concurrence. From this, the paper suggested that displays should support higher parallel processing capacity through Skills-and Rules-based perception of process data. The paper used the term pattern-recognition for this; in addition, the paper suggested that displays should support micro-macro (both detailed and overview information) readability of process information. This was inspired by Tufte´s work on information visualization.

Paper 2 described how control room operators had different roles in control room work, and that displays should support this, from slower self-paced “researcher” to fast “fire-fighter”. The paper suggested that operators are unnecessarily forced into slower knowledge-based reasoning by traditional display approaches, and IRD should support strategies for faster paced situations, Figure 33 was proposed on the basis of this.

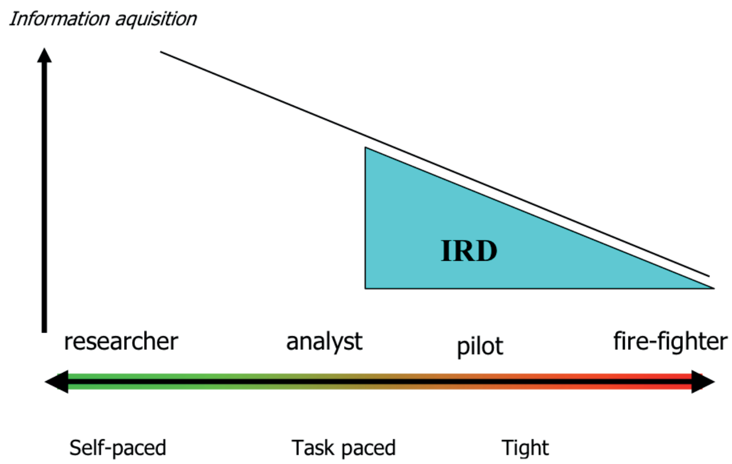


Fig. 33: Positioning IRD as a display concept that supports different operator roles.

Paper 2 described problems in relation to how current display designs only revealed a fraction of the total process, referred to as the keyhole effect. This suggested that IRD should present information in a more condensed form, through a higher data-ink ratio, reducing the total number of displays avoiding complex display hierarchies. Papers 1 and 2 proposed a generic mathematical normalized indicator (building-block) as a possible solution to the objectives of micro-macro readability, for rapid perception of data and having a high data-ink ratio, see Figure 34.

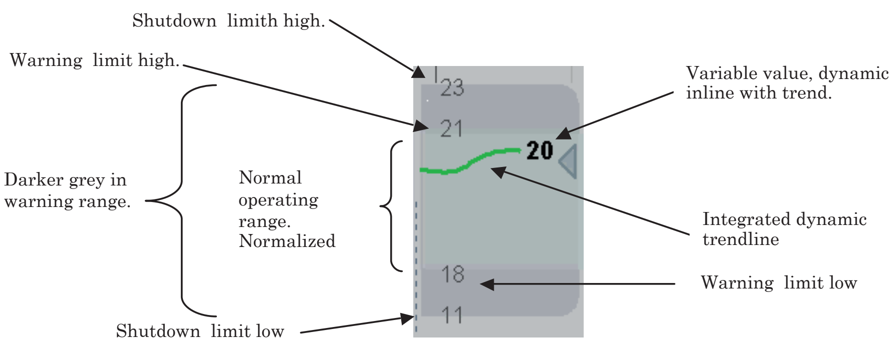


Fig. 34: The first IRD building block, integrating many cues into a generic indicator.

The IRD graphical objects used part-wise mathematical normalization of the measuring scale, which made them suitable for alignment and grouping of larger data-sets.

The quality of this generic qualitative indicator was demonstrated by aligning several building blocks. Figure 35 shows how it was used for three separators.

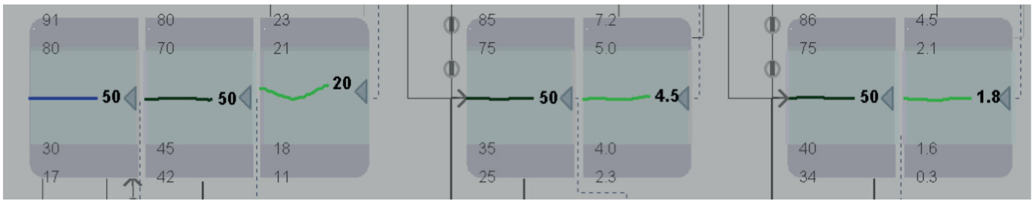


Fig. 35: Aligning IRD building blocks, supporting macro reading of the whole situation. Blue is water level, dark green is oil level and light green is gas pressure.

These graphical elements were the result of design exploration through a full-scale petroleum simulator; graphics were implemented on desktop displays.

6.5.2 Applying the concept for Large-Screen Displays, the first user-test

After publishing the two first papers, the initial IRD graphical objects were design patented by Braseth, Veland and Welch. Following this, graphic elements were surprisingly rapidly adopted and used by the Norwegian Petroleum Industry for commercial LSD applications. There was also an interest in IRD from Swedish and Finnish nuclear power plants. They initiated a research project with the objective of developing LSDs for full-scale nuclear simulators. Paper 3: "Realizing the Information Rich Design for the Loviisa Nuclear Power Plant", and paper 4: "Evaluation of the Fortum IRD Pilot" were based on the first research-oriented 1^{st} generation Loviisa LSD. It was installed on a full-scale nuclear simulator in Helsinki. The author and expert Fortum operators designed the LSD. The papers 3 and 4 were written together with research colleagues from the Finnish research institute VTT (Laarni, Koskinen, Salo and Norros), and Nurmilaukas from Fortum.

Paper 5: "Lessons learned from Halden Project research on human-system interfaces" discussed, in addition to IRD, other research-oriented display concepts studied in the Halden Reactor Project. The paper was written with research colleagues from IFE: Nihlwing, Svengren, Veland, Hurlen and Kvalem.

Paper 3 was based on the research process for developing the Loviisa LSD, which was designed through five workshops over a one-year period. The paper focused on developing goals and requirements for a whole functional LSD. Based on this work the paper proposed how LSD should:

- Be complementary to existing desktop workstations, support process monitoring, but not interaction.
- Function as a frame of reference in the control room and support pattern recognition of process variables.
- Support operators in both normal stable and abnormal disturbances, including key process and safety parameters, but not including outage and accident states.
- Provide an alarm presentation not in conflict with desktop workstations, particularly harmonizing the use of colours.

Paper 3 proposed new graphics, where one contribution was an integration of explicit alarm information within the mini-trend symbol, see Figure 36.

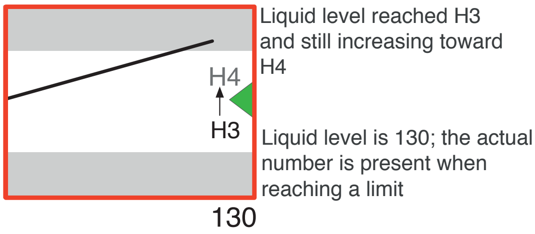


Fig. 36: Extending the original functionality with externalized in-detail alarm information, digital process value added for some process variables where high accuracy was needed.

Another new symbol proposed for LSD design, was the innovative pump symbol designed by Svengren at IFE, originally developed for other display concepts. The symbol offered higher data-ink ratio than traditional pump symbols, and integrated pump speed rapidly perceivable in a qualitative way in it´s outer ring, see Figure 37. The pump symbol was in accordance with objectives for IRD graphics.

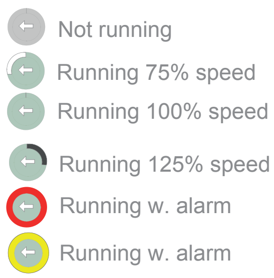


Fig. 37: Adopting an innovative information-rich pump symbol designed by H. Svengren at IFE.

The paper focused further on how to support perception of larger data sets, and how to reduce the visual complexity. The paper found how horizontal, and vertical alignment of graphical components was suitable for this. Figure 38 shows the Loviisa LSD.

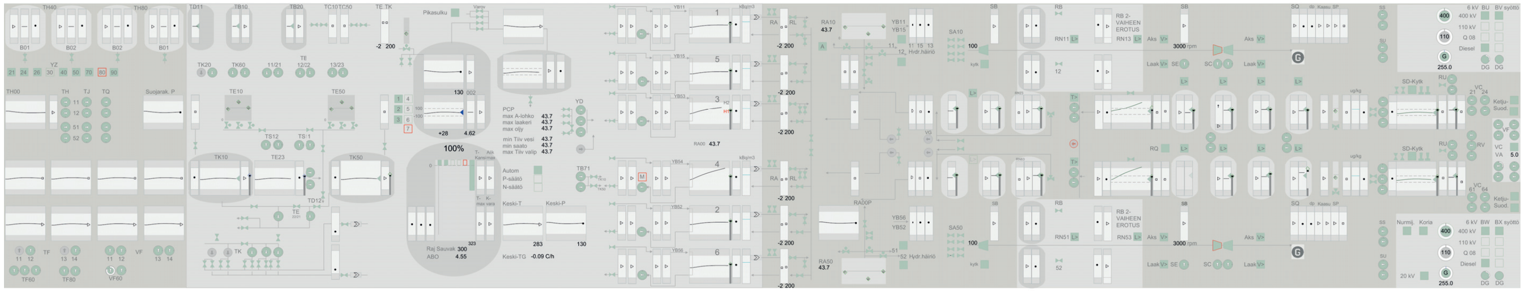


Fig. 38: The Loviisa LSD 5.7 x 1,1 m: reducing clutter by aligning information horizontally and vertically.

Paper 4 found promising results on operator performance for failure detection times in scenarios using crews of certified operators. The Loviisa LSD (IRD), was compared to a traditional "schematic type" designed Loviisa overview display, see Figure 39. From this, the paper suggested that the IRD display was applicable to the detection, identification and diagnosing of failure states for the nuclear process.

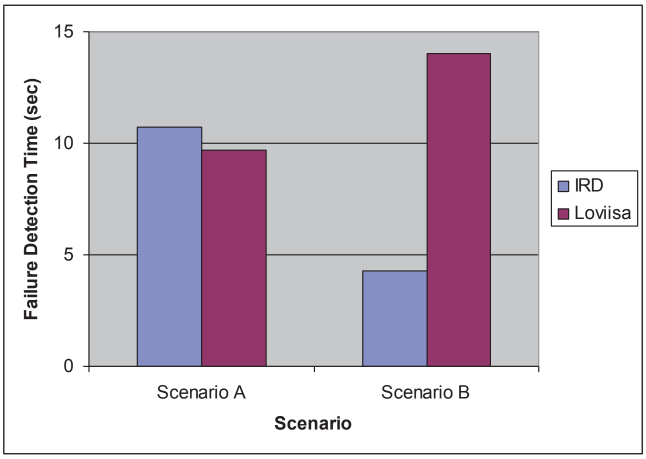


Fig. 39: The user-test of the Loviisa LSD (IRD) using crews of certified operators: failure detection time for two scenarios compared with traditionally designed Loviisa overview display, permission by paper´s 1.st author J. Laarni.

Based from the operators' subjective feedback, paper 4 reported several problems for the Loviisa LSD. The main issues were poor readability and inconsistencies in the colour-layering concept (glary and tiring background). The usefulness of part-wise mathematical normalization of the measuring scale was also questioned. The paper suggested that the iterative action and reflection design process was well suited for developing LSDs within a limited timeframe.

Paper 5 summarized key lessons learned on research-oriented displays for nuclear and complex processes from research in the Halden Reactor Project:

- LSDs can help to increase teamwork transparency.
- Displays should be designed to support early detection of disturbances.
- Displaying aggregated information as by Ecological Interface Design (EID), and Function-Oriented Displays can help operators to discover and diagnose disturbances earlier than traditional display approaches.
- Displays should support pattern recognition of process data; examples are IRD and EID. A colour-layering palette is suitable.

6.5.3 Improving the concept, the second user-test, proposing design principles

This section summarizes the contribution from two papers, first paper 6: "Improving alarm visualization and consistency for a BWR large screen display using the Information Rich Concept", written together with IFE colleagues Karlsson and Jokstad, secondly paper 7: "Visualizing Complex Processes On Large Screen Displays: Design Principles Based On The Information Rich Design Concept". Paper 7 was written together with research colleague Øritsland from University of Science and Technology in Trondheim.

The Swedish and Finnish nuclear power plants supported further research and development of the IRD concept. Both papers focused on the successor of the Loviisa LSD, the 2^{nd} generation HAMBO LSD. The author designed it with help from IFE colleagues. The objective of the LSD was to mitigate problems reported from previous Loviisa LSD. Paper 7 had a broader scope, to expand the theoretical framework through design studies. Further, it presented a user-test of the HAMBO LSD; based on this, the paper proposed design principles for LSDs.

The HAMBO LSD, which was presented in paper 6, was a response to findings in the earlier Loviisa LSD. The paper proposed improved graphics for alarm visualization, suggesting how equally sized filled squares are better than alarm frames (used in Loviisa). Further, proposing improved graphics for integration of automation data, which was poorly understood on the Loviisa LSD. A more intuitive approach was developed for the HAMBO LSD, where the controller output (square) and actual valve position (line) were arranged for visual alignment. Later, paper 7 argued that controller movement from closed (bottom) to fully open (top) is in line with intuitive natural use of metaphors. In Figure 40, the controller signal and valve position are aligned and ok. The visual pop-out is stronger on the improved HAMBO design, where the H3 alarm limit is violated, moving toward H4 when the process value is 48.

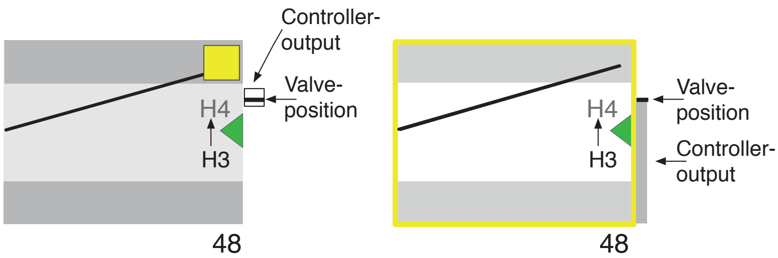


Fig. 40: Improved HAMBO graphics to the left, stronger alarm pop out, more intuitive automation visualization.

Paper 6 proposed a dynamic alarm-spot as a response to overcome the problem of visually separating incoming alarms from old standing alarms. It worked as a gentler animation on top of the new alarm, creating a strong pop-out effect. Figure 41 shows how it was implemented for a red alarm on green open valve. The dynamic alarm-spot worked consistently in the same way for all alarms on all display process objects.

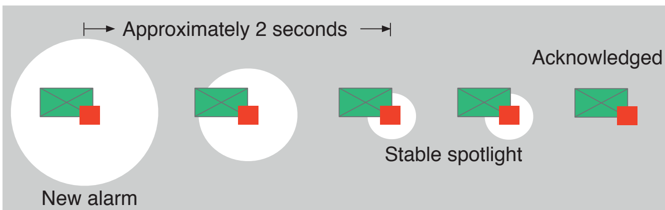


Fig. 41: The dynamic alarm-spot used for visualizing incoming alarms.

A darker flat grey background was proposed for the HAMBO LSD, avoiding a garish and tiring display as reported in the Loviisa LSD. Further, it was proposed to use a more saturated green colour for improved readability of grey-green, which was used for indicate active states (running, open). Figure 42 shows the HAMBO LSD.

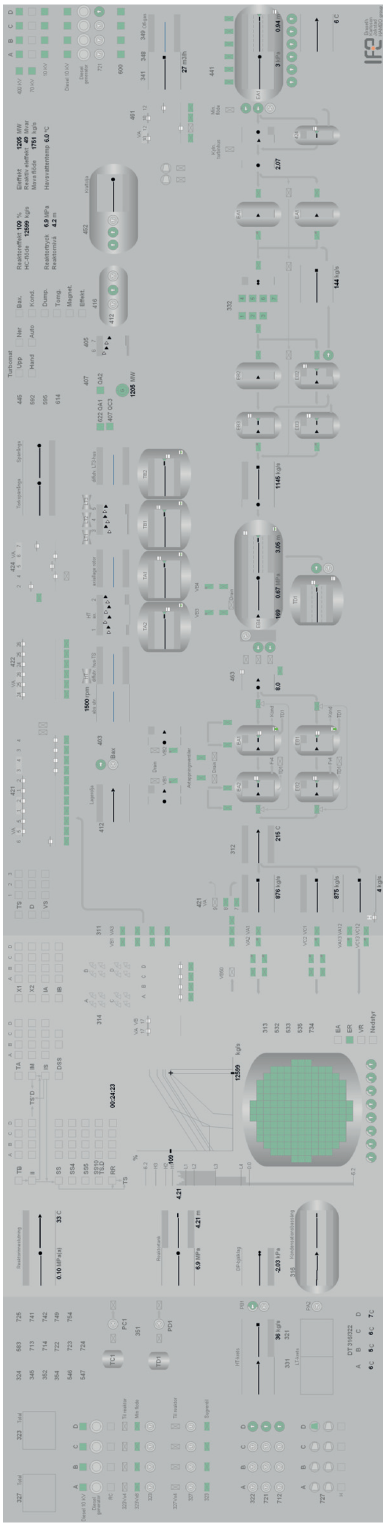


Fig. 42: The HAMBO LSD, 6m x 1.5 m, using upgraded elements and darker background than the previous Loviisa LSD.

Paper 7 took up design studies again, referring to recent research on LSDs, which showed that such displays are genuinely different from smaller user interfaces, and, from this, the paper proposed that LSDs must be designed for it´s purpose from the ground up. The paper found the concept of Situation Awareness usable in discussing larger displays, referring to: inaccurate mental models; cognitive tunnel vision; data overload and the requisite memory trap.

The user-test of the HAMBO display in paper 7 concluded that the colour concept was given negative feedback. Further, that pattern recognition through normalization of variables and the alarm-spot were given positive feedback, see Figure 43.

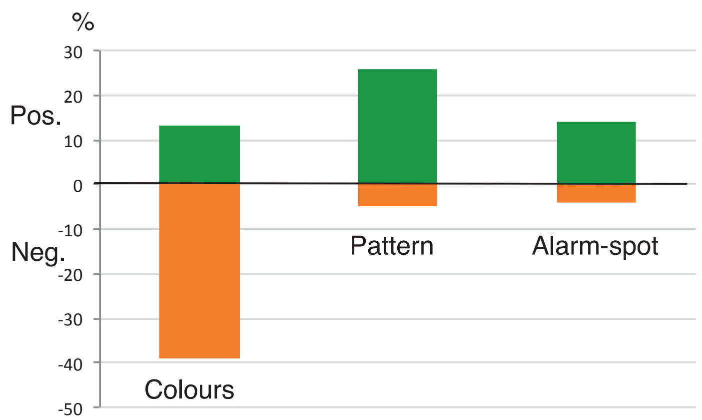


Fig. 43: The user-test of HAMBO LSD with crews of certified operators. Negative feedback on colours, positive on pattern recognition and the alarm-spot.

From the paper´s theoretical discussions, the user-tests of the Loviisa, and the HAMBO display, paper 7 proposed principles for LSD design (see paper 7 for details). The paper looked briefly at guidelines for the nuclear domain and related display concepts, and suggested that IRD was not in conflict with well-known industrial guidelines. It was also explained how IRD and the proposed principles extend on earlier research in the literature for desktop displays.

6.5.4 Extending the theoretical foundation, the third user-test, revised design principles

This section summarizes the contribution from papers 8 and 9. Paper 8: "Seeing the Big Picture: Principles for dynamic process data visualization on Large Screen Displays", was written together with Øritsland. Paper 9 was: "Evaluating usability of the Halden Reactor Large Screen Display: Is the Information Rich Design concept suitable for real-world installations?" The papers were based on research for the successor of the earlier HAMBO and Loviisa LSDs, the 3rd generation Halden Reactor LSD. The author and expert IFE operators designed the display.

Paper 8 focused on extending the theoretical foundation for LSD design through design studies and exploration, positioning IRD and describing the research contribution. The paper focused particularly on how to visualize dynamic process response in a natural way. Paper 9 compiled and demonstrated the use of the proposed design principles and graphics, and it evaluated the IRD concept for real-world installations through a user-test. Data collection, and Figures 45, 46 and 47 were based on an internal Halden Reactor Work report HWR-1073 (Braseth et. al, 2013). The report was written together with IFE colleagues: Magnhild Kaarstad; Stine Strand and Pål Thowsen.

Paper 8 explained how graphics should support rapid visual scans, while not overly challenging limited visual memory. LSDs should support visual top-down search strategies, and bottom-up data driven processes through strong pop-out effects that avoid masking primary data. The paper found additional inspiration for direct perception of process plant dynamic response in Ecological psychology. Based on this, the paper expanded further the theoretical foundation from paper 7, and proposed the revised design principles (see paper 8 for details). The paper positioned IRD as a state-of-the-art approach for LSDs for complex processes, extending what others have done on desktop displays.

Paper 8 demonstrated the use of the revised design principles and IRD graphics through the 3rd generation Halden Reactor LSD. Figure 44 illustrates this LSD (it´s main functionality is described in paper 8). The main difference from the earlier 1st and 2nd generation LSD designs was a stronger focus on supporting top-down visual search through: lines; multi-scaled structuring elements; grouping; and open space. Secondly, the LSD focused on visualizing the plant's dynamic response by presenting more trended data.

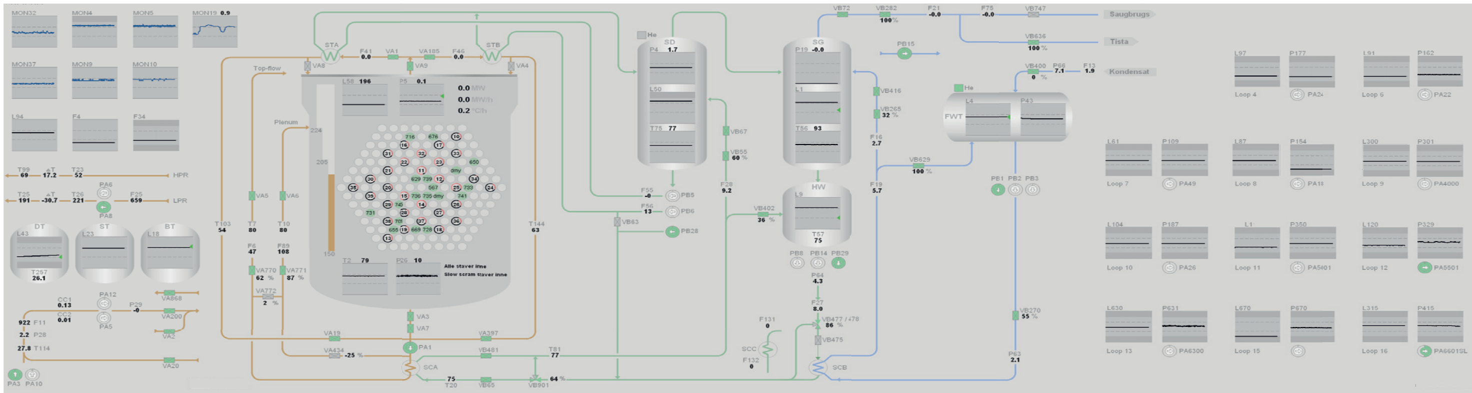


Fig. 44:The Halden Reactor LSD (4.5 m x 1.4 m): based on proposed design principles and IRD graphics. It is installed and used in the nuclear research reactor´s control room.

Paper 9 compiled and reorganized the LSD design principles (see paper 9 for details), which were based on the previous papers 7 and 8. Paper 9 evaluated the usability of the IRD concept as realized through the Halden Reactor LSD. The evaluation was based on feedback from control room operators having used the LSD for a couple of months in the control room. The usability score was determined and compared with the control room´s older analogue panels, and the earlier 2nd generation IRD HAMBO LSD.

Figure 45 shows the summarized System Usability Scale (SUS) score. It scored 83 of 100 for the Halden Reactor LSD, the replaced analogue panels score 77, and the earlier HAMBO LSD score was 59. The result for the Halden Reactor LSD was encouraging, representing among the top 5% of scores for historical SUS data (based on data from Sauro 2011).

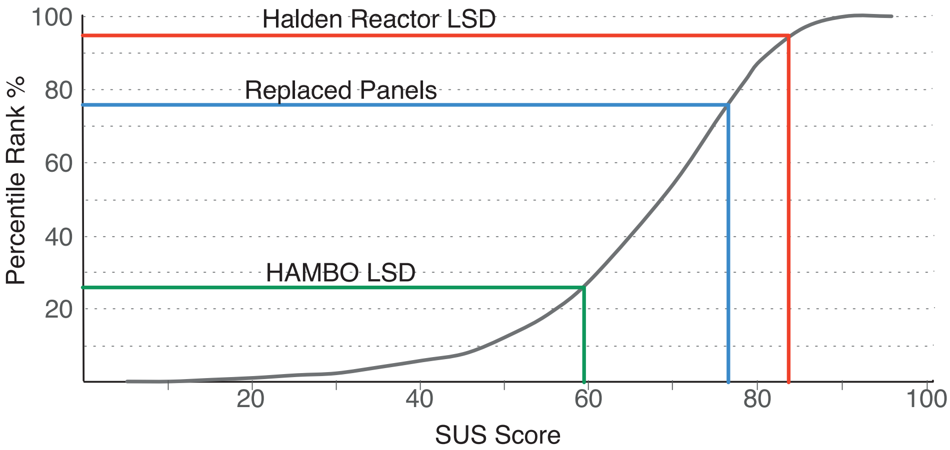


Fig. 45: The user-test of Halden Reactor LSD with crews of certified operators: comparisons with replaced analogue panels and the earlier HAMBO LSD. Summarized scores converted to a percentile rank: the method, historical SUS data and the figure were based on Sauro (2011).

Figure 46 shows the individual SUS dimensions. The Halden Reactor LSD scored equal or higher on all dimensions compared with the replaced panels and the older HAMBO LSD.

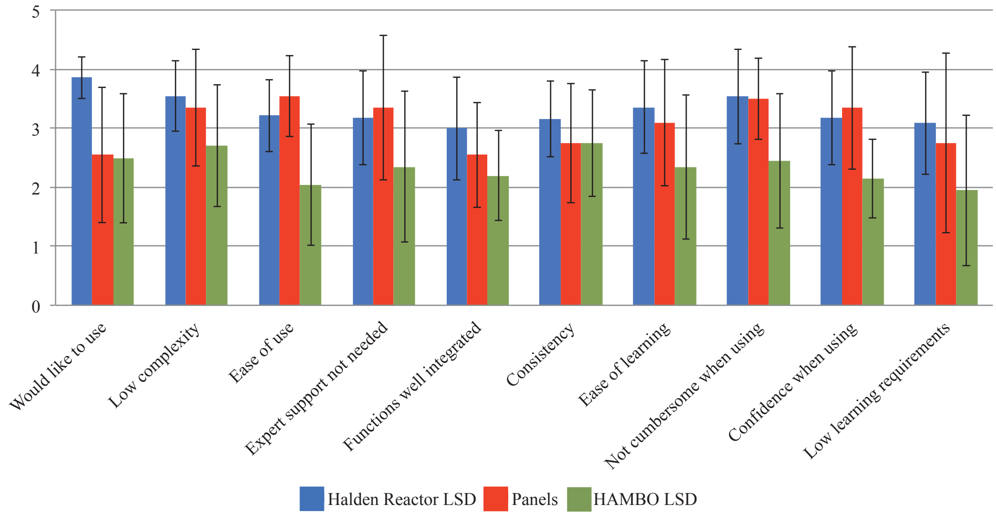


Fig. 46: Individual SUS scores. (1: Strongly disagree; 5: Strongly agree).

Figure 47 shows the degree of perceived support. Operators rated the Halden Reactor LSD significantly higher than the replaced panels.

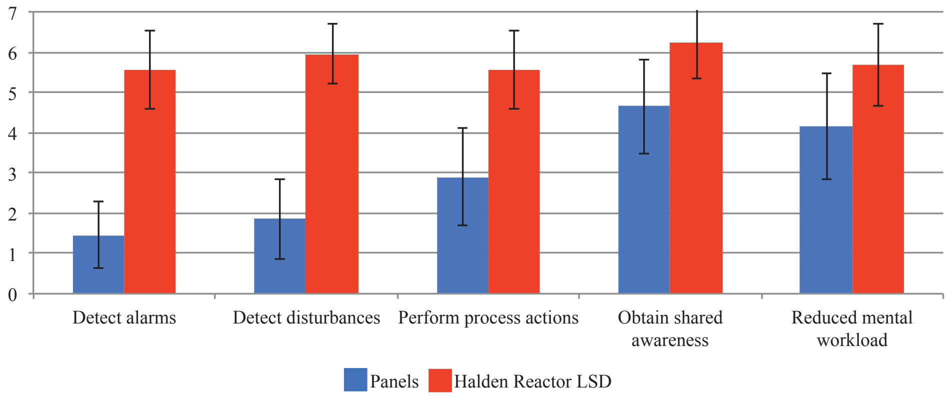


Figure 47: Perceived support of Halden Reactor LSD, using with crews of certified operators: (1: Low degree, 7: High degree).

Based on the user-test, paper 9 suggested that the IRD design principles and graphics had matured and were suitable for use in real-life processes from a user experience point of view. On the positive side, the paper noted that the LSD was used in a real-life operational control room, which strengthened findings. However, the paper stressed that the data did not represent operator performance, only perceived usability, and also that definitive conclusions could not be drawn since the Halden Reactor LSD and the HAMBO LSD were tested under different conditions.

6.5.5 Information-Rich Design for user-centred design

Paper 10 is the most recent work included in this thesis: "Information-rich design for large-screen displays: A new approach to human-machine interfaces has produced a radically different design of control room displays". The paper summarized the IRD concepts research for LSDs and rephrased earlier design principles. The article looked at IRD in the larger perspective of user-centred design. It asked: what is needed using IRD in a user/human-centred approach for industrial applications?

By examining the standard ISO-9241-210 (2010) for human/user-centred design, and referring to Norman´s and Endsley´s work on user-centred design, the paper found that IRD was a reasonable approach to LSD design through it´s non technology-oriented approach. The paper proposed how IRD graphics and design principles should be part of a larger system´s perspective for control room design. For user-centred design, the design process should include the formation of a focused design team with a broad skills profile including designers, process experts and industrial vendors. Design should reflect the work-domain analysis findings, which could imply the need to harmonize colours and graphics with a control room´s other display interfaces and the inclusion of other graphic elements. Examples were: long-term trends for key variables; and visualization of plant safety and integrity functions. The design process should be iterative. IFE researchers and the author have found Microsoft Visio, Concept Draw and OmniGraffle suitable for iterative prototyping of LSD graphics.

7. DISCUSSION

This chapter discusses the research in this thesis. The chapter´s material is mostly new, as it concerns the outcome as a whole, rather than each papers detailed research. Please refer to the research papers for in-depth discussions, and more comprehensive references to other work. In the following sections, the validation approach is explained in section 7.1, and the thesis concept´s validity and position is discussed in sections 7.2 - 7.8. Based on this, section 7.9 outlines the resulting research contribution.

7.1 Validation from a broad perspective

Validation of a display concept can be done in different ways; Flach, a prominent figure in applying Ecological psychology for information systems stated (in Flach et al., 1995, p. 7): "*It is important for us to realize that hypothesis testing is not the only way to validate our theories. Design of products and the success or failure of those products is another way of validating the implicit and explicit theories that guided design… Good science demands a balance between these two forms of validity."* The following section describes how the validation methods should match the complexity of LSD design research.

Chapter 4 "Research Methods for Large-Screen Display Design" described how LSD design represents an ill-defined and wicked problem. From this, the research methods in this thesis were based on a broad research perspective, combining three research activities: design exploration, design studies and design practice. Building on Flach´s view, it can be argued that it is reasonable to approach the question of validity from the same broad perspective. For this reason, the following sections validate the LSD concept internally from the theories, the methods and the questions that guided design, and explicitly through user-tests, and through feedback from industrial applications.

7.2 There was a need for a LSD concept

The thesis section 3.1 described how LSDs should be designed from the ground-up, referring to research, industrial standards and guidelines. They provided some guidance, so was there really a need for a concept? Firstly, the guidance for LSD design in industrial standards and guidelines is not detailed enough for performing design work. Typically, human factors based standards and guidelines, as referred to in Appendix A, are more useful for reviewing display designs, than for designing displays. Secondly, even though research by others has been important for describing challenges and opportunities for larger display surfaces, their work was not targeted at designing graphics for process plants.

For this reason, it is reasonable to propose a concept based on research for how to visualize a plant´s process data and characteristics. Referring to Friedman´s and Buchanan´s categorization (Table 1 in section 4.2.1), there is a need for applied research that provides an explanation of the theories for design of LSDs, with enough detail to be usable for clinical real-world applications. This is confirmed by the response from the petroleum, nuclear and mining industries to the IRD concept.

7.3 Were research questions suitable?

The following section first discusses the two research questions, asking, were they suitable for the research process and the research outcome? Then follows a brief discussion on the research papers research questions. The first research problem asked by this thesis was: "how to design for rapid perception of industrial-scale data sets?" Others have also identified the importance of this.

Reising and Bullemer (2008) proposed process overview displays which supported direct perception, and overview at-a-glance. The industry standard IEC 61772 (2009, p. 26), and guidelines NUREG-0700 (2002, p. 316) described how larger displays should support at-a-glance situation overview. Endsley (2013, p 103) described SA demons (challenges). One of them was data overload. She explained how the human brain becomes a bottleneck if designs do not accommodate rapid processing. These examples show how the first research question is relevant for designing graphics for larger displays; however, it could have been asked differently using slightly different terms.

The second research problem was: "how to avoid keyhole effects in complex processes?" Others have also identified this as a problem, however, sometimes using other terms and slightly different meanings. In their description of challenges for building sufficient Situation Awareness (SA) for complex systems, Endsley (2013, p. 102) described attentional tunnelling as a SA demon (challenge), where people typically lock in on certain features while solving problems. This is quite similar to when process operators experience an unfortunate keyhole effect. Another SA demon described by Endsley was the requisite memory trap. It was described as difficulties remembering features or situations; this is also a typical result of unfortunate keyhole designs where operators must remember information that is scattered in a display hierarchy. These examples suggest how the research question could have been reformulated using other terms than "keyhole". There are, however, no major problems with using the term "keyhole"; it is a widely accepted concept, and it is a well-described problem in display design.

This thesis has focused on externalized information graphics (for avoiding keyholes), graphics triggering primitive rapid feature channels (rapid visual perception), and graphics that support operators in fast visual top-down search for information in large display surfaces (rapid visual perception). It is reasonable to suggest how these focus areas stem from the way the research questions were asked. This corresponds to the suggestions by Rittel and Webber (1973). They described how a formulation of a wicked problem corresponds to a formulation of a solution. Section 4.1.2 in this thesis, described how LSD design and the two research questions represented such wicked problems. From this, it is reasonable to suggest how other problem formulations could have directed the work in slightly different ways. However, a weak spot in the thesis research questions is the lack of explicit concerns for plant safety, which should be a motivation for design. Neither the thesis nor it´s research papers described this concern explicitly. Rather, it was brought up implicitly through other concepts such as SA. Further research questions and research work should therefore focus more explicitly on safety.

By examining the research papers questions, it is clear that the early papers were wide angled. They were less focused on specific topics, and they were written without asking specific research questions. One explanation for this was that in the early phase of the research process there was a greater focus on making the IRD concept implementable, to make it work rather than for answering explicit questions. Later papers had a narrower scope where specific questions were asked; they focused on improving graphics through user-tests, and to validate the concept from usability data. Along this research process, the increased insights into LSD design also increased the capacity to ask more precisely formulated research questions. This process corresponds well with Buchanan´s (1992) description. He described this as typical for wicked problems in design thinking. He explained how it is difficult to ask well-formulated and well-defined questions up-front. This is in contrast to more traditional scientific approaches, which typically approach research through a linear step-by-step process with distinct phases: first a problem definition up-front, then a problem solving phase, and at the end, validating the result.

In summary; the two research questions were well suited to the objective of creating a concept for larger displays. They were appropriate for framing characteristics of the underlying issues and problems of the interplay of control room operators, the display and the process plant (Figure 6). The research questions are well known, and others use them, although sometimes phrased using other terms.

7.4 The research process, from idea to concept

The following section discusses the research process from the initial idea to the concept presented in this thesis. The research process is validated against Fallman´s model (2008) for interaction design research. The present author initiated the research for the IRD concept in 2000. In the beginning, inspiration and ideas for process display graphics was found from information visualization principles from other domains, such as maps, statistics and Gestalt principles. After making initial prototypes of the generic mathematical normalized indicators, researchers Øystein Veland and Robin Welch joined the author to form a design research team. In the following years, the IRD concept was implemented on a process simulator at IFE, and the design team improved the IRD graphics through design exploration and design studies. The research work was published in the first two conference papers. Looking back, there is no doubt that forming a small focused design team was fortunate. The collective skills of the team provided momentum for the research process. The members made proposals and gave critique, and there was also considerably "healthy tension" between the team members, which made the whole difference between a display concept for the drawer and an implementable design useable for industrial applications.

The first research period lasted approximately 4-5 years. The next research phase was largely concerned with design practice (Figure 5). The main outcome from the second period was to make the concept implementable for industrial plants. One challenge in this work was to find the sweet spot for LSDs visual complexity. The present author experienced how some operators accepted the abstract looking and information dense IRD graphics after a while, while other operators did not accept the quite unfamiliar looking graphics. Norman described how the users competence level could play an important role in the acceptance for complexity (Figure 12). He suggested that experts have a higher preference for complexity than novices. However, the general feedback from the plants operators suggested that less visually complex LSD designs worked better than the more complex ones. Others have found similar results for working software for real-life systems design. Poppendieck (2010, p. 27) wrote: *The lean frame of reference focuses on simplicity. Lean thinkers know that complexity clogs up the flow of work and inevitably slows things down*.

Another lesson learned from industrial design practice was how designing LSDs is a team effort. It is about putting together a team with a broad skills profile. Lessons learned suggested that the team should include a LSD graphics designer, control room operators and team members with detailed knowledge of instrumentation and hardware. This was also suggested by the industrial standard for user/human-centred designs, ISO-9241-210 (2010). They explained that a design team should have multidisciplinary skills and perspectives. Another lesson learned was that a rapid iteration approach was suitable for industrial LSD design. In this approach, the author or other designers drew simple sketches of the LSD, and the design team reflected and learned from the actual designs. This approach was used instead of big up-front analysis, which typically produces a set of detailed specifications. This confirms what others have found for designing digital artefacts (Löwgren and Stolterman, 2004). ISO-9241-210 (2010) for user/human-centred designs confirmed this, as they suggested refining design through an iterative design process.

The third research phase commenced in 2009 and focused on usability testing and building a more solid theoretical foundation for the IRD concept (Figure 5). It came, however, as a surprise to the author how difficult it was to participate in the data-collection when process operators were interviewed. It was difficult to behave objectively and remain unbiased to the operators' opinions. I suspect this was related to my personal role in developing graphical components and LSD designs. Using experienced human factors researchers for this work solved this problem. This was also beneficial in other ways; it helped by broadening the projects competence profile, and it contributed by looking at design problems with a fresh view. The approach of exploring the IRD concept through three displays designed successively, with lessons learned from one LSD integrated into the next, was a decision from the reference group of Nordic power plants and the research institute (IFE). Looking back, this was a fortunate decision; it made it possible to learn through three designs starting with a "blank sheet". During the research process, it was also valuable to have the possibility of implementing the concept for three different nuclear processes; it contributed to developing a more robust implementable concept.

The process of building the theoretical framework for the IRD concept was not structured. Instead, the theoretical foundation was built when needed, and at times when the knowledge and the insights made it possible. Looking back, it is interesting to see how the more abstract ideas for the theoretical foundation, which came from Ecological psychology, were applied quite late in the research process (papers 8 and 9). This is in contrast to some other research-oriented concepts. One example is the Ecological Interface Design (EID) concept, which had built a strong theoretical foundation from the very beginning. The difference from IRD could stem from the different positions of the concepts. EID originated from the human factors inspired work from Vicente and Rasmussen (1990, 1992), and human factors typically approach problem solving by clarifying the design rationale up-front. This IRD concept, on the other hand, is an interaction design-oriented approach, were the design rationale has been formed though the research process, through an action and reflection process. It should be noted that the research activities in this thesis matches quite well to "research for design" as described by Archer and Frayling, see table 1 in section 4.2.1. The downside of the IRD approach was a lack of an explicit theoretical framework, which could have been communicated to others in the earlier years; instead it used largely tacit skills-based knowledge. On the positive side, it is a usable concept, with a robust broad-scoped theoretical foundation shaped through a long research process.

What should I have done differently in the research process? The time period from the initial theoretical foundation was produced to the first user test in 2009 was too long (Figure 5). It was the feedback from the first (Loviisa LSD) and second (HAMBO LSD) user-tests that most helped to improve the concept. The user-tests explained how the grey colour-layering concept had poor readability in well-lit control rooms, how the operators found the LSD graphics too abstract and too information dense, but that they liked the alarm-spot and visual patterns created by the normalized graphics. This feedback helped scoping problem areas. Initial design studies were performed in the early years (2000-2004), but the time before taking up design studies again (around 2011) was too long (Figure 5). I was made aware of Fallman´s (2008) model for interaction design rather late in the research process (Figure 7). If research had taken this model into account earlier, it could have prevented research from being stuck in positions for too long (in this case stuck in industrial practice). The research process should have paid more attention to his advice. That the most rewarding results do not come from taking specific positions, rather, it comes from moving dynamically between them. If the design studies and the user-tests had been performed earlier, research would have progressed faster.

In summary, although I was not aware of Fallman´s (2008) model for interaction design research early in the research process, the research process had elements from that model. It had a broad research perspective of applying several research activities in an iterative process, and it was well suited for the ill-defined, wicked problem of developing a LSD concept.

7.5 A theoretical validation of the concept

The following section validates the theoretical foundation for LSD design. The section discusses first the validity of the theoretical framework, and secondly, to which extent the theoretical framework was found reasonable and useful for LSD design. The theoretical framework for the IRD concept is partly based on research for computer graphics, by well-known resources such as Ware (2008, 2013) and Healy and Enns (2012). Their research is relevant for the purpose of creating rapid perception graphics, and for how to avoid keyhole effects through their focus on research on limited visual memory resources. Their work was, however, not intended for larger scaled displays. This thesis concept is also influenced by rule-of-thumb visualization principles as suggested by Norman (2002), and Tufte (1990, 2001, 2006). Their contributions to information graphics have wide acceptance, and are relevant as inspiration for designing LSD graphics. The weakness is that their work was not intended for LSD design; it was mainly targeted at information presentation for printed-paper or smaller display sizes. The more abstract part of the IRD theoretical foundation stem from Gestalt and Ecological psychology. These theories have had major influence on computer graphics, and others have also found inspiration from them for designing display graphics. However, neither Gestalt psychology nor Ecological psychology was intended for LSD design for complex processes.

The following sections discuss how the theoretical framework was applied for designing LSDs; it discusses the usefulness of the theoretical framework, and if it was reasonable when performing LSD design. The IRD theoretical framework advises using a colour-layering concept. In this approach, the objective is to highlight safety critical and dynamic data, while backgrounds and static information are presented in faded colours. This is in line with Tufte´s work on information visualization; he suggested using colour-layered visualizations (Figure 13). He demonstrated and explained how dynamic data should be top-level salient information, while static information could be less emphasised. Lidwell et al. (2010, pp. 146-147) explained this as a general advice for information visualization. Van Laar (2001) also suggested using colour-layered graphics for displays. This is also suggested through work on attention getting computer graphics from Ware (2013, 2008) and Healey and Enns (2012). From this, the conclusion is that IRD uses colours as advised by the theoretical framework for design. However, the grey colour-layering concept was not a success. To the contrary, this thesis shows how it was difficult to use such grey-layered colours for LSDs, particularly when used on front mounted video projectors in well-lit control rooms.

IRD developed mathematical normalized indicators for creating simple visual patterns of process data (process value, target value, alarm-limit) in LSDs. Use of alignment and grouping is generally suggested for rapid perception of data; this is described by sources used for building the IRD theoretical framework. It was described as alignment in Tufte (2001, p. 174), as a Gestalt principle in Ellis (1997, pp.72-75), as a design principle in Lidwell et al. (2010, pp. 24-25), and patterns for design in data graphics by Ware (2008, p. 58). This suggests that the IRD concept is in line with this part of the theoretical framework for design. Norman (2002, p.17) and Endsley (2013, pp. 97-98) described, however, the importance of designing for building true mental models. Endsley described how mental models are important for integration of bits of information to comprehend the purpose and function of systems, and if used correctly, it can increase SA levels. However, IRD indicators distort physical reality for the purpose of creating visual patterns (Figure 25). This explains how the graphics concept in this thesis is not in accordance with a true mental models approach. There is a trade-off between rapid data perception (as used in IRD), and physical “trueness” for supporting a correct mental model of the process. The IRD concept is therefore in conflict with parts of the theoretical foundation for design.

The IRD graphical indicators use a stable normalized measuring scale; which does not re-scale during plant operation (Figure 25). The mathematical normalization of each indicator is set from alarm limits and process target values considered as reasonable for the plant´s normal operation. The positive effect of this is that graphics behave visually consistently in a wide variety of plant operational situations. The downside is that the indicators do not align in situations that they were not calibrated for. Examples are start-up, shutting down, and major disturbances and out of plant design basis. Feedback from industrial LSDs suggested, however, that this is an acceptable trade-off when the LSD was used as a supplement to desktop workstations.

The IRD mini-trend uses a similar trend-time on x-axis for all mini-trends (typically 10 minutes). For process plants, this represents a problem since pressures can fluctuate rapidly within seconds, while liquid levels can take minutes to change, and temperatures react even more slowly. From this, it is evident how there is a trade-off between consistency (same timescale) and purpose-built timescales for each variable (individual timescales). This explains how IRD graphics are challenged in providing an optimum visualization for each variable (individual timescale), and the need for a consistent behavior of all graphic indicators in the LSD. In this case, the IRD concept has so far chosen to use a theoretical framework for design that supports designing for consistency (same timescale), which is typically preferred by industrial standards and guidelines

The IRD concept uses three different indicators for visualization of process data (Figure 26). One of them applies trended graphics. Tufte (2006) proposed using such small trends for computer graphics, which he named “sparklines”, see Figure 14. Ecological psychology (Gibson, 1986) explained the importance of perceiving events, which this thesis interpreted as showing time variance for plant disturbances (Figure 9). This explains how the IRD trended indicator is designed in accordance with the theoretical framework for design. It suggests also how the trended indicator is better than the other IRD indicators for the purpose of visualizing dynamic responses. It should, however, be noted that the polar-star (Figure 26) is better suited than the mini-trend for grouping larger data sets. This display element is particularly in line with the concept´s theoretical framework objective of creating high data-ink ratio graphics.

This thesis developed graphics for showing qualitative automation data. This functionality was added to the original IRD indicators (Figure 28). They inform the user of controller value and the actual position. Endsley (2013, p. 103) described the importance of being informed of automation in relation to SA. Christoffersen and Woods (2002) explained that for automation in complex systems: “*users need to be able to see what the automated agents are doing and what they will do next relative to the state of the process, and users need to be able to re-direct machine activities fluently in instances where they recognize a need to intervene”*. They explained also that a patterns-based presentation is suitable for quick scans, and that this is favourable rather than having to mentally integrate individual pieces. This explains how the IRD concept is designed in line with the theoretical framework for automation, and that it is a reasonable approach on automation visualization for avoiding keyhole effects, and to support rapid perception of automation data.

IRD graphics integrate a rate-of-change cue as an arrow (Figure 29) that pops-up in an alarm situation. Such cues are not a part of plant´s automation systems, nor does it represent instrumented process variables. The cue is for this reason calculated from past process values, and it can be used for predicting future values. Yin et al. (2011) showed in an empirical study that explicit rate-of-change cues in process control operations improve operator performance. However, the study did not conclude on what is best, a trended line or explicit information showing the direction of change. A rate-of-change-cue can also be used to increase SA level 3 (project future status). The rate-of-change cue is designed in accordance with the theoretical framework for design, and it is a reasonable approach.

The dynamic alarm spot (Figure 31) was developed as an alternative to intrusive blinking for incoming alarms. This is suggested for data visualizations by Ware (2008, pp. 36-37). He explained how motion generates a powerful visual response, and he describes how a carefully slower smoother effect is gentler than blinking (visual pollution). This suggests that the dynamic-alarm spot is a reasonable approach on alarm graphics and it is in line with the theoretical framework for design. The downside is that this type of animation can be difficult to implement for industrial graphics tools, which might lack support for graphics motion.

The thesis suggests presenting process data without a display hierarchy, the main reason for which was to avoid unfortunate keyhole effects. Norman (2002, p. 55) explained how externalized available knowledge (in-the-world) is better than memory challenging knowledge (in-the-head). Ware (2008, 2013) and Healey and Enns (2012) explained how visual working memory has poor capacity for data graphics. However, Norman explained in his Stanford University speech (2011) that complexity could be manageable when it is converted into internal complexity. The approach of hiding complexity is used by concepts that apply display hierarchies. In such approaches, each hierarchical layer reveals a small part of the plant complexity; one example is the Function-Oriented Design concept (Pirus, 2002). In sum, the theoretical framework for design is not conclusive. The IRD concept has chosen not to hide complexity; this approach represents a trade-off by limiting the available visual data-space (no hierarchy) while presenting data in line with human capacity for visual memory capacity (explicit data).

The IRD concept uses lines, multi-scaled structural elements, grouping and open areas for efficient top-down visual search. Ware (2008, pp. 40, 58) explained how multi-scaled structures and grouping are efficient for visual search, and he suggested using lines to describe how elements are related to each other. Hornof and Halverson (2003) explained how open space is not harmful for search in displays. Grouping principles are also described by Gestalt principles for design. This thesis concept is also in accordance (in a abstract way) with Ecological psychology (Gibson, 1986), which suggested how rapid perception can be aided through: *substances* to represent physical plant structures, *mediums* for visualizing fluids, and *surfaces* which display events. This explains how the IRD concept is in accordance with the theoretical framework for design for rapid visual perception of data.

To summarize; the theoretical framework, which stems from human-computer interaction research for limited visual memory, and from for our built in apparatus for pattern finding mechanisms, is suitable for the purpose of designing LSDs. It has the right focus for creating rapid perception graphics and to mitigate keyhole effects. However, IRD uses mathematical normalized scales, and it distorts reality, which can cause operators to build wrong mental models. The more abstract part of the theoretical foundation, which was found from Ecological psychology, is also a reasonable choice, and others use it, however, in slightly different ways. Even though the framework is found to be reasonable, it was originally not intended for LSD design, and for this reason, it was more relevant for identifying mechanisms for design, rather than for the purpose of performing LSD design. For this reason, it was necessary to perform research on cases of LSD design, as described in the next section.

7.6 External validation: user-tests and industrial applications

This section validates the IRD concept from industrial practice and user-tests. IRD graphics were used by the Norwegian petroleum industry for LSD design from approximately 2005. IFE researchers and the author assisted oil companies in this activity, where LSDs were designed foremost for offshore control rooms. Industrial vendors such as, ABB, Siemens and Kongsberg Offshore realized IRD graphics by modifying their graphics libraries. This confirmed that the proposed graphics were implementable, and had initial industrial acceptance. Feedback from the process operators that used the concept in industrial applications, suggested how the less information dense and less abstract graphics were preferred. The trended IRD indicator had a better acceptance in use than the other normalized IRD indicators. Operator feedback suggested that colours were often too washed out, too “dull”. However, the usefulness of this feedback was limited, as these applications were not tested under controlled conditions, and the feedback was not systematically collected. It was therefore welcomed when a consortium of Nordic Power Plants and IFE financed further research on the IRD concept by supporting the development of the Loviisa and HAMBO LSDs. In addition, IFE supported later the development of the Halden Reactor LSD.

The first research-oriented design was the Loviisa LSD (Figure 38); it was installed on Fortum´s full-scale development simulator in Helsinki. Through the design process, it was found that the LSD should foremost be designed for monitoring purposes, while in-depth interaction was left for the desktop workstations. Further, that graphics should inform operators through externalized alarm information (Figure 36). It was found that both horizontal and vertical alignment of graphical objects was important in reducing visual clutter. The Finnish research institute VTT performed a user-test of the Loviisa LSD. Although the performance data were promising (Figure 39), the subjective feedback from the operators was quite negative. They reported that the display suffered from poor readability (glary and tiring background), and the usefulness of the normalized indicators was questioned. This was the main concern, and became a topic for further research for the next HAMBO LSD.

The HAMBO LSD (Figure 42) was installed in IFE´s laboratory on a full-scale nuclear simulator in Halden. The design process focused on improving the alarm and automation visualization (Figure 40); to reduce the glary background by using a darker background. The dynamic alarm-spot was developed for visualizing new unacknowledged alarms (Figure 41). The normalized indicators and the grey colour-layering concept were kept for the indicators, however, with some minor modifications. The user-test of the HAMBO LSD (Figure 43) showed positive results for the normalized graphics, (patterns in LSD) and the results were positive for the dynamic alarm-spot. The grey-layered colour concept was still given negative feedback, which confirmed the results from the former user-test and feedback from industrial applications. This suggested that the colour problem was a combination of several factors: a well-lit control room; front projection technology; and the IRD grey layered colour-concept.

The next design was the Halden Reactor LSD (Figure 44). It was installed and used for monitoring purposes in a control room for IFE´s nuclear research reactor. It was designed accordingly to the proposed design principles using IRD graphics (sections 6.2 - 6.4). The main design objectives were to improve top-down search by adding coloured flow-lines, multi-scaled structures and more open space. The result was a less information dense, and less abstract looking display. The reactor dynamic response was visualized by using only trended indicators. A lighter colour palette was used to avoid the too dark appearance of the former HAMBO LSD. A user-test was performed a few months after installation in the control room. The user-test showed high and even scores for usability (Figures 45 and 46). The total SUS (based on data from Sauro, 2011) score of 83 was among the top 5% for historical SUS data; the older HAMBO scored 59; the replaced analogue panels scored 77. The user-test provided also high and even scores for perceived support (Figure 47). While these results were promising, it was not performance data.

To summarize; the IRD concept is used in industrial applications in several domains (petroleum, nuclear and mining). This suggests that the IRD concept has acceptance for real-world use. This is backed up with good and even scores for perceived support and SUS scores (Halden Reactor LSD). The concept has positive feedback on pattern recognition and for the dynamic alarm-spot (HAMBO LSD). It has also promising initial performance data for failure detection times (Loviisa LSD). Based on this, this thesis suggests that IRD is a reasonable approach to LSD design for industrial applications. However, definitive conclusions should not be drawn yet, since most of these results are based on qualitative subjective feedback, and more performance data is needed. The results from the user-tests suggest that a problem area is the colour-layering concept, which needs to be further investigated.

7.7 Is Information-Rich Design in conflict with industrial best practice?

Section 3.1 and 3.2 describe how industrial standards and guidelines objectives for LSD design are in accordance with the IRD concept: to design from the ground-up; to support overview at-a-glance; and to minimize the cognitive workload for the users. The following section examines industrial standards and guidelines in more detail: on the use of colours; for graphics formats; and for graphics layout on LSDs. The following discussion is based on background material from a literature review with detailed page references attached in Appendix A.

IRD uses a grey colour-layering concept, where signal colours such as red and yellow are used for alarms. IEC 61772 (2009) advised to use visual layering in LSDs, and to highlight alarms and alerts. They suggested further to use faded colours for less important or shut down systems. IEC 61772 suggested using, as few colour codes as possible, and they described how lighter backgrounds are less prone to loss of contrast by scattered light. They explained how unsaturated colours could be difficult to read from longer distances. Although the material was not intended for LSDs, the ASM Consortium guidelines (2013) suggested using colour layering, applying a limited colour palette and to reserve signal colours (red, orange, yellow) for critical information. From this, there seems to be a consensus that for display design in general, and for LSDs in particular, colour layering is suitable by applying: a limited colour palette; muted backgrounds; and signal foreground colours. This is in accordance with the IRD colour-layering concept. In addition, as this thesis research also suggests for LSDs, the IEC 61772 described how it is difficult to have enough illumination for written material in the control room, without undesirable reduction of screen contrast.

This thesis research work for LSDs has explained how generic analogue graphics are suitable for visualizing process data. IEC 61772 (2009) described how LSDs graphics should allow for visual comparisons for similar components, for which they mentioned normal, presets and alarm limits. NUREG-0700 (2002) suggested designing graphics for directing operator’s attention, and to visualise both major changes, such as alarms, and minor changes, which have not crossed into alarm conditions. The ASM Consortium guidelines (2013) were not written specifically for LSDs, but they provided general recommendations for overview display design. They suggested that qualitative analogue graphics are suited for overview purposes. From this, there is a shared view that analogue graphics are suitable for the purpose of displaying process data. This is in accordance with this thesis approach on LSD graphics. However, IRD extend further by applying part-wise mathematical normalized graphics, and by integrating automation data, alarm status, and rate-of-change cues within the graphical indicators. Animated graphics, such as the IRD dynamic alarm-spot, is not covered by standards and guidelines. They are however aware of the problems related to blinking/flashing. ANSI/HFES 200 wrote that blinking/flashing must be less than three flashes per second; ASM Consortium guidelines wrote that blinking should be reserved for critical activities. From this, there should be no problem in substituting flashing with a gentler animation for displaying safety critical information.

For faster top-down search for information in larger displays, this thesis proposes a graphics layout using lines, multi-scaled elements, grouping and open space on a flat externalized layout, and further applying Gestalt principles to reduce visual complexity. Standards and guidelines outlined some advice on how to organize a LSD graphics layout. NUREG-0700 explained how LSDs generally should support search (top-down), and data driven (bottom-up) processes, and they suggested using perceptual landmarks for long shot views. They described how a mimic style layout should be included if it is helpful in explaining functional relationships between components. They explained also how reducing the number of components could reduce the demand on short-term memory. The ASM Consortium guidelines suggested that a shallow broad display hierarchy is better for navigation purposes than a deep one. ANSI/HFES 200 (2008) explained how Gestalt principles could be used for visual data presentation in displays (displays in general). This guidance is in line with IRD design principles and graphics, and they share the objective of creating displays that support operators both in top-down search for information, and bottom-up data driven processes.

Industrial standards and guidelines pay particular attention to consistency issues. ISO 11064-5 (2008) and NUREG-0700 (2002) focused on possible consistency issues between LSDs and the control room´s other human-machine interfaces. IRD graphics use purpose-built graphical components, which are different from the ones used in traditional workstation displays and this approach has a potential for inconsistency. Another issue for the IRD concept, which is already mentioned, is the use of part-wise mathematical normalization of the variables measuring scale, which can also lead to inconsistent visualization of process data, and can cause operators to build wrong mental models of plant process characteristics.

To summarize; the IRD concept is generally in line with standards and guidelines for interface design, and LSD design in particular. However, the mathematical normalized graphics as used by IRD can cause a consistency problem between LSD graphics and other graphic interfaces in the control room.

7.8 Positioning the Information-Rich Design concept

The following section is relevant for determining the IRD concept´s contribution; it is a short discussion positioning IRD relative to some well-known display concepts. The thesis research work has developed analogue indicators for LSD graphics. Others have used quite similar approaches; one is the ASM Consortium approach for desktop overview displays for the petroleum industry, see Reising and Bullemer (2008). They proposed using generic qualitative indicators for rapid information perception (Figure 21); the same indicators were also suggested by the ASM Consortium guidelines (2013, p. 22). However, there are differences in comparison with this thesis concept, which might stem from IRD´s focus on larger display surfaces. Where IRD focuses on reducing graphics visual complexity through an integration of visual cues within few generic components, the ASM Consortium approach used “standalone” built components for each function. This thesis concept uses a mimic-style layout for rapid top-down visual search in large surfaces, compared to the ASM approach, which instead suggested using a condensed functional grouping for increased data-ink ratio.

Ecological psychology is used as the abstract foundation for IRD graphics. The EID concept was also based on ideas from Ecological psychology. It was a scientific approach on display design for complex processes, combining concepts from Ecological psychology with human factors engineering methods for analysing plants work domain. EID was more focused on identifying process variables and their constraints than for developing graphics components for computer displays. However, Burns and Hajdukiewizc (2004) suggested suitable graphics for EID displays that were quite similar to the ones proposed by the ASM Consortium approach. EID was not designed specifically for LSDs.

The concept of designing graphics for limited human capacity, while also reducing visual complexity in displays is an objective for the IRD concept. Both the Hawkeye concept (Husøy and Enkerud, 2010), and the Function-Oriented Design concept (FOD) (Pirus 2002, Figure 20) shared this objective, but used different means to achieve this. The HawkEye concept applied a zoomable approach, while the FOD concept used a deep hierarchical structure. Thus, the concepts reduced the visual complexity by hiding unnecessary details. They made details accessible only in the deeper levels of the hierarchy, or by zooming. The IRD concept uses no zooming or display hierarchy; complexity is not hidden. Complexity is instead made manageable by data graphics tuned to natural human perception capacity.

There are approaches that use visualization techniques to support pattern recognition in displays in a quite similar way as the IRD concept; one is the Parallel Coordinates concept (Brooks et al. 2012). The concept visualizes constraints and clusters of operational states through vertically aligned axis (Figure 19). The concept has a high data-ink ratio, but it produces a quite abstract looking graphics. The Parallel Coordinates concept is focused towards process optimization through high visibility of constraints and process values, rather than for general process plant-monitoring purposes. The IRD polar star (Figure 26) is more closely related to the Parallel Coordinates concept than other IRD indicators. It draw lines between each process value for radial axis in the same way as the Parallel Coordinated concept drew them between vertical axis. The main difference is that IRD uses mathematical normalized scales.

Modern industrial workstation displays and industrial LSD design have much in common (Figures 22, 23 and 24). They use colour layering with signal colours to visualize alarms. They represent process variables as digital numbers for high accuracy, and as analogue type indicators for rapid perception. The layout is often based on a mimic style layout with flow-lines. The main difference is that the IRD concept is based on a few generic graphical objects; which use mathematical normalization of the measuring scale for alignment and grouping purposes. IRD graphics also have a stronger focus on information integration, where alarm and automation data are visualized within the graphical elements. The dynamic alarm-spot is also different from traditional display designs, which typically use blinking for visualizing unacknowledged alarms.

Summarized; the IRD concept shares similarities with other display approaches. The theoretical foundation for design, and the graphical components are quite similar to those used by other concepts. However, the difference from these stem from IRD´s intended purpose as a LSD concept for large-scaled data sets. This explains why the IRD concept is not a radical or revolutionary contribution; rather, it builds further on well-known principles for display design. IRD has an innovative contribution in the way it uses part-wise normalized scales for LSD graphics, and the dynamic alarm-spot is an innovative contribution to alarm visualization.

7.9 The research contribution

This thesis contribution is a LSD concept, which is a research-oriented approach for complex processes. It has ben developed to support rapid visual perception of industrial-scale data sets, and to mitigate keyhole effects. The outcome is design principles and accompanying graphics. The contribution is positioned for human-computer interaction, as applied research for LSD design. The concept is validated internally theoretically, and explicitly through user-tests for whole functional LSDs, and through industrial applications in several domains. This thesis research contribution is in line with general design conventions from control room standards and guidelines; however, there are concerns for consistency issues and colour readability. This thesis suggests that IRD is a reasonable approach to LSD design and the research problems. The research contribution is not radical or revolutionary; rather it extends what others have found for computer graphics for smaller displays. The innovative contribution is design-patented graphics.

8. CONCLUSIONS, RECOMMENDATIONS AND FURTHER WORK

This chapter first outlines conclusions based on the research in this thesis, and then recommendations for policymakers, operational companies and vendors (designers). The chapter lastly describes topics for further research work. This chapter´s material is new.

8.1 Conclusions

Research showed that there is a need for a Large-Screen Display (LSD) concept for industrial processes. The response proposed in this thesis is the Information-Rich Design (IRD) concept, which is a graphic concept for designing LSDs. LSD design was categorized as an ill-defined wicked problem, and research methods were for this reason based on a broad perspective, asking two questions: i) how to design for rapid perception of industrial-scale data sets? And, ii) how to avoid keyhole effects in complex processes? The research involved three major activities, which were in accordance with recommendations for interaction design research: i) design studies, ii) design exploration, and iii) design practice. The thesis concludes that the research process and the research questions are well suited for developing a LSD concept.

The theoretical framework that guided LSD design was based on research that explained mechanisms for rapid visual perception of data, and how people have limited visual memory resources. The framework applied rules-of-thumb information visualization principles, and lessons learned from other display concepts. It is found reasonable to provide operators with the bigger picture through the LSD, while leaving details for desktop workstations. This thesis identified mechanisms for LSD graphics: information must be presented externally rather than hidden in display hierarchies (avoiding keyhole); it must include a means for rapid top-down visual search. Further, graphics must support bottom-up data driven processes that trigger primitive pop-out channels for rapid visual perception, and to avoid masking primary data in LSDs. The main weakness is that the research material was not originally meant for LSD design. For this reason, it was necessary to perform user-tests of LSD applications and experience from industrial LSD applications. Based on this research, the IRD theoretical framework is explained through design principles. The thesis concludes that the theoretical framework as a whole is suitable for creating a robust concept.

Design-patented graphic elements have been developed for the IRD concept. The IRD generic indicators which use mathematical part-wise normalized indicators were developed to create visual patterns from process values and their alarm-limits. This is a reasonable approach on rapid perception of process data. Only the trended indicator is found suitable for visualizing plant dynamic response. However, the use of a normalized scale as used in IRD can cause operators to build wrong mental models. The generic indicators visualize: target value; rate-of-change cue; automation data; and alarm information. This is a reasonable approach on keyhole effects by avoiding the need to visit different parts of displays to mentally construct a situation overview. For rapid visual awareness of incoming alarms, a dynamic-alarm spot was developed. This is found to be a reasonable solution and a better alternative to intrusive blinking/flashing for LSDs. The thesis concludes that it´s innovative contribution is the design-patented graphics for LSD design.

The IRD concept is validated from a broad perspective: internal from theories that guided design; and external through user-tests for whole functional LSDs; and from industrial applications in the petroleum, nuclear and mining domain. The IRD concept is mostly found to be in line with industrial standards and guidelines for design. Based on this, the conclusion is that the IRD concept is suitable for real-world use, and it is a reasonable approach to LSD design. This thesis concludes that the IRD concept extends and builds further on research for desktop displays. However, there are some issues raised that need further study. There are concerns for consistency by using mathematical normalized scales in IRD indicators, and for the readability of the grey-layered colour concept for well-lit control rooms. In addition, the IRD concept can cause a consistency problem between the LSD and control room´s other human-machine interfaces.

8.2 Recommendations for policymakers and operating companies

Based on the thesis research work, this section outlines recommendations how the LSD concept can be used. The material in this section is new. Although focus areas for LSD design are mentioned in standards and guidelines, they can benefit from a stronger focus on why companies, which are responsible for safe and environmental operations, should examine their own motivation for LSD design. This thesis contributes by explaining how LSDs must be designed with specific needs in mind. It also suggests how LSD design must be done from a systems perspective, where the LSD presents the general plant overview through specifically designed graphics, while leaving details for desktop workstations. The contributions can also be used for suggesting how to approach problems more specifically at an applied level through proposed design principles and graphics. The detail-level of this thesis proposed design guidance (sections 6.2 – 6.4) accompanied with visual explanations, which should be quite suitable for inclusion in general control room standards and guidelines. One example of how this could be done was suggested by the ASM Consortium guidelines (2013), which combined visual explanations and text. This approach made design guidelines much easier to understand and comprehend compared to the often-used "text only". In addition, as described in section 7.7, the graphics and design principles in this thesis are in line with general recommendations from industrial standards and guidelines. From this, a reasonable approach for policymakers, which are governing bodies who regulate or advise industry, is to extend the existing recommendation with contributions for LSD design from this thesis.

Some industries are more safety concerned than others, and for this reason more conservative when implementing new technology. One such industry is nuclear, where the potential for loss of life and environmental concerns are paramount. One way of approaching this is to provide more quantitative performance-based research data, which could indicate how graphics proposed in this thesis can have a performance benefit compared to other LSD graphics. However, it should be noted that it is the operating energy companies such as Statoil, Shell, E.ON, Fortum and others who ultimately decide on which technologies to use.

Because the contribution from this thesis is at an applied research level, operating companies cannot use the design principles and graphics in this thesis literally or slavishly without further consideration; they must adapt and harmonize LSD graphics with the control room´s other display interfaces for consistency. Below is a summary of the recommendations for governing bodies and operating companies:

- LSD is a reasonable solution for improved Situation Awareness based on operators need for seeing the greater picture of plant´s situation. This thesis suggests how the LSD should provide operators with the big picture, while details can be left for desktop workstations.
- Specific design guidance must be done for LSDs; they cannot be scaled up versions of desktop display pictures. This thesis explains in particular how unfortunate keyhole effects can be avoided through LSD design, while supporting rapid perception of industrial scale data sets.

- The proposed design principles and LSD graphics are useable at an applied level as guidance for LSD design. But the design must be harmonized with the other graphic interfaces in the control rooms; handbooks or guidelines must consider this.

The final question has to do with detailed design based on operating companies' specifications. This is often left for industrial vendors, such as ABB, Siemens, Honeywell, or consultant companies with graphics design skills. Again, the principles and ideas developed in this thesis cannot be used directly in a specific vendor's graphics library – they will need to be adapted to the specific circumstance (often to the level of individual projects delivered by that vendor).

8.3 Recommendations for Large-Screen Display designers

The graphics and design principles from this thesis can be used as a reasonable starting point for LSD designers (sections 6.2 - 6.4). Some vendors, such as ABB, Siemens and Kongsberg-offshore have already implemented versions of IRD normalized graphics into their software libraries. This makes it easier and faster for designers and developers to design LSDs. However, as the thesis explains, there is more to LSD design than just the provision of a library of standard graphic elements. Designers should pay attention to specific plant concerns in graphics layout: following plant conventions for flow directions; for elements position; and to include familiar physical structures for providing context for process data.

Designers should pay particular attention to colours and visual complexity, which are two problematic areas in design of larger scaled displays. Although colour layering is a well-known and accepted concept, it has proven difficult to "tune" in to this for LSD design. There is a risk of either ending up with too-bright, tiring LSD, or too washed-out, giving sub-optimal readability. LSD designers should also pay attention to finding the sweet spot for visual complexity (Figure 12). It was not the information-dense LSDs, such as the Loviisa LSD (Figure 38) that operators accepted; it was rather the less complex and less abstract Halden Reactor LSD (Figure 44). Recommendations for designers are to design for visual simplicity, focusing on: key variables; including open space; and showing physical structures and lines for improved top-down search and visual familiarity. This has also a secondary positive effect, as it is easier to implement and service a less complex LSD. Designers should also consider strengths, and weaknesses with different display technologies. In particular front-mounted video projectors have been problematic in well-lit control rooms using the grey-colour layering concept.

A user-centred process is suitable for industry LSD design (section 6.3, and in paper 10). Designers should encourage a process concerning: base design upon an explicit understanding of users, tasks and environments; involve users throughout design and development; refine and drive design through user-centred evaluation; use iterative design process; address the whole user experience and lastly; include multidisciplinary design team with broad skills and perspectives. Designers should sketch prototypes early in the development process, and show them on the actual LSD technology in a live control room setting (or a mock-up or laboratory of reasonable fidelity). This can minimize problems later in implementation in the field, as both background and foreground colours can be adjusted prior to installation.

Based on the author and the IFE design-team´s industrial experience, an iterative design process is best supported through rapid sketching tools, rather than trying to use implementation software for LSD prototyping. IFE´s design team has used Microsoft Visio, Concept Draw and OmniGraffle for sketching LSD graphics, rather than to build prototypes directly using a vendor's interface and symbol library. In this approach, the end result is a "static" LSD picture, which can be used as basis for implementable graphics. The advantage of this approach is how designers can easily make changes, creating new elements and do re-design rapidly.

8.4 Further research work

As mentioned earlier, safety-oriented domains such as nuclear authorities are conservative when it comes to new design concepts. They demand well-documented, quantitative results demonstrating good performance, sometimes including a validation test of whether a new design will perform at least as well as older solutions as a minimum requirement. This suggests that there is a need for more performance data for external validation of the IRD concept, to include measurement of Situation Awareness levels, and to make comparisons with other concepts. Eye-tracker data showing operators scanning strategies for IRD displays could be beneficial for this purpose. Such data can provide insights in how effective graphics work for top-down search, and how bottom-up pop-out effects trigger a response from the operators. More research should be done on the consistency issues with other control room interfaces, and the effects of using part-wise mathematical normalization in the IRD concept. Do the normalized graphics proposed in this thesis affect process operators' mental models of the process in a negative way? This is important for ensuring that control room graphical interfaces support a good user experience and high performance. Since IRD graphics and the design principles are meant for industrial control room applications, as a part of a larger systems perspective for control room design, it is clear how the IRD concept could benefit from more focus on how to ensure a user-centered design process is followed. Further work should therefore focus on the design process for integrating LSD holistically in control room design.

One challenge in design is finding the sweet spot for complexity and innovation. Should new ideas be embraced, or rather should one stick with tradition? As this thesis suggests; building on traditional conventions explored through full-scale implementations is a quite safe route for getting the concept useable. This view is also supported by Norman (2004), in discussing screen interface principles, he stated: *Those who violate conventions, even when they are convinced that their new method is superior, are doomed to fail*. However, sometimes conventions must be challenged. One example is the Ecological Interface Design concept. They created a concept supportive for unlikely and unanticipated events by challenging the typical industrial Single-Sensor-Single-Indicator (SSSI) philosophy (Vicente and Rasmussen, 1990). Instead, they explored and visualized higher order fundamental domain properties. It is evident how it may be necessary to go beyond SSSI philosophy for LSD design, particularly for safety-concerned domains. It is therefore reasonable that the IRD concept also could benefit from graphics visualizing the plant´s more fundamental properties (energy, enthalpy, entropy etc.).

There is a need to look into the effects of display technologies, for which the current technologies used for displaying larger display surfaces are: front-projection, rear-projection and LCD panels. The effect of these technologies is particularly interesting when used in well-lit control rooms. IFE researchers and the present author have recently designed LSDs using high-resolution display cubes (eyevis, 2013) for commercial applications for the petroleum domain. Even though this type of technology introduces unfortunate visible frames in the LSD as thin lines, it also increases the contrast ratio and brightness. Such technology appears to us as an advantage, particularly when using grey-scale colours.

So far, the IRD concept has only been concerned with one modality, visual perception. Technology is however evolving rapidly, and there is more to explore in emerging technologies. Touch technology is particularly interesting. Can operators interact directly with the process through touch technology on larger high-definition surfaces? What opportunities exist for the use of haptic feedback from the display surface? Audio signals have traditionally been used for announcing new alarms; could it be integrated in better ways with LSD graphics? Other domains, such as finance and economics also experience challenges by coping with larger scale data sets. Some of the problems in finance and trading are quite similar to operating industrial processes. That is to perceive the larger picture of financial situation, comparing values with target rates, look for deviations from expected values within constraints. Can the generic mathematical normalized IRD indicators be used for this purpose? It could be interesting to look into this, to transform these data sets into simpler visual patterns for rapid visual perception.

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Part II: Research Papers (papers 1-9)

The research papers of this thesis given in chronological order:

Paper 1: Braseth A.O., Welch R., Veland Ø. (2003). A Building Block for Information Rich Displays. Paper at IFEA conference, Gardermoen, Norway.

Paper 2: Braseth A.O., Veland Ø., Welch R. (2004). Information Rich Display Design, paper in Proceedings, Forth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Controls and Human-Machine Interface Technologies NPIC&HMIT, Columbus, Ohio, USA.

Paper 3: Braseth A.O., Nurmilaukas V., Laarni J. (2009). Realizing the Information Rich Design for the Loviisa Nuclear Power Plant. Paper in Proceedings, Sixth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies NPIC&HMIT, Knoxville Tennessee, USA.

Paper 4: J. Laarni, H. Koskinen, L. Salo, L. Norros, A.O. Braseth, V. Nurmilaukas (2009). Evaluation of the Fortum IRD Pilot. Paper in Proceedings, Sixth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies NPIC&HMIT, Knoxville Tennessee.

Paper 5: Braseth A.O., Nihlwing C., Svengren H., Veland Ø., Hurlen L., Kvalem J. (2009). Lessons learned from Halden Project research on human system interfaces, Nuclear Engineering and Technology, An International Journal of the Korean Nuclear Society, Vol. 41, No. 3, pp. 215-224.

Paper 6: Braseth A.O., Karlsson T., Jokstad H. (2010). Improving alarm visualization and consistency for a BWR large screen display using the Information Rich Concept. Paper in Proceedings, Seventh American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies NPIC&HMIT, Las Vegas.

Paper 7: Braseth A.O., Øritsland T.A. (2013). Visualizing Complex Processes On Large Screen Displays: Design Principles Based On The Information Rich Design Concept, Elsevier Displays, No 34, pp. 215-222.

Paper 8: Braseth A.O., Øritsland T.A. (2013). Seeing the Big Picture: Principles for dynamic process data visualization on Large Screen Displays, in Proceedings of Complexity, Cybernetics, and Informing Science and Engineering, Porto, Portugal, pp. 16-21.

Paper 9: Braseth A.O. (2013). Evaluating usability of the Halden Reactor Large Screen Display: Is the Information Rich Design concept suitable for real-world installations? International Journal of Nuclear Safety and Simulation, Vol. 4, No. 2, pp. 160-169.

PAPER I

A Building Block for Information Rich Displays

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Abstract

This paper presents a feature called "the building block" developed for use in design of *Information Rich Displays. The purpose of Information Rich Displays (IRDs) is to condensate* prevailing information in process displays in such a way that each display format (picture) contains more relevant information for the user. The need for a new approach to offshore display design is in particular based on shortcomings in today's designs related to the *key-hole effect*, where the display format only reveals a fraction of the whole process. Furthermore, the upcoming introduction of larger off- on-shore operation centres will increase the control room operators' *work domain* and workload due to the need of operating several processes in parallel. The proposed *IRDs* aim to meet this increasing workload by providing more relevant information to the operator.

Background

We have experienced several shortcomings related to today's VDU process control display design when participating in offshore control room modernisation projects. The problem often relates to the operator's lack of relevant process information. Today's VDU displays only reveal a fraction of the total process; this is often referred to as the *key-hole effect*. Operators are struggling to get the whole view of the process; an often heard statement from operators is "I need more VDUs to get a good overview". The work domain and work style will probably also change in the future due to larger operation centres where operators must operate several processes in parallel. By introducing parallel processes the operator's mental capacity is challenged and one can expect a reduction in performance, referred to as the *cost of concurrence* [1]. Introducing parallel processes to the operator with today's display design practise which is vulnerable to the *key-hole effect* might lead to poor operator performance.

Many companies have taken a technical approach to solve these problems in later years; this technical approach often includes purchasing expensive large screen displays and/or introducing a huge amount of small flat screens. This approach to solve the *key-hole effect* often fails due to poor quality of the information presented. Even if the wrapping is new and shiny, the information presentation is based on the same old presentation principles.

Our approach to solve these problems is to bring forward a new process control design based on *good design principles*. These *principles* are founded in many areas of design such as maps, statistics, electronics and others. The design approaches in these areas are often more mature and in better accordance with *good design principles* than today's process control displays.

Approach

Our main goal is to reduce the problems related to the *key-hole effect* by reducing the total number of process control displays compared to today's offshore standard. The total number of displays often exceeds 300 in ordinary process control systems; and since one operator only uses 2-4 VDU's actively, he only sees a fraction of the total process at one given time. Reducing the total number of displays lead to more information on each VDU. This might seem to be an odd approach because looking at standard displays they might already look crowded. The reason for this *cluttered* look is however related to poor design and not the amount of information presented. The design typically consists of static information presented with thick lines and vibrant colours. The valuable dynamic information essential for the operator is "hidden" in this *cluttered* design. A typical VDU process control display consists of typically 10 - 40 valuable dynamic entries. Compared with good design within other areas such as medicine, health and cartography this is "catastrophic"; it is not unusual to se designs where 1000 – 10.000 relevant data points can be presented. This means that there is a considerable potential to be exploited.

Our goal is not only to present the information in a *condensed* form, meaning presenting just more data on each display, but more to present *Information Rich Displays (IRDs)*. Our language has a large number of terms to describe different ways to pick up information, such as to see, view, read, inspect, perceive, check, monitor, examine, study, observe, inquire, glance at, be drawn to, verify and analyze. *IRDs* are designed to support the diversity found in this list of words. The purpose of *IRDs* is to be similar to the flexible and adaptive way in which we perceive our natural environment in everyday tasks.

IRDs should also be designed to meet the challenge related to the *cost of concurrence* described earlier. This cost is highly dependent on what kind of mental resources that the interface design relies on. The simple *Skills*-, *Rules*- *Knowledge* (SKR) model [7] describe the wide range of mental capabilities we use in everyday situations:

- *Skill based* behaviour is found in very "low level" control activities like positioning a mouse cursor or steering a car, where we perceive a continuous stream of signals from our environment and process it extremely efficiently into appropriate action. We can do this almost without paying attention to it, and the parallel capacity for such behaviour is large.

- *Rule based* behaviour is used when we encounter a familiar situation or event and perform a corresponding "normal" response. These automated responses are triggered by visual *cues* in the environment, like stopping on red light, or stopping when a car comes in from the right hand side. Rule based behaviour requires previous experience from similar situations in an environment that has allowed us to learn to recognize complex patterns that can serve as cues.

- *Knowledge based* problem solving is a complex process of gathering and integrating information from various sources, interpret it to find out what is really going on, planning and executing a proper response. This is mentally demanding and requires full attention, the response is slow and error prone and has poor parallel capacity.

Today's displays direct the users to knowledge based reasoning because they require them to memorize, compare and integrate different data while navigating between different information sources. The visual appearance of the displays remains practically unchanged regardless of the situation, and therefore provides few visual cues for effective *rule* based behaviour. The basic information coding and interaction principles in today's displays are often based on reading digital values and thus they do not supporting *skill* based operations.

Information Rich Displays on the other hand, aims to support operators in utilising their powerful *skill* and *rule* based capabilities in their work, by coding individual data in visual elements that can be perceived directly, and by integrating and arranging these different elements into complete displays in which multiple levels of pattern recognition can be applied by the user. This will support problem solving by freeing mental resources that would otherwise be tied up in "trivial" subtasks.

Our initial task was to develop a building block, which could act as a basis for representing basic components such as separators, heaters, valves etc. We soon came up with several different types of building blocks, but we have concentrated our efforts first on a building block for the separators, as they are very important units to present correctly.

Design principles supporting information rich design

Some overall requirements have been defined for the design of *Information Rich Displays*

- Avoid *key-hole effect by aiming for high information density* (number of data points per unit area) in the displays.
- Provide a wide variety of reading strategies for different task requirements.
- Provide a clear mapping between importance and visual salience (noticeable).
- Make the exact value of each individual data point directly available.
- Provide means for simple visual comparisons between different data points.
- Support *pattern recognition by providing* means to identify patterns in the data set as distinct and recognizable.

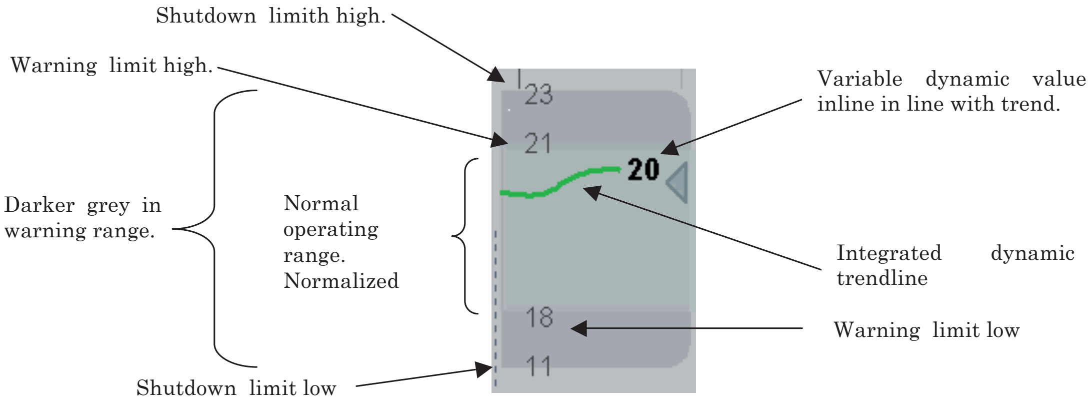
The individual "building blocks" should be designed not only to work optimally as individual pieces, but with careful consideration on how they combine into larger objects and structures and how these influence the visual search and scan patterns of a user. Tufte [2] describes this as *micro-macro* representation of data. *Macro* representation takes into account the operators' powerful *pattern recognition* skills and supports these. For instance, we have noticed that the experienced operator often prefers to read variables as time series in trend plots. During the work with the *IRDs* we came to share this view and it became therefore our goal to integrate time series to support *pattern recognition* and therefore *micro-macro* readability.

Careful design of symbols and use of colour and contrast can support the impression of several visual layers in the graphics. Visually salient layers should contain important information to be scanned easily. This means that such designs need to be based on knowledge of the relevant relationships between data, the consequences of deviation, and the sequences in which they should be inspected.

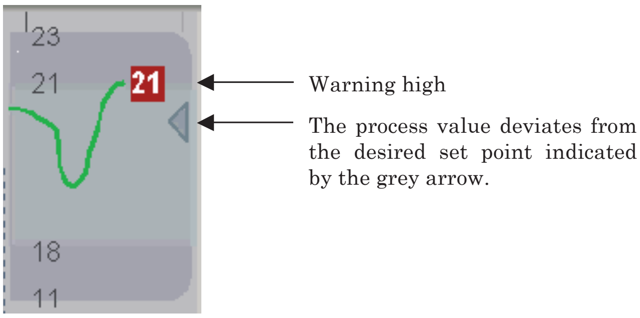
In our work on large screen overview display designs we have developed the *Dull Screen* principle for using colour to reduce visual clutter in displays to a minimum [6]. In this concept, bright and saturated colours like red and yellow are reserved for signals requiring urgent actions like warnings and alarms, while static elements with little meaningful information content are presented in a faded grey not to interfere with the more important information. This principle was inspired by the mature graphical design principles found in i.e. cartography, and this idea has recently been supported by empirical research on colour use and visual search strategies in process control displays [8], [9]. The dull screen concept reduces the undesired visual complexity, and in the *IRDs* we utilise the possibility this creates for actually increasing the amount of useful information in each display.

Design of the separator building block

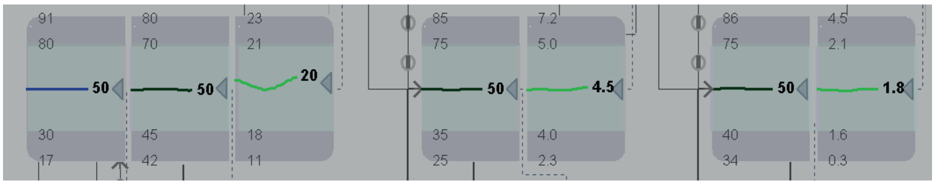
The main building block for the separator is shown below:



The process value is presented by both a trend line and the actual value. The building block consists of two darker grey areas and one light grey area. The light grey area represents the normal operating range. When the trend line and variable enters the darker grey area a warning is given by a symbol as shown in the figure below:



The power of the building block appears as it is integrated to several units. The figure below shows a three-phase separator followed by two two-phase separators.



The colours indicate the variable type: blue is water, dark green is oil and light green represents the gas phase.

This design supports *pattern recognition* by the fact that the ideal variable set point can be identified to be in the middle of the light grey area on the building block. Viewing all the three separators it is evident that the user (operator) can get the overall status of the separators by a glance, just by checking whether the timeline is roughly on a horizontal line. This is supporting the idea of *micro-macro* readability, and the user can choose to either read each exact digital value or just view the timeline values. When looking at the display as a *macro* representation with the timelines as *patterns*, it supports the demand of operating at *skill* and *rule* based level.

The building block is created by means of the highly flexible Picasso [5] software package developed by IFE.

Further work

Other units such as pumps, compressors etc. will be developed and tested to match the already existing building block to give a uniform design supporting the ideas of *Information Rich Displays.* The suggested building block will be used when building prototypes of *IRDs*

Conclusions

A new feature called "the building block" has been developed in the context of *Information Rich Displays.* The purpose of IRDs is to condensate prevailing information in process displays information for the user. The first in a series of building blocks have been discussed as well as how the building blocks can be aligned in a horizontal design where they provide in such a way that each display format (picture) contains more relevant *macro* readability that can support *pattern recognition* and *skill* and *rule* based readability.

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PAPER II

Forth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Controls and Human-Machine Interface Technologies (NPIC&HMIT 2004), Columbus, Ohio, September, 2004

Information Rich Display Design

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ABSTRACT

This paper presents the concept Information Rich display Design (IRD). The purpose of Information Rich Design is to condense existing information in process displays in such a way that each display picture contains more relevant information for the user. Compared to traditional process control displays, this new concept allows the operator to attain key information at a glance and at the same time allows for improved monitoring of larger portions of the process. This again allows for reduced navigation between both process and trend displays and ease the cognitive demand on the operator. The concept is based on weighing and classifying the relevance of types of information presented to users. By using well-proven principles from graphical design it visualizes this information in a manner that reflects its relevance. The IRD concept can supplement and complement other design concepts that are innovative in terms of their information content and/or visual form.

The concept was originally created for the operation of offshore petroleum production facilities. An offshore control room operator has to deal with a complex process where there is little redundancy in the main process functions. Due to the nature of the process medium, potentially hazardous situations may arise if safety constraints are not respected. Therefore there is focus on early detection and handling of abnormal conditions and events that may affect both production and safety. A new approach to offshore display design is necessary due to shortcomings in current design. The keyhole effect is one important cause to problems, as each display only reveals a fraction of the whole process. The IRD concept should also be relevant and easily applicable to other industries where the detection of incipient abnormal events may be critical to maintaining production and safety, such as the nuclear industry.

The information content and amount being presented to the operator in a display should be viewed in context of the wide range of different roles the operator is likely to have when using the display. For instance, an operator in a highly stressful situation with high workload within a limited amount of time should not have to deal with large amounts of information that is not relevant to that situation.

We describe how we have attempted to gain high quality feedback by engaging users and other personnel in in-depth dialogue so that responses become better reflected. A conscious use of iterations has also been an important part of the approach used, because creative design work should not be reduced into a set of sequential steps. This paper also describes how and why we have tried to look behind the traditional ways of improving existing display formats and instead have attempted to create a new design using an approach that goes beyond merely considering user preferences or following existing guidelines for display design.

1. INTRODUCTION

A user working with a lot of information that is badly displayed will often use a lot of mental effort on memorization and calculation. In addition to being time-consuming, these tasks are cognitively complicated and therefore greatly affect the work the user is able to do with traditional designs. This means that traditional displays can confine the way the user works and therefore limit what he/she is capable of.

In the last few years a new way of considering information visualization has emerged. In this new method, the role of the designer changes quite dramatically from merely taking an existing display and "upgrading" it by enhancing usability and other factors, to looking behind existing display concepts and considering what information the user actually needs. This information should then be presented in a manner that supports both existing and new ways in which the user can understand and use the information. This new approach has been labeled "User Enabling", and aims to allow the user to develop and use entirely new strategies for how to work.

The IRD concept has been created while designing display prototypes for offshore petroleum production facilities. Offshore installations basically consist of wells, separation trains (where oil, gas and water are separated from each other), an oil tax measurement system (where oil quality is measured and the pressure increased to allow for export), gas compression (compression of gas for export) and utility systems (water treatment, chemical systems etc.). This means that an offshore control room operator has to deal with a complex process where there is little redundancy of main process functions. In addition, due to the nature of the process medium, potentially hazardous situations may arise if safety constraints are not maintained. Therefore there is focus on early detection and handling of abnormal conditions and events that may affect both production and safety.

Both the content and visualization of content in today's VDUs include several shortcomings. Displays only reveal a fraction of the total process; this is often referred to as the keyhole effect. Operators struggle to get a complete understanding of the state of the process; an often-heard statement from operators is "I need more VDUs to get a good overview". In addition, the work domain and work style will probably also change in the future due to the introduction of larger operation centers, where operators may have to operate several processes in parallel. By introducing parallel processes the operator's mental capacity is challenged and one can expect a reduction in performance, referred to as the cost of concurrence (Wickens, 1984). This effect will be further amplified if today's display design practice is continued.

Many companies have taken a technological approach to solve these problems in later years, such as introducing large screen displays and increasing the number of VDUs. However, this approach often fails due to poor quality of the information presented.

2. Approach

The ideas and concepts presented in this paper have emerged from practical design work that has been mainly problem-driven rather than theory-driven. This means that we have attempted to address challenges and problems we have observed within the offshore industry. Our proposed solution is a new human-system interface design concept based on established graphical design principles from other areas of graphical design such as cartography, statistics, and others. These areas are often more mature and in better accordance with good design principles than today's process control displays are.

We have attempted to look behind the traditional display designs in offshore installations and instead focused on visualizing the information in a manner that supports the operator in different situations.

The simple Skill, Rule, and Knowledge based (SKR) model (Rasmussen et. al. 1994) describes the wide range of mental capabilities human beings use in everyday situations:

· Skill based behavior is found in very "low level" control activities like positioning a mouse cursor or steering a car, where we perceive a continuous stream of signals from our environment and process it extremely efficiently into appropriate action. We can do this almost without paying attention to it, and the parallel capacity for such behavior is large.

· Rule based behavior is used when we encounter a familiar situation or event and perform a corresponding "normal" response. These automated responses are triggered by visual cues in the environment, like stopping on red light, or stopping when a car comes in from the right hand side. Rule based behavior requires previous experience from similar situations in an environment that has allowed us to learn to recognize complex patterns that can serve as cues. Parallel capacity at rule-based behavior is moderate.

· Knowledge based problem solving is a complex process of gathering and integrating information from various sources, interpret it to find out what is really going on, and planning and executing a proper response. This is mentally demanding and requires full attention, the response is slow and error prone and has poor parallel capacity.

This lead us to try to analyze what roles an operator has while doing his/her job and what kind of mental capabilities should be supported in these roles, and through this decide the information that is relevant to visualize. In doing this, we created a diagram, see figure 1, that shows the roles an operator can fill in a modern control centre setting and his/her need for information to support each role.

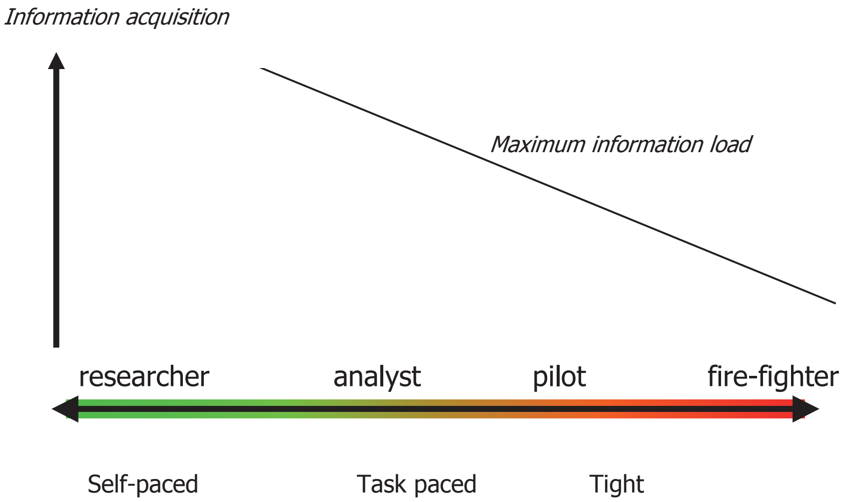

Figure 1. The different roles of an operator.

The operator is often viewed only as the traditional real-time “process pilot”, whose main tasks are to monitor the plant and make corrections if necessary. However, if the operator is only presented information to support this role, then information the operator needs to fill the other roles would be less easily available or in some cases not even available at all. In critical situations the operator acts more as a “fire-fighter”, working at high stress levels and great concentration to understand and find the solution to a problem. In situations like these, the operator should easily be able to pick up necessary information from a known environment. It is also important to avoid elements that may confuse the operator. Showing temporal information is also positive since the operator’s sense of time may be distorted in a highly stressful situation. In the “process pilot role” the operator needs to be able to get an overview of the process situation at a glance making him/her able to efficiently monitor the process. It is also important to make sure that the information the operator needs includes overviews logically displayed so that time and mental resources is not spent to find and interpret such information.

When the operator has more time available, he/she may perform more slowly paced tasks like analysis and research in addition to the real-time operation of the plant. These types of tasks are voluntary for offshore process operators and in addition each set of tasks is unique. Because of this, it may be difficult to decide which information that should be presented to support these tasks through traditional methods such as task analyses. As an “analyst”, an operator examines situations and attempts to get important knowledge by comparing them with similar patterns from similar situations. While these tasks may be complex, the presence of clear goals and previous experience can allow operators to rely on rule-based behavior if information is displayed in a way that supports this. This means that the display should reveal patterns so that it becomes easier for the operator to compare situations. Temporal information can also allow the operator to recognize and compare dynamical situations more easily.

As a “researcher”, the operator attempts to get information about the process not only through recognizing patterns and comparing them, but also by using knowledge based behavior and attempting a more in-depth study of the process. Not having well-defined goals, the operator is mostly trying to gain knowledge about the work domain rather than responding to a specific event or looking for a predefined piece of information.

Users are often forced to rely unnecessarily on knowledge based reasoning because they have to memorize, compare and integrate different data while navigating between different information sources. The visual appearance of the display formats remain practically unchanged regardless of the situation, and therefore provides few visual cues for effective rule based behavior. Furthermore, the basic information coding and interaction principles in display formats of today are often based on reading digital values and therefore do not support skill-based perception.

Information Rich Design on the other hand, aims to support operators in utilizing their powerful skill and rule based capabilities in their work, by coding individual data into visual elements that can be perceived directly, and by integrating and arranging these different elements into complete display formats in which multiple levels of pattern recognition can be applied by the user. This will support problem solving by freeing mental resources that would otherwise be tied up in "trivial" subtasks. This is invaluable when the operator is doing real-time tasks such as “fire-fighting” or “process-piloting”. As can be seen in figure 2, IRD is mainly designed to cover these two operator roles, however, as it contains some features that support rule-based behavior it may also somewhat cover the role of an “analyst”.

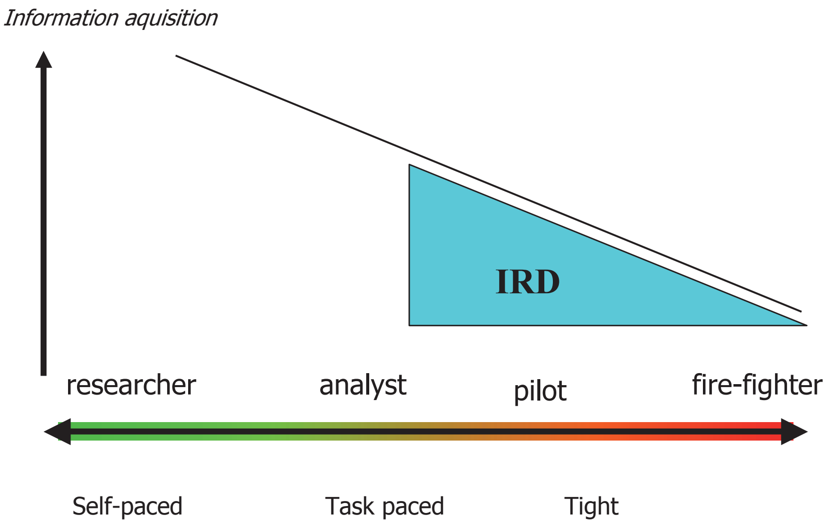

Figure 2. The roles covered by IRD.

When designing Information Rich displays we have attempted to gain high quality feedback by engaging users and other personnel in in-depth dialogue so that responses become better reflected. This is to make sure that the information we choose to present is also the information the users need and that the way we choose to present the information is comprehensible to the users. It is however important to realize that it can still be quite challenging to find the needs of the user. This is because the user may not be aware of what information she/he actually needs. A reason for this can be that the user has long experience with an existing system and knows its weaknesses so well that they are no longer seen as weaknesses. Another important reason is that the user may not be aware of what or how information is used. This is tacit knowledge for the user and we experienced that this information could be obtained from users through dialogue. Users were questioned about how they understood the process so that they became conscious about how they think and therefore they became more easily able to convey their needs.

We have also used iterations consciously to make the design process as efficient as possible. Iterations are important, as they allow the designer to step back and consider the effects of decisions that have been made and then use them to improve the design. We found that an effective way of using iterations was to partially implement unfinished and imperfect designs in early prototypes, and use this rapid prototyping to discover new possibilities to be included as well as problems that need to be fixed.

3. THE GOALS OF INFORMATION RICH DESIGN

IRD aims to reduce the problems mentioned earlier related to the keyhole effect by reducing the total number of process control display formats. The total number of display formats often exceeds 300 in ordinary offshore process control systems; and since one operator only uses 2-4 VDU's actively, she/he only sees a fraction of the total process at one given time. Reducing the total number of displays lead to more information on each VDU. While standard displays may already look crowded, this visual clutter is more due to poor design than to the amount of information presented. The design typically contains static and dynamic information at the same visual level. For instance, thick lines and vibrant colors are commonly used to show static information, while the valuable dynamic information is "hidden" in this cluttered design.

A typical VDU process control display format consists of typically 10 - 40 valuable dynamic data points. Compared with good design within other areas such as medicine, statistics and cartography this is really low. It is not unusual to find designs where 1000 – 10.000 relevant data points are presented. This means that there is a considerable potential to be exploited.

The goal of IRD is not only to present the information in a condensed form, meaning presenting just more data on each display, but also to present true information rich design. Information Rich displays are designed to be used in a similar fashion as the flexible and adaptive way in which we perceive our natural environment, and therefore allow the operator to work in a manner that best suits the situation or his/her personal preferences.

Many human-centered design approaches concentrate on how to identify the information content while being either vague or conventional when it comes to how to actually present this information. While not specifying a method for identifying the information to be visualized, the focus of IRD is on weighing and classifying the relevance of types of information as well as visualizing this information in a manner that reflects its relevance. Through deemphasizing less relevant display items it becomes possible to create displays with high information density that at the same time are easily readable.

The IRD concept can therefore supplement and complement other design concepts that are innovative in terms of their information content and/or visual form, such as Ecological Interface Design.

4. GENERAL DESIGN CHOICES

Our design uses individual shapes or "building blocks" that are the foundations used to represent basic process units. These building blocks are designed not only to work optimally as individual display elements, but also with careful consideration of how they combine into larger objects and structures and how these influence the visual search and scan patterns of a user. Tufte (1983, 1990, 1997) describes this as micro-macro representation of data. Macro representation takes into account the operators' powerful pattern recognition skills and supports these.

It is well known that instead of reading exact process parameters, experienced operators often prefer to monitor the development of parameters over time using trend plots. Based on this, an important design goal was to integrate trends in the basic building blocks and thereby allow operators to use pattern recognition in observing process behavior.

Careful design of symbols and use of color and contrast can create the effect of having several visual layers in the graphics. For instance, visually salient layers should contain important information to be scanned easily. Designs that utilize layering to support effective reading and interpretation need to be based on knowledge of the relative importance of different types of data and ways in which data types are related.

In earlier work on large screen overview display designs we have developed the Dull Screen principle for using color to reduce visual clutter in displays to a minimum (Haukenes et. al., 2001). In this concept, bright and saturated colors like red and yellow are reserved for signals requiring urgent actions like warnings and alarms, while static elements with little meaningful information content are presented in a faded grey tone, to avoid interference with the more important information. This principle was inspired by the mature graphical design principles found in e.g. cartography, and this idea has recently been supported by empirical research on color use and visual search strategies in process control displays (Van Laar, 2001 & 2002). The Dull Screen concept reduces the undesired visual complexity, and in IRD we further utilize the opportunity this creates for actually increasing the amount of useful information in each display.

We hope that through these design choices IRD should be able to:

- Avoid keyhole effect by aiming for high information density (number of data points per unit area) in the displays.
- Provide a wide variety of reading strategies for different task requirements.
- Provide a clear mapping between importance and visual salience
- Make the exact value of each individual data point directly available.
- Provide means for simple visual comparisons between different data points.
- Support pattern recognition by providing means to identify patterns in the data set as distinct and recognizable.

5. DESIGN OF THE SEPARATOR BUILDING BLOCK

The separator is an important piece of equipment in the offshore petroleum process. It can either be a two-phase separator, used to separate oil and water, or a three-phase separator, used to separate oil, gas and water. Figure 3 shows a traditional representation of a two-phase separator:

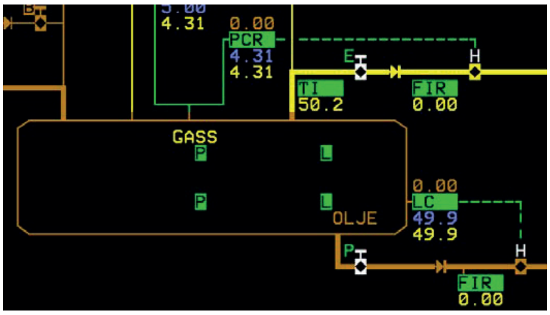

Figure 1. Traditional representation of a separator.

The IRD main building block for the separator is shown in figure 4. A two-phase separator consists of two such building blocks, one for oil and one for water. A three-phase separator consists of three building blocks, also one for each fluid type.

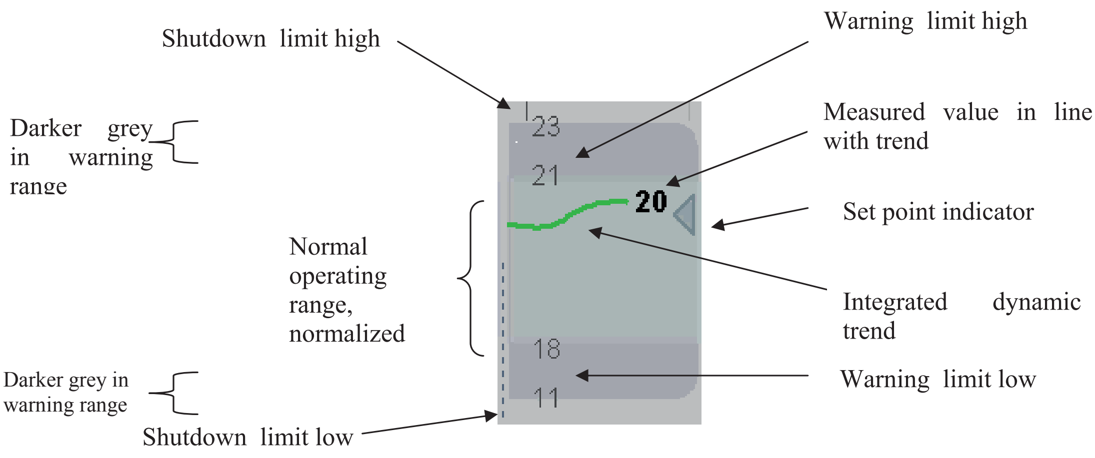

Figure 4. The separator building block.

The process variable is presented by both a trend and the actual value. The building block consists of two darker grey areas and one light grey area. The light grey area represents the normal operating range. This is in accordance with NUREG 0700 - 1.1.17,18 and 19. When the process variable enters the darker grey area a warning is given by a symbol as shown in the figure below:

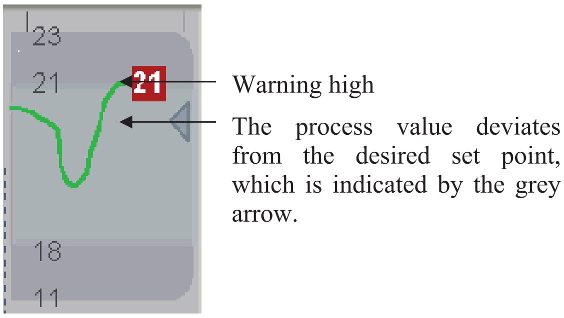

Figure 5. Functions of a separator building block

The power of the building block appears when it is integrated together with several units. The figure below shows a three-phase separator followed by two two-phase separators.

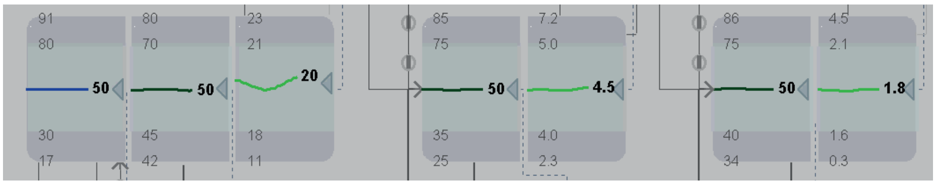

Figure 6. Using pattern recognition to support micro-macro readability

The colors indicate the variable type: blue is water, dark green is oil and light green represents the gas phase.

This design supports pattern recognition because the normal process design set point is located at the exact centre of the light grey area on the building block. When viewing all three separators the operator can get the overall status of the separators at a glance (in accordance with NUREG 0700 - 1.1.14), just by checking whether the trend is roughly at the vertical centre of the unit. This supports micro-macro readability and the user can choose to either read each exact digital value or just view the trend values. This feature is in accordance with NUREG 0700 - 1.1.35.

The Information Rich displays are information “rich” and not just “dense” because they allow the operator to see several different types of meaningful patterns ranging from a detailed measurement level and up to an overall situation overview level. This allows the operators to work more on the simple skills and rule based levels of behaviour.

The building block is created by means of the highly flexible Picasso (www.ife.no/picasso) software package.

6. CONCLUSIONS

The purpose of Information Rich Design is to condense existing information in process displays in such a way that each display picture contains more relevant information for the user. The concept is based on weighing and classifying the relevance of types of information presented to users. Through deemphasising less relevant display items it becomes possible to create displays with high information density that at the same time are easily readable. The IRD concept can supplement and complement other design concepts that are innovative in terms of their information content and/or visual form, such as Ecological Interface Design and Function Oriented Design.

In addition we have tried to look behind the traditional ways of improving existing display formats and instead have attempted to create a new design based on user requirements. To do this, we have created a simple conceptual model of how an operator’s focus, capabilities and limitations vary between the different roles that he/she is expected to fill in the control room under different circumstances. We have used this model to illustrate how the IRD concept supports both the needs of the “pilot” and “fire-fighter” roles in the same display. Through dialogue with operators we have managed to confirm that the chosen information is relevant in these situations. A conscious use of iterations has also been an important part of the approach used. We believe that creative work cannot be reduced to a set of sequential steps.

A separator building block has been discussed, as well as how several units of the building block can be aligned so that they together provide more relevant macro readability compared to regular display formats. This type of display formats supports visual scanning, and skill and rule based readability in a more efficient way. While not described in this paper, other unit symbols such as pump-, compressor-symbols have been developed and tested to match the already existing separator building block to give a uniform design supporting the ideas of IRD. The analysis and design methods will also be used for developing new display format concepts to verify that they can be applied to display format design in general.

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PAPER III

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REALIZING THE INFORMATION RICH DESIGN FOR THE LOVIISA NUCLEAR POWER PLANT

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ABSTRACT

The Information Rich Design (IRD) concept has since 2005 been widely accepted as the industry standard for Large Screen Displays (LSD) for the Norwegian offshore oil industry. The IRD design has so far only been used for oil and gas process implementations, but the nuclear power plants in Sweden and Finland have recently expressed their interest in developing large screen display prototypes based on the IRD concept. The first prototype has been developed for the development simulator for the Loviisa nuclear power plant in Finland. The development of the Loviisa IRD prototype was performed in 2007 and early 2008. This paper provides a motivation and explanation of some of the main principles behind the IRD concept, and gives a short description of the design process of the Loviisa LSD. A brief description of the Loviisa process is also given. At the end of the paper some specific design examples and symbol explanations are described.

Key Words: Large screen display, IRD, LSD

1 INTRODUCTION

The Information Rich Design (IRD) concept is developed by Braseth, Veland and Welch [1, 2]. It is design patented by IFE and is currently becoming the reference design standard for Large Screen Displays (LSD) for Norwegian oil and gas installations. The concept, initially designed as an operator type of display with interaction possibilities, has however solely been implemented as a LSD type of display. The main reason for this is that it is considered easier to implement the design for LSDs, as this does not require a "full" reflection of all components and all modes of actual operation.

The interest in IRD from the Nordic nuclear power plants was clearly stated when they participated in presentations showing the IRD design realized for the petroleum domain. A joint project was initiated with the intention of developing LSD nuclear prototypes. The prototypes should be developed sequentially with lessons learned integrated from one design into the next LSD. The first LSD prototype was developed for the Loviisa nuclear power plant, and the implementation is done at the Fortum development simulator reflecting the Loviisa nuclear process.

2 THE LOVIISA NUCLEAR POWER PLANT

The Loviisa nuclear power plant consists of two VVER 440-type pressurized-water reactors, which were connected to the grid in 1977 (LO1) and 1980 (LO2). A power upgrade was implemented in the year 2000. In year 2007, the load factors were 94.6% (LO1) and 96.1% (LO2).

Table 1 Key parameters for the Loviisa units

Reactor type	Pressurized water reactor VVER-440
Electric power, gross	Electric power, gross 510 MW
Electric power, net	Electric power, net 488 MW
Annual electricity generation	Ca. 4 TWh (LO1+LO2: 8 TWh, roughly 10 % of annual consumption in Finland)
Total efficiency	34 %
Thermal power	1 500 MW
Number of fuel bundles	313
Amount of fuel replaced annually	12,5 t
Number of boron steel control rods	37
Primary coolant circuits	6
temperature of cooling water to reactor	265 °C
temperature of cooling water from	300 °C
Pressure	123 bar
Steam generators	6
Steam flow	440 kg/s
Steam pressure	44 bar
Turbines	2
Nominal power	260 MW
Rotation speed	3000 rpm
Cooling water flow	25 m^3/s, from the Gulf of Finland

An operational life of about 50 years is planned for the plant. To support this objective, a large-scale automation renewal project is going on. The automation renewal is planned to be implemented in four stages between years 2008 - 2014 for both units.

The Loviisa nuclear power plant is located near Loviisa town in south Finland, approximately 100 km east of Helsinki. It is owned and operated by Fortum Power & Heat Ltd / Fortum Generation. In the Table 1 the technical specification is given per unit (main parameters). Differences between LO1 and LO2 are minor.

3 A MOTIVATION FOR THE IRD CONCEPT

Designing visual interfaces raises several challenges, one of the main issues is to avoid information overload. A process display might cover hundreds of data points. This might lead to overload and strain on the operators, since our knowledge-based memory typically only holds 5-7 arbitrary digits. There are however methods to access the brain in more efficient ways; one model that the IRD principles are based upon is the SRK model; Skills, Rules, Knowledge [3, 4]:

Skills : Based largely on unconscious processes; large capacity

Rules : Partly unconscious; high capacity but more demanding

Knowledge : Knowledge-based principles; low capacity (5-7 arbitrary digits)

Conscious control systems (knowledge-based) are easily disrupted by affective state, neurological or psychological disability, whereas unconscious systems (skills/rules based) are robust and resist interference from external sources. Unconscious systems are also relatively invariant across the population [8].

It is possible that the evidence of overload reflects more an inappropriate display than limitation of the perceiver [8, 9]. So the challenge is to reach the process operators' unconscious brain capacity supporting skills/rules based operation. One possible way to do this is by supporting pattern recognition. In the examples below the traditional oil process separator display is replaced by an IRD separator design.

Figure 3-1 Traditional design

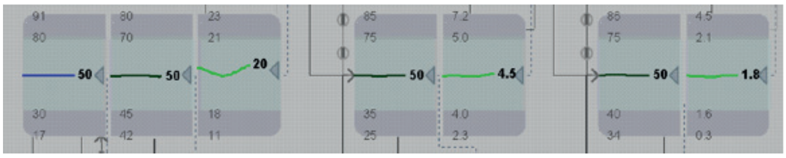

Figure 3-2 New IRD design

As long as the IRD mini trends are forming one long line (Figure 3-2) all variables are on set point, hence the problem is converted from an internal memory task (knowledge-based) to an external visual search [1, 5]. This allows us to design the Loviisa LSD in far more detail, introducing large quantities of data without the risk of constructing operator overload situations.

4 IRD MAIN DESIGN PRINCIPLES

The "Information Rich Design" concept refers to data displays that combine the dull screen color principle [10] with analogue normalized integrated trends to obtain high data density displays without causing information overload. A key feature is that visual forms should be possible to read using different strategies depending on the user's current preference: A brief glance should provide essential information, while closer inspection should yield more detail.

One cornerstone of the IRD concept is the use of normalization. The purpose of parameter normalization is to prepare a group of data for rapid visual scanning. By adjusting the mapping between physical measurement scale and the actual display scale for each data point, states such as ideal, high/low alarm, etc., can be associated with visual properties such as alignment or symmetry. With appropriate design, a group of objects with such properties will appear to the visual system as one single object that can be processed reliably and efficiently. In the example given in figure 4-1, the set point (75 %) is normalized to the centre of the mini trend symbol on the right hand side. H (H1) alarm is (80 %) and L (L1) alarm (50 %).

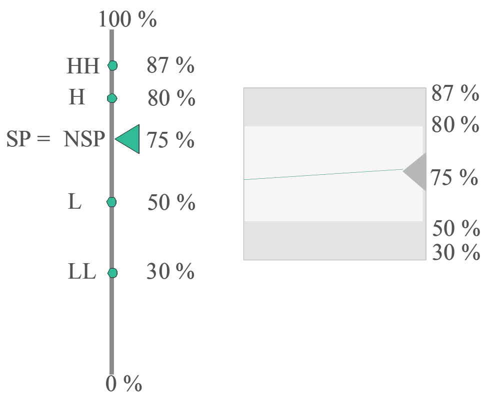

Figure 4-1 Normalization of variables

The effect of normalization can be studied in Figure 4-2 below; all mini trend lines give a continuous line if they are all on the desired normalized set point.

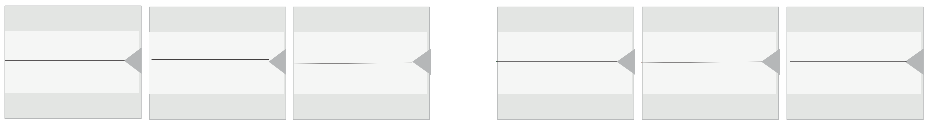

Figure 4-2 Mini trends with normalization

The same example without the IRD specific normalization might look like Figure 4-3; the effect can be observed, as each parameter must be read separately.

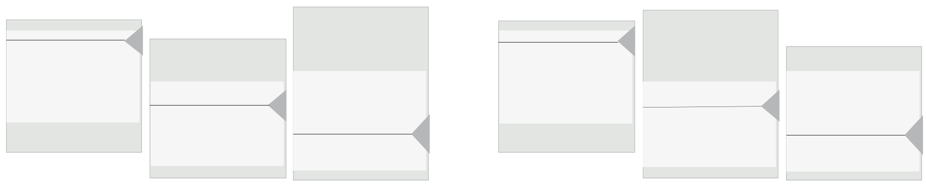

Figure 4-3 Mini trends without normalization

Another cornerstone of the IRD concept is the dull screen principle [10]. The LSD might look a bit dull and out of “focus” at first glance. The reason for the use of grey colors and low contrast in normal operating mode is to provide a display where abnormal situations with alarm colors (red, yellow) easily can be detected.

The LSD shall also contribute to a pleasant working environment for the operator, hence the strong vibrant colors and high contrast can be exhausting in the long run. As can be seen in Figure 4-4; the strong color and contrast on the right hand side map does not provide the reader any additional information [6, 7]:

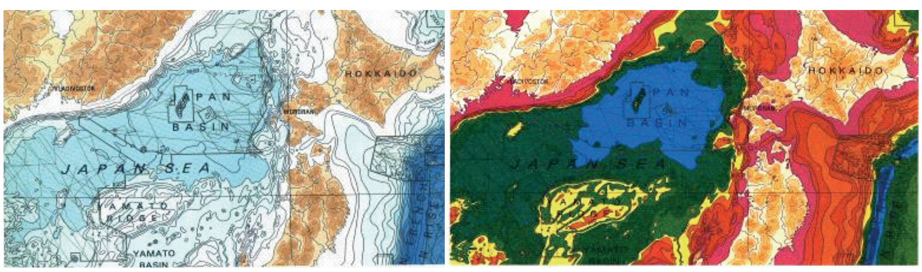

Figure 4-4 Dull screen vs. saturated high contrast map

The concepts and principles presented here aim to align the “automatic” behavior of the human “visual system” with the actual significance of what is presented. Blinking colors are not suitable in this color scheme, as blinking overrides the subtle effects on the visual system that is utilized. A useful categorization of information types in the display are:

- Deviations are important type of information that is given the highest priority by using saturated/bright colors, typically alarms.
- Dynamic information is parameters and states that change continually or occasionally during normal operation. The information is presented by easy readable fonts and dark colors.
- Static information is considered to be of less importance, hence presented typically grey/very low saturation to avoid causing undesirable side-effects for perception of other colors.

5 LOVIISA LSD GOALS AND REQUIREMENTS

During the first project group meetings prior to designing the Loviisa LSD, the project goals were stated as follows:

- Provide relevant and usable information supporting operators work
- Reduce the physical and mental workload
- Increase situation awareness
- Reduce the potential for human errors

The unique role and capabilities of the large screen shall also be used to meet the following additional design goals:

- Provide shared information to facilitate cooperation such as communication, coordination, increasing awareness of tasks.
- At least parts of the large screen should be reserved for permanent, spatially dedicated information such as important process parameters. This shall provide experienced users direct visual access to key parameters and facilitate pattern recognition.
- The LSD shall support normal operation with the possibility to detect deviations as well as support safety related operations.

From these project goals; some general LSD requirements were derived. The LSD shall provide complementary information to the existing workstations. The LSD shall support the operators in normal stable operation, as well as in abnormal process states with a more transient behavior (start-up, normal operation, disturbances). Both key process parameters and safety parameters shall be included. Outage and severe accident situations shall not be included in the design. Although it might be necessary to develop more than one large display to be able to cover the different desired process states, the number of displays shall be as few as possible to ensure that the operators are familiar with the display at any time.

The LSD shall function as a common frame of reference and support easy reading through pattern recognition. Deviations from normal state of operation should be possible to detect prior to appearance of the alarm, and the LSD shall mainly be designed for monitoring, not operation.

Alarms shall be detected in the LSD. Alarm priority and colors shall not be inconsistent with alarm presentation on the operator stations. The LSD shall provide necessary information to help the user understand complex automation in the process where necessary.

6 THE DESIGN PROCESS

The development of the Loviisa LSD differs from the traditional way of designing VDUs, where the operators have practical experience and are familiarized with the typical traditional P&ID type of design. A rapid prototyping technique was used in the design process. This enabled the project participants to experience an action-reflection process [11]. By utilizing this process, new ideas could be accepted or rejected as solutions for the Loviisa LSD. In order to let the design solutions mature, the time span in this type of design process should not be too short. The Loviisa design was developed for more than a year with five intermediate workshops; especially important in this process was the participation of former Loviisa operators, providing valuable input to the design.

During the design process the contents of the large screen display were altered due to comments, discussions and operator influence as long as it did not violate the IRD design principles.

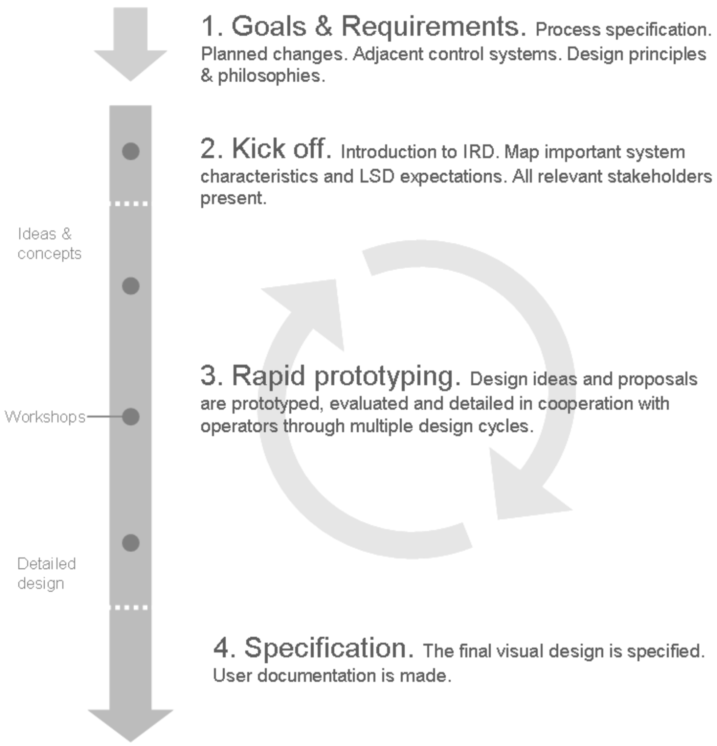

Figure 6-1 The design process used to develop the IRD large screen

Since the Loviisa plant already had a functional but traditionally designed LSD (Figure 8-6), this was used as a starting point for the selection of process variables.

7 THE NEW FORTUM LOVIISA LSD SYMBOLS

The new Loviisa LSD is realized using IFE's graphical tool ProcSee [12], which is especially well suited for designing complex graphical symbols. Some of the main dynamic symbols used in the Loviisa LSD are described in this chapter.

The traffic light as seen in Figure 7-1 is used to aggregate information into a simple representation of functional status based on certain logic conditions.

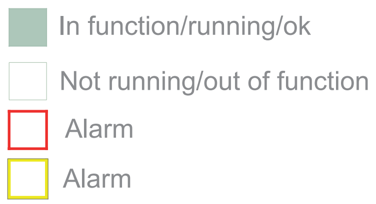

Figure 7-1 Aggregated information in traffic light used in the IRD display

The pumps (Figure 7-2) are presented in a fairly standardized way; one detail is however the outer ring describing the pump load; full ring is 100 % load.

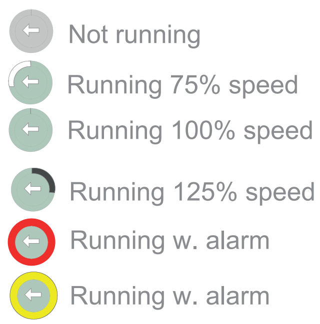

Figure 7-2 Pump symbols used in the IRD display

The normalized mini trend symbol is used for main components such as the condenser. The symbols for temperature, pressure, flow and liquid level is shown in Figure 7-3.

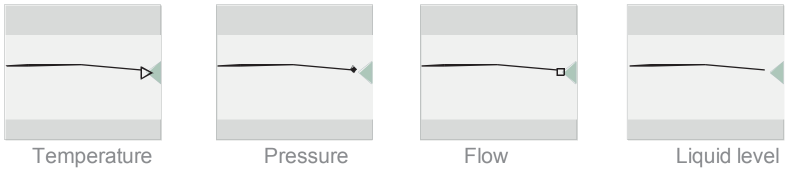

Figure 7-3 IRD mini-trend symbol for different types of variables

One example of alarm presentation for the normalized mini trend symbol is shown in Figure 7-4. Here the H3 alarm limit is violated and the value is still increasing towards the next alarm limit (H4):

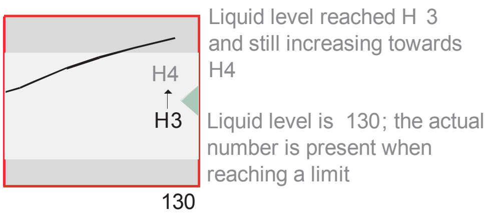

Figure 7-4 Example of alarm in IRD mini-trend symbol

8 THE COMPLETE FORTUM LOVIISA LSD

Front projectors are used for presenting the LSD at the Fortum development simulator, and the dimensions of the new IRD display are approximately:

Length : 5.7 m

Height : 1.1 m

The overall layout (figure 8-1) follows the layout of the traditional LSD; the primary side on the left and the secondary side on the right hand side.

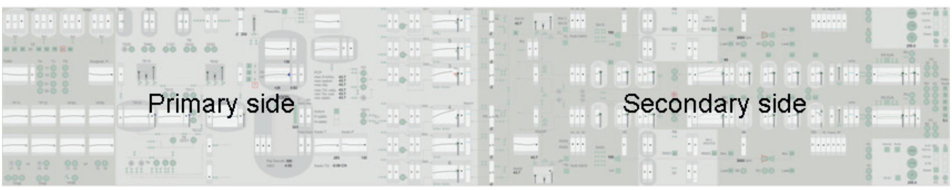

Figure 8-1 Primary and secondary side on the new IRD large screen display

The six steam generators form six main horizontal bands of information in the LSD. This ensures horizontal alignment, and supports visual scanning formed by the normalized objects, see Figure 8-2 and 8-3.

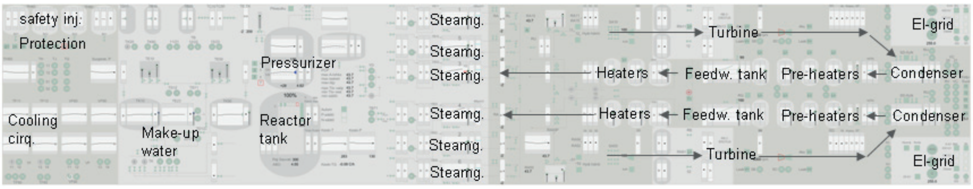

Figure 8-2 Identifying the main components in the IRD large screen display

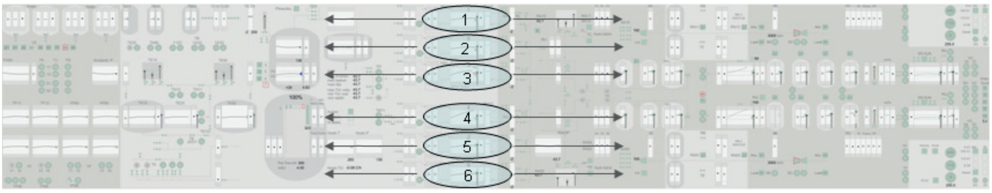

Figure 8-3 Six steam generators forms six horizontal bands of information

The design does also use vertical alignment to reduce clutter and increase readability (figure 8-4).

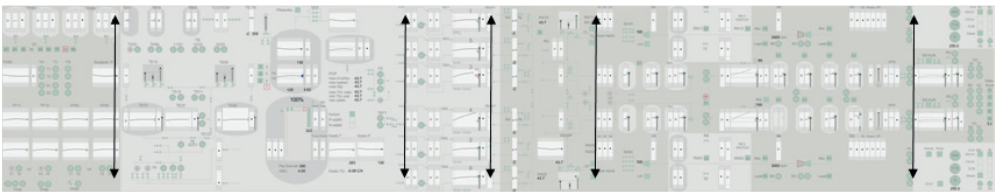

Figure 8-4 Vertical alignment of variables increases readability

The careful use of color and contrast in the display should make it easier to detect abnormalities; in Figure 8-5 the lower condenser has reached an H1 limit, and approaching the H2 limit. Notice also the alarm state of the two turbines.

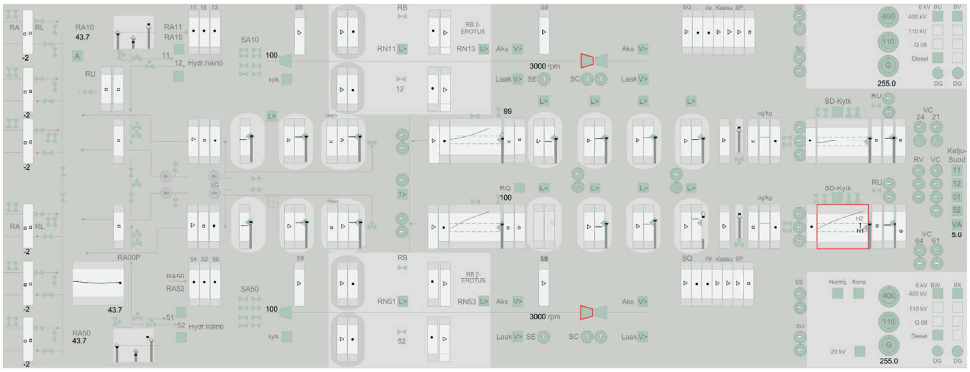

Figure 8-5 Secondary side with three alarms (turbines and condenser)

In comparison, the existing LSD's secondary side (Figure 8-6) with alarms on the two turbines and the lower condenser looks quite cluttered. It should also be noted that the existing LSD below relies on digital number presentations in contrast to the analogue graphical representations of the IRD display. The IRD display consists of approximately 1700 data points; this is approximately three times more than the original LSD display; hence the name Information Rich Display.

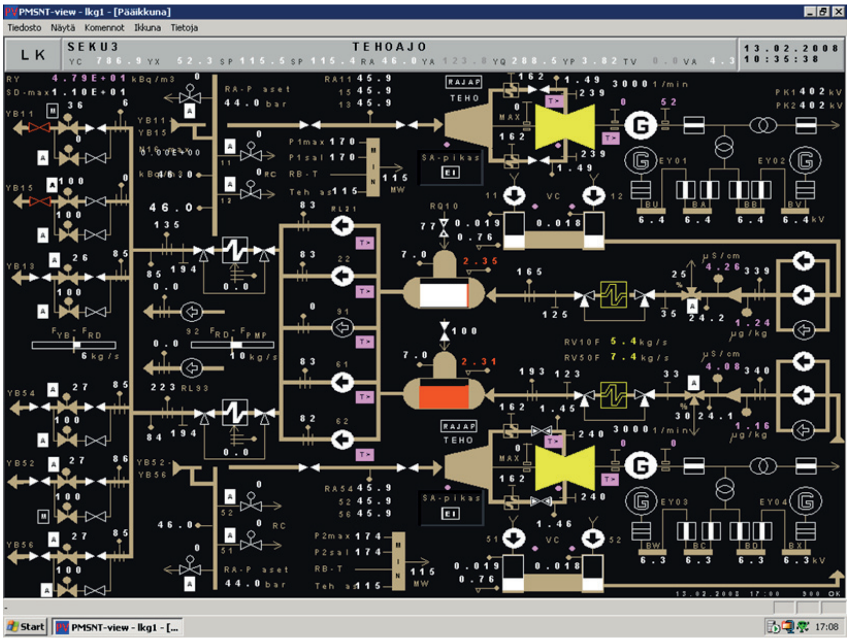

Figure 8-6 the existing traditionally designed LSD secondary side

9 CONCLUSIONS

The first fully functional IRD LSD is developed and installed at the Fortum Loviisa development simulator. The IRD design has been tested in a small-scale evaluation [13]. The future development of IRD-based large screen displays will be decided later, depending partially on this user test. It is well recognized that large screen overview displays will be needed in tomorrow's nuclear power plant control rooms in order to support crews' situation awareness. However, experience of operating IRD large screen overview displays in the nuclear industry is not available. Thus, at the moment it seems too early to conclude on the suitability of an IRD display in a real plant installation. More complete analysis and tests have to be carried out. When considering the possibility of using an IRD in a real plant, usability is not the only relevant factor. Also things like safety classification and system connectivity challenges have to be carefully considered.

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PAPER IV

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EVALUATION OF THE FORTUM IRD PILOT

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ABSTRACT

The paper presents the results of the evaluation of the Fortum Information Rich Design (IRD) pilot display set which is the first application of the IRD concept to the design of displays for the operation of the nuclear power process. Displays based on the IRD concept emphasize the essential information by making it more salient and de-emphasize the less relevant information by reducing its visibility. The final IRD prototype is formed by a mix of both traditional Process & Instrument Diagram type features and new innovative design features.

In the present study, the design process of the Fortum IRD pilot displays have been observed at design workshops and the designers have been interviewed. We have also carried out a usability test of the pilot and gathered information about user experiences through discussions with the participating operators. It was found that the prototype display can function both as an overview display providing useful information of the overall state of the power process and as a supplementary display that helps operators to early detect failure and problem states in the power process. On the other hand, it would be better if there is no need for compromises in the application of IRD principles for the design of displays for NPP control rooms, since compromise solutions may somewhat limit the value of the IRD displays in the detection and diagnosing of process failures.

Key Words: Large Screen, Display Design, Human Factors, Situation Awareness

1 INTRODUCTION

1.1 Background

Large screen displays (LSDs) play an important role in digital control rooms (CRs) based on desktop-based workstations in the presentation of the essential information of the system. It has been suggested that they could solve some of the main problems caused by digital technology [1].

Overall, it is supposed that large screen displays can provide an overview of the state of the process and information of important process changes, disturbances and alarms in a way that is easy to detect and identify, and help users rapidly move to the place where the essential information is located [2]. By providing an overview of the state of the system they can help users to develop a better mental model of the process. It is said that by this way the LSDs can improve situation awareness both at the individual and at the team level. They can also support co-operation and collaboration between operators and co-ordination of activities by providing information of what other users are doing. The LSDs may help users to locate themselves in the information space and tell them by which way they can navigate from one display page to another. Since more information can be presented at the same time on a large screen, there is less need to scroll the display, open new windows or change the display content. By this way the LSDs should help to reduce the load caused by the secondary tasks.

On the other hand, the design of LSDs for the CR environment is challenging. They are not only bigger in size, but they are also qualitatively different from desktop-based workstations, and therefore user-interface metaphors developed for small displays are not necessarily adequate in the design of LSDs [2].

1.2 Key design features of the IRD concept

If LSDs are qualitatively different from other kind of displays, new types of interface metaphors and display concepts - such as Ecological Interface Design (EID) or Function-Oriented Design (FOD) concept – are apparently needed. These concepts are, however, not specifically aimed to the design of LSDs for process industry.

Rapid, easy and accurate detection of changes and failures can be improved, for example, by developing new types of displays that emphasize the essential information by making it more salient and de-emphasize the less relevant information by reducing its visibility. Displays based on the Information Rich Design (IRD) concept have been developed for those purposes for offshore production facilities [3],[4].

Some of the central aims in the development of IRD displays have been to provide overview information, support early detection of failures and disturbances and help operators to diagnose the problem and stabilize the process. According to Veland and Eikås [4], IRD displays should reduce working memory demands of operators by providing immediate visual access to frequently used data. By this way they could support the development of an acceptable level of situation awareness based on an overall view of the plant performance. They could also support collaboration and co-operation between operators and co-ordination of activities within a crew.

The IRD concept is based on such design principles as display normalization, Dull Screen principle and information richness [3],[4]. The aim of display normalization is to help users to automatically detect deviations. Two types of graphical objects have been developed, normalized mini trends and normalized bar-like symbols without mini trends (Fig. 1). These objects adjust the mapping between physical measurement scale and the actual display scale for each data point [3], [4]. As a result, a set of graphs can be grouped together in such a way that the group is

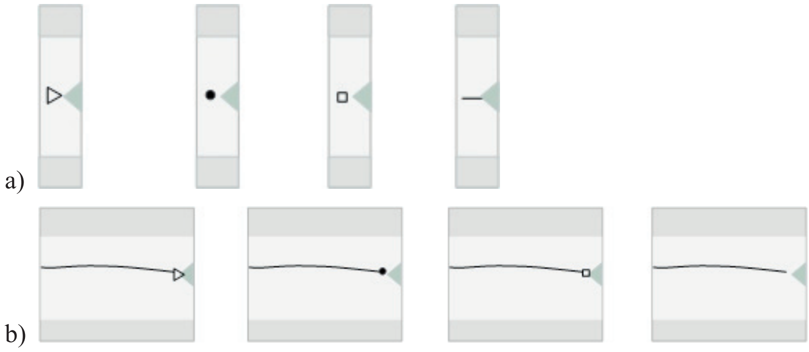

Figure 1. Normalized bar graphs (a) and trends (b) indicating temperature, pressure, flow, and level [8].

considered as a single object, and small deviations from the baseline can be immediately detected.

The aim of the Dull Screen principle is to make the display clearer and prevent visual noise by using specific colouring rules [5],[6] that emphasize essential information and suppress less essential information. In general, essential information is shown by using salient fonts and colours, and information that is less important is presented by low-saturated colours. Flicker is not used for alarm purposes, but, instead of that, alarms are indicated by highly saturated colours (red or yellow).

IRD displays are dense with information – that is, a lot of information is presented on a small display area. Fig. 2 shows a good example of the presentation of accurate valve position with a special panel in which a lot of information is presented in a small space. The controller output is presented by a vertical bar outside the graph area. The expected position is presented by a diamond and the actual position by a black rectangle. Different symbols are used for flow, level, pressure and temperature [3],[4].

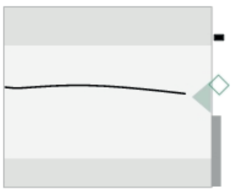

Figure 2. A normalized trend including information of valve position [8].

1.3 The starting point for the development of the Fortum IRD pilot

Displays based on the IRD concept were originally developed for Norwegian offshore petroleum facilities. In 2006 an idea appeared to study the applicability of displays based on the IRD concept as overall displays in the monitoring of the nuclear power process. The HAMBO large screen display project was planned in September 2006, and after that the development of overview displays that are based on the IRD concept were suggested to be included in the HAMBO reference group program. The Fortum IRD pilot is the first application of the IRD concept to the design of displays for the nuclear CR (see Fig. 3). During 2007 it was planned that VTT could participate in the evaluation of the Fortum IRD pilot within the frame of the Finnish SAFIR/O'PRACTICE project.

Figure 3. The four Fortum IRD pilot displays that were used in the usability test.

2 RESEARCH METHOD

Different types of research activities have been taken place during the evaluation project [8]. First, designers of the displays have been interviewed, and secondly, the design process of the Fortum IRD pilot displays has been observed at design workshops. Thirdly, we have carried out a usability test of the Fortum IRD pilot, and gathered information about users' experiences and conceptions. This paper is mainly based on the results of the usability test. In this test, three crews of operators (ie., pairs of operators) were participated in the simulation test that was carried out at the Loviisa development simulator. Two types of overview displays were included in the test, IRD displays and displays that are based on process computer displays (in the following they are called Loviisa displays). In addition to that, process computer displays were presented on monitors of the desktop workstations. Before the usability test, a one-day training session was arranged. The aim was to familiarise the operators participating in the test with the key principles of the IRD concept and with the Fortum IRD pilot, and to gather some first comments on the design solutions. For both crews the same set of six scenarios was provided. In debriefing the main phases of the simulation were discussed through together with the operators. The aim of the interview was to find out what events the users considered most important, and what kind of information they used in order to manage the event. At the end of the session, the operators were interviewed on their experiences about the LSD displays that they have used in the test.

3 RESULTS AND DISCUSSION

3.1 Results concerning operators' performance

Even though the emphasis was on the interview data, some dimensions of operator performance were also measured providing quantitative information of the use of LSDs. The following measures were used: source of the first deviation detected, duration of time to event detection for each scenario, detection of failure from the first signs and percentage gazing time to different information sources and number.

The information that was shown on the IRD displays was used in the detection of failures: in 16 of the 18 simulation runs the failure was first detected from the IRD display [8]. The results in the comparison condition in which the more traditional Loviisa large-screen displays were used were quite similar: in most of the simulation runs the failure was first detected and identified on the LSD display. These results suggest that both types of LSDs provide useful information that help operators in the detection of failures and problems. It was also found that the failures could be detected quite fast on both types of displays suggesting that the Fortum IRD displays at least do not disturb the operators' ability to detect the failures (See Fig. 4).

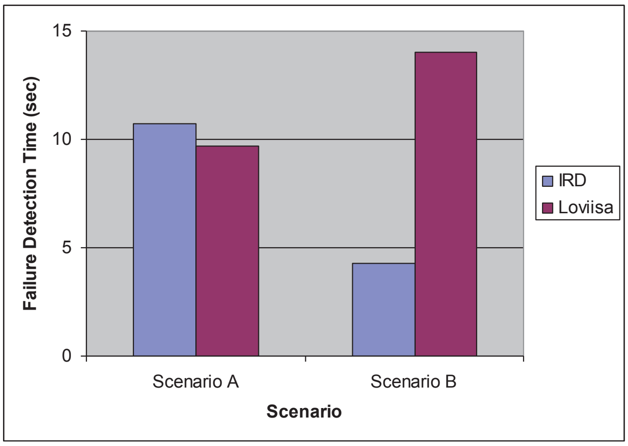

Figure 4. Failure detection time for two scenarios in the IRD and Loviisa display –conditions.

Since the IRD displays are developed for the early detection of failures, one interesting question is whether an operator could detect a failure from the first signs (e.g., from the change of the slope of a trend curve) before the alarm sign was triggered. Unfortunately, since the events in most of the runs were rapidly evolving, the 'first signs' can be seen nearly at the same time as the alarm information is displayed [8]. Therefore, in most of the runs, the operators detected the failure from the displayed alarm information (ie., from the changes of the symbol colour or from the sudden appearance of a surrounding frame). The result might have been different if the failures have been more slowly evolving.

The percentage gazing time to different information sources (ie., LSD, desktop screen, other operator) provides information of how long LSDs are gazed in relation to other information sources. There were some differences in gazing times between Fortum IRD and Loviisa display conditions for the operators that were naïve to the purpose of the test (see Fig. 5) [8]. For example, for Scenario 2 the operators gazed a little bit longer for IRD displays than for Loviisa displays. This finding suggests that Information Rich -displays may provide at least as useful information as more traditional large screens.

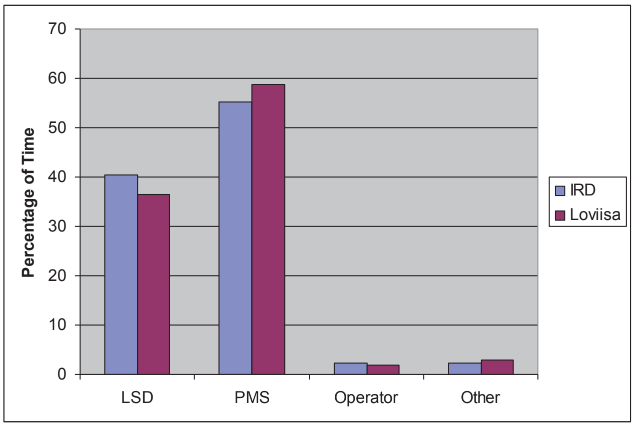

Figure 5. Percentage of time operators gazed to different information sources (LSD = large screen display, PMS = process monitoring system) for the IRD and Loviisa display -conditions.

3.2 Operators' thoughts on the key design features of the IRD-concept

3.2.1 Display normalization

During debriefing a lot of comments were received regarding the graphical presentation of information. For example, normalization of information was critically commented by several operators. The main idea of the original IRD concept is that when the scaled trends and bar graphs are put along a line, comparison of aligned mini-trends and bar graphs is made possible, and even very small deviations are easily detected making possible the detection of failures before the alarm is displayed. However, the value of the display normalization was considered to be quite small, and some operators thought that the normalized graphs are nearly useless if the exact numerical values are not continuously present to complement visually presented graphs. It seems to be that display normalization (providing the comparison of aligned graphs) was not a very useful property, since there were other types of information that could be used in the detection of the failure. It seems to be that the strict placement of display elements along the horizontal/and vertical lines is not very reasonable if the information of the plant architecture familiar to the operators is lost. However, the operators still thought that providing history information through trend graphs was positive and arrows showing the direction of change after the violation of an alarm limit were considered useful.

Our test results do not provide much evidence of the usefulness of normalization. This is a deficiency since display normalization is one of the most important properties of the IRD concept. It is possible that display normalization shows its usefulness and importance in other types of test scenarios. Different types of test scenarios are, thus, needed in which the consequences of failures emerge more slowly.

3.2.2 Use of colour

The application of the 'dull screen' principle is one of the key design features of the IRD concept. Concerning the chosen colours, the operators' opinions differed quite much: Some operators thought that the 'dull screen' with the grey background is a good choice; other operators, however, thought that the grey background is not suitable, for example because of the grey background other shades of grey are not distinct enough [8]. The main aim in the use of 'greyish' dull screen is to improve the visibility of the alarm colours. The used alarm colours (red and yellow) were mostly experienced satisfactory even though the visibility of the yellow colour appear to be more sensitive to the quality of the display technology. Our results, however, suggest that the chosen set of colours make other state changes even more difficult to detect. While the visibility of alarm colours was good, the colour coding for state changes in different plant instrumentation (e.g. pumps and valves) were experienced inadequate.

The green colour was considered most problematic, since it has been widely used and it has several meanings [8]. Especially, the colour green and dark grey are difficult to distinguish from the grey background when looking far away, and in this way some of the important changes or deviations from the normal state do not catch operators' attention. Some operators also had difficulties in distinguishing the green colour from yellow and from the grey. This was especially problematic in the case of pump symbols in which the coloured frame around changed the hue of the central part of the symbol, because of colour contrast. The operators also had problems in noticing by-passes and components that are not connected, since they were not able to distinguish different shades of grey from each other.

3.2.3 Information richness

'Information rich' trends and graphs were considered useful, but due to the lack of practice the operators were not able to utilize all the information that was presented on them [8]. It is possible that with practice they could better utilize these clusters of information. But it seems to be that the symbols in these graphs should be larger, and they should be located farther away from each other so that it would be easier to identify the cluster and interpret its total meaning.

3.2.4 Fortum IRD pilot

The Fortum IRD pilot displays are aimed for an overview display for 100% power and for rapid detection of failure states [8]. It is one of the central claims that the IRD displays should help users to detect deviations from normal [3], [4]. Even though this is important, it is necessary that these kinds of displays should also serve other purposes. For example, they should be useful when diagnosing failures or trying to stabilize the system. In fact, the IRD displays should also function as overview displays that help operators to maintain accurate situation awareness. However, it seems to be that in order to attain situation awareness and perform the operational tasks that follow from the rapid detection of failure states more detailed information is needed [8]. It is not clear whether and to what degree Fortum IRD pilot display is suitable for these purposes. Our claim is that in the nuclear field overview displays should be based on process architecture and on the functional analysis of the target system, not only on a particular design principle. It is questionable to sacrifice several screens for this purpose if these displays are nearly useless at other plant states. The apparent answer according to operators is no if their content is fixed. The situation would be different if it could be possible to change their content according to the plant state so that some parts of the IRD displays change as the plant state is changing

Some operators critically commented the way the process is displayed on the Fortum IRD pilot, the fact that on the left-hand side of the diagram the information is read from left to right, on the right-hand side the direction is, however, partly reversed, and the information is read from right to left [8]. Overall, it seemed to be that, in the long run, the operators will have no problems to get familiar to this characteristic, but in the beginning it may seem to be a complication.

The visual ergonomics of the IRD displays needs to be improved. The participating operators criticized that many of the alphanumerical characters, symbols and other graphical elements were too small in size so that they had problems to identify them from the distance [8]. This is a real problem, since CR operators do not normally have a possibility to walk closer to see what is displayed on the screen. Neither have they any reason to move closer especially because the IRD displays are only for reading, not for operating. An additional problem was the inconsistency of element size: For example, the size of letters could vary from one part of the display to another.

Even though some of the pipelines are presented on the display, they may be more confusing than they are helping since only fragments of them are displayed [8]. A general hope was that pipelines that in the reality are different in size should be also presented with different-sized lines. The operators also had problems to understand the arrows located at the end of the pipelines.

Even though the Fortum IRD pilot displays look different from more traditional overview displays, in general, the new displays were well received [8]. A promising finding was that the experienced operators were able to utilize Fortum IRD display despite of the fact that the presentation format differs from what they have used to. However, some inconsistencies between traditional overview displays and IRD displays disturbed them to some extent. One of the main nuisances was that the symbols of components that belong together are not located near to each other on the display but they are dispersed over the display. Since the elements are lacking labels and other identifiers the operators had serious problems in the identification of displayed elements. Because of the short training time, the operators also had some problems to remember to what different symbols (i.e., dot, line, triangle and diamond) were referring to.

The final version of the Fortum IRD displays looks quite different from the first one, since a lot of information has been added on the display during the design process. Even though the amount of information has increased, the operators still made suggestions of components they would like to see on the display [8]. For example, some operators hoped that information of detached components could be seen on the display. Contrary to that, some operators also mentioned components information of which could be removed from the display (e.g. information of electrical systems).

3.2.5 Design of the Fortum pilot

The design process based on the rapid prototyping methodology was shown to be useful [8]. It is also the only possible way to develop a testable prototype especially if there is a lack of time and resources. Some method based on the functional analysis of the NPP process would be preferable, but it may not be feasible in this kind of project.

All the stakeholders had an important role to play in the design process [8]. Since IFE designers knew the IRD concept, their task was to design the Fortum IRD pilot displays in such a way that they support the detection of failures. Fortum designers' participated in the implementation of the designed solution, and they also functioned as mediators between IFE designers and the operator designers that participated in the design work. Since the three operator designers were experts of the nuclear domain, their function was to provide domain expertise in what information should be presented in the overview display and by which way it should be presented.

Many of the good and bad properties of the Fortum IRD pilot were added during the design process, and they are not based on the IRD concept as such. For example, the Fortum IRD pilot displays are filled with a lot of process information which make them suitable as overview displays that support the acquisition of accurate level of situation awareness [8]. Originally, the IRD displays were, however, aimed for rapid detection of failures, and their principal aim was not to function as overview displays. Since a lot of information is displayed on the Fortum IRD pilot displays, they are also suitable for stabilization and diagnosing of failures which was not the original intent.

The final prototype has thus weaknesses that cannot be blamed on the IRD concept. For example, it is not caused by the IRD concept that the displays were considered a bit cluttered and confusing. As the designers said, these defects are mainly caused by the way the prototype was designed: It is characteristic to the rapid prototyping that the development process proceeds in a quite spontaneous and ad hoc manner [8]. The designers also complained about the hastiness of the design process which may also have made the final prototype look a bit unfinished.

4 CONCLUSIONS

This paper presents the results of the evaluation of the Fortum IRD pilot which is the first application of the IRD concept to the design of displays for the operation of the nuclear power process. We have observed the design process of the Fortum pilot displays at design workshops and interviewed designers of the displays; we have also carried out a usability test of the Fortum pilot, and gathered information about user experiences. The results suggest that the Fortum IRD pilot displays have shown to be applicable to the detection, identification and diagnosing of failure states in the nuclear power process.

4.1 Usefulness of IRD design principles

One of the most salient features of the IRD displays is that they are different from more traditional type of large-screen displays. Despite of the novel form of presentation experienced operators were able to take advantage of the Fortum IRD pilot and detect deviations successfully. The Fortum IRD pilot displays were also used during the process stabilization phase along with the process monitoring system displays. In addition, they offered operators a common view to the process. Therefore, it can be said that by these means the development of situation awareness was supported. It seems to be that it is not a fatal problem for the overview displays if the presentation format is different from what the operators are used to. However, it is necessary to take care of that some consistency and familiarity with the other interface elements of the CR is maintained. Because of the IRD concept's novel features, it is clear that in order to be able to use the display in an efficient way, sufficient training is needed.

As said, display normalization is intended to support rapid visual processing and detection of failures when several normalized graphs are set along a horizontal line. Operators did make use of trend information in the simulator runs, but they, however, said that display normalization is not a very informative property, and some of them even doubted if normalization is suitable for the presentation of information of the nuclear power process. Our results, thus, do not provide much support for the usefulness of display normalization. It can be that display normalization would have been more useful in other types of scenarios in which the changes occur more slowly.

The aim of the Dull Screen principle is to make the display clearer and prevent visual noise by using specific colouring rules. The main aim in the use of the principle is to improve the visibility of alarm colours. Our results, however, suggest that the chosen set of colours make other state changes even more difficult to detect. While the visibility of alarm colours were experienced fairly satisfactory, the colour coding for state changes in different plant instrumentation (e.g. pumps and valves) were experienced inadequate.

Our claim is that 'information richness' of graphs is one of the most useful features of the IRD concept for expert operators. However, because of the lack of sufficient practice and training, the operators were not able to take use of all the information that was placed in trends and bar graphs. It is probable that with more practice they would have improved in the ability to use this information.

4.2 Evaluation of the Fortum IRD pilot

Despite the rapidity and 'ad-hocness' of the design process, the final prototype is surprisingly mature, accurate and well-structured. This finding suggests that this kind of agile approach is well suited for the development of overview displays for industrial purposes. The approach would further benefit if it could incorporate into itself more systematic mode of operations that are based on functional modelling of the target system.

Our results suggest that the Fortum IRD pilot displays have many useful features such as presentation of history information through trend graphs, use of Gestalt grouping principles in element clustering and information richness of graphs. These features make the displays pleasant looking, and they also help operators in the identification and diagnosing of failures if they have had enough time to practise them. However, the displays have also several features that make them poorly suited to their purpose. Inconsistencies in the presentation of information (e.g., varying direction of reading, varying font size and inconsistent use of grouping principles) are one of the biggest problems. Lack of labelling and lack of exact numeric information was also considered problematic.

The final prototype is some kind of hybrid of IRD displays and traditional displays based on process and instrumentation diagrams. This hybrid has its benefits, and as our results suggest, it can function both as an overview display providing useful information of the overall state of the power process and as a supplementary display that helps operators to early detect failures and problems in the power process. However, we propose that for neither of these purposes it is the best solution. Our suggestion is that the overview displays should be based on process architecture, and IRD principles should not be applied in their design very rigidly. On the other hand, we suggest that there could be one dedicated IRD display specially designed for rapid detection of changes in the main process parameters. In the design of this display all the IRD principles would be followed. Our hypothesis is that this kind of real and genuine IRD display may be useful in the rapid detection of failures even in the nuclear field.

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PAPER V

LESSONS LEARNED FROM HALDEN PROJECT RESEARCH ON HUMAN SYSTEM INTERFACES

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Innovative Human System Interfaces (HSIs) has been a major topic of research of the international Halden Reactor Project (HRP) for many years. Different design concepts have been addressed and prototypes have been implemented and evaluated in the experimental control room facility of HRP. Many of the concepts go far beyond traditional P&ID type displays, and utilize advanced computer graphics and animations. The paper briefly describes some of the concepts, their advantages and disadvantages experienced through evaluations and feedback from users.

KEYWORDS : Human System Interfaces, Display Design, Process Control Displays

1. INTRODUCTION

Over the last years parts of the nuclear industry has moved towards replacing the traditional, panel-based interfaces with computerized operation environments. Such decisions are motivated by aspects such as future maintenance problems and costs and upgrade flexibility, and not so much by human performance issues. In general, today's computerized control rooms consist of P&ID-based process displays, backed up with traditional trend and alarm systems. There is, however, a general consensus that there is a great potential for improvement with regards to how information is being presented in such systems.

The goal of the Halden Project is to provide the nuclear industry, i.e. utilities and vendors, with knowledge and ideas for improving information presentation in hybrid or fully computerized control rooms. This goal is being met by designing prototypes which is implemented in full-scope nuclear simulators, evaluating them in user tests and larger-scale experiments in HAMMLAB (Halden Man-Machine Laboratory), and providing lessons learned, design recommendations and technical basis for guidelines to the industry.

This paper addresses challenges of computerized interfaces, and how lessons learned from the HSI research of the Halden Project contributes to solving some of these challenges.

2. CHALLENGES AND OPPORTUNITIES IN COMPUTERIZED HUMAN SYSTEM INTERFACES

The present generation of computerized interfaces within the nuclear industry is more or less screen-based replicas of the traditional mimic-based hard-panelled interfaces. Although a natural first step, this approach introduces new challenges from a human factors perspective. It also fails to take advantage of the new possibilities the new digital medium offers, see Fig. 1.
Some of the known challenges with present computerized HSIs are:

- *The "key-hole effect"*: In traditional control rooms the interface covers a large part of the room's walls and desks. In computerized environments the operator's interface is located on a number of computer screens. The result is that operators often loose overview of the complete process. The interface fails to support the behaviour of "stepping back" to get the "big picture", focusing exclusively on smaller parts of the process, screen by screen, as through a key-hole [1].
- *Interface management issues*: As the interface is distributed over many displays limited in size, operators will have to navigate through them to access the information they are looking for. The display shown on each screen is chosen by the operator, e.g. mimic-based displays, trends, alarm systems, etc. While this flexibility offers some advantages, studies have shown that operators often get lost, experiencing a hard time managing screens and finding the information they are particularly looking for and thus reducing operator performance [2].
- *Visual patterns disappear*: Key features of traditional

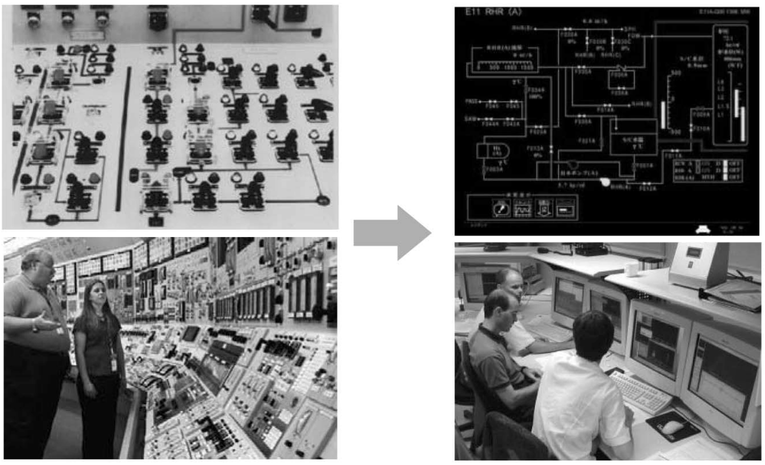

Fig. 1. Moving from Traditional Hard-panelled Interfaces to Computerized HSIs Introduces Both Challenges and Opportunities from a Human Factors Perspective

panel-based control rooms are analogue display elements spatially distributed throughout the room (analogue meters, tile-based alarms with a single lamp representing a single alarm, etc.). These and other analogue display units seem to better support fast recognition of overall process status than is the case in their computerized counterparts. Four arrows pointing at 12 o'clock and a number of alarm tiles lighting up in different places in the control room (often with sounding alarms coming from different locations as well) are more rapidly and accurately interpreted than mere numbers and lines of text appearing on a screen.

- *Teamwork transparency*: In a traditional control room it is easy for operators and the shift supervisor to see what others are doing. As every element in the interface has a fixed location operators may conclude with a certain accuracy what colleagues are doing simply by noticing where they are in the control room. In contrast, in most computerized environments the actions of others are often not that evident. Operators are located at desks, acting on displays that are not easy to read from a distance. This reduces each team member's awareness of others' actions, making coordination more difficult [3,4].

The HSI research performed at the Halden Project in recent years has sought to address these challenges while at the same time exploring the new opportunities offered by computerized interfaces. Digital control systems and presentation media is highly flexible, making it possible to design information in any way one think is beneficial, not limited by physical constraints. Information can be synthesized to more effectively convey the current status of a system function and its availability for control by the main control room. The digital HMI can also be shaped to better support early detection of deviating system states, grabbing operator's attention and support the inspection of detailed information while keeping the overall perspective.

This has led the Halden Project to develop and test a number of novel interface concepts presented on media ranging from workstation screens to large screens, and even ultra-large screens (up to 16 meters wide). Through the lessons learned the Project is confident that as computerized human system interfaces mature, one will be able to merge the qualities of the old-fashioned interfaces with the opportunities of the new technology to overcome the above challenges and to further enhance human performance and reduce the risk of error.

3. DISPLAY CONCEPTS

The Halden Project research on HSIs is very broad in the sense that different display concepts are being investigated, some based on theoretical foundations, such as function-oriented and ecological display designs, some based on knowledge obtained through long-time user experience. The design of prototype solutions differ substantially in that for some of the concepts a formalized design process has been followed, while for other concepts no strict design process is followed. Likewise, display evaluations differ substantially in that some concepts are thoroughly tested in full-scale experiments, while others are evaluated in a more qualitative fashion based on user feedback.

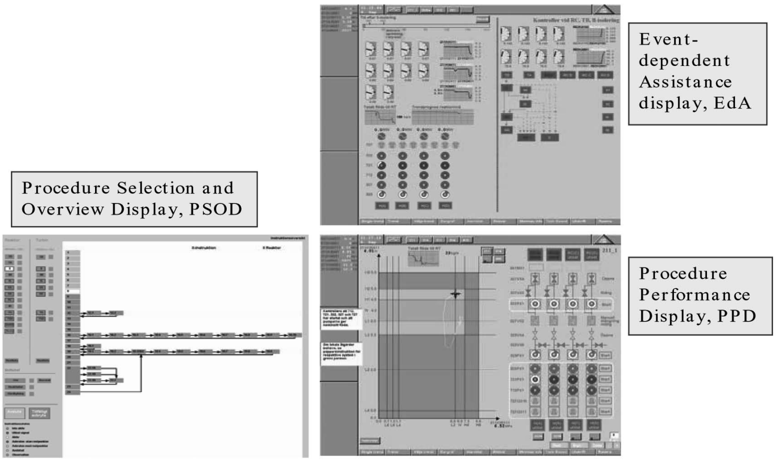

Fig. 2. Task-based Displays

This chapter summarizes some of the addressed concepts, Task-based interfaces, Ecological interfaces, Function-oriented interfaces, Large screen overview displays and Information Rich Displays.

3.1 Task-based Displays (TBD)

The main idea of the task-based approach is to design displays that provide operators with all information needed to perform a certain pre-defined task as effectively and safely as possible. Initial work indicated that procedure-based tasks were particularly suited for such an approach, and later work aimed at studying how emergency operating procedures can be fully integrated with process displays to enhance operator performance.

Three different kinds of displays are developed for a BWR simulator in HAMMLAB. The three types of displays complement each other, and together they constitute the "Task-based display concept": the Procedure Selection and Overview Display (PSOD), the Procedure Performance Display (PPD), and the Event-dependent Assistance Display (EdA). The three display types and their location relative to each other are shown in Fig. 2.

In short, the procedures are selected in the PSOD picture, and the corresponding PPD and EdA displays appear. The PPD is applied for executing the selected procedure. The EdA display contains information about the most important parameters and components relevant for the actual situation and event, and the information presented on this display thus depends on the selected procedure and the overall situation. All displays are continuously updated on the basis of actuated safety systems and procedure status.

When executing procedures, it is necessary for the operators to perform regular checks of the most important parameters and components relevant for the actual situation and event. The intention of the EdA display is thus to make the most important procedure-relevant information available to the operators and to ensure that this information is located physically close to the procedure displays. The information in the EdA display depends on the selected procedure and the overall situation.

3.1.1 Evaluation Results

Overall, the results from a few user tests of the concept show that the participants generally considered it quite easy to learn how to use the TBD concept and all the operators stated that the amount of training they had received (approximately 4 hours) was sufficient for learning to use the displays [5]. The operators were furthermore comfortable with using the Task-based displays when operating in the simulator, and anticipated that they would be relatively comfortable with using the Task-based displays even in their home plant. The operators did not perceive the TBD system as complex; they found it easy to use; they considered the organization of the various functions as good; and they felt confident and safe using the TBDs.

60 % of the operators preferred computer-based procedures (as presented in this test) over paper-based procedures. Some even stated that the TBD concept is completely necessary for operation in a computerized control room, and it was asserted that this provides better overview, is less time consuming, and probably will lead to less errors compared to paper-based procedures.

3.2 Ecological Interface Design (EID)

The EID project aimed at guiding the development of user interfaces that support rapid perception and correct

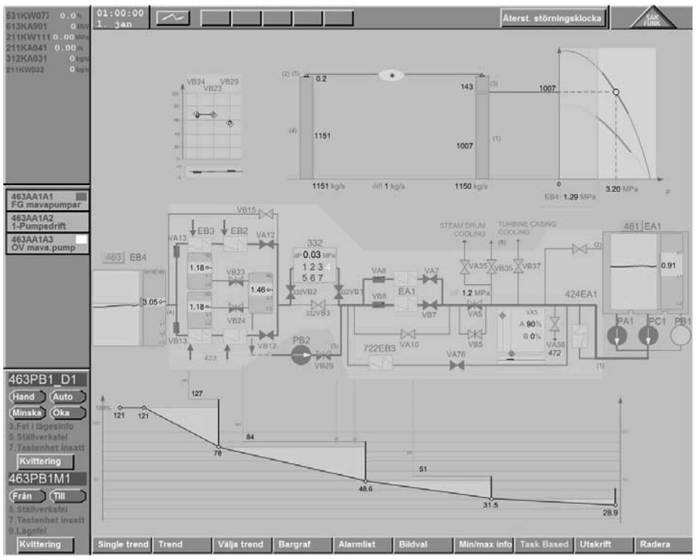

Fig. 3. The EID Condenser & Feedwater Display

interpretation of process data, especially when dealing with abnormal and/or unfamiliar conditions. Research on smaller scale processes has indicated that EID leads to innovative new designs with the ability to improve operator performance and situation awareness in such potentially hazardous situations. The HAMMLAB EID implementation aimed to study the impact of ecological interfaces on operator performance in a full-size process, gain experience with a large-scale design and document the design process itself. The EID project was carried out in close cooperation with the Canadian universities of Toronto and Waterloo.

Prototypes of a few ecological displays were implemented on the BWR simulator in HAMMLAB. A proper Cognitive Work Analysis (CWA), which is an important part of the Ecological Interface Design (EID) process, was completed prior to design and implementation of the displays. Five displays were designed and implemented, covering the turbines, the condenser, the seawater system, the feedwater system, and the generator of the secondary side of the process [6].

In Fig. 3 one example is given of the condenser and feedwater EID display, where some prominent features of the EID design is given, e.g. mass flow balance, temperature profiles, pump curves etc.

3.2.1 Evaluation Results

An experiment was carried out in HAMMLAB in January 2006 with operators from a Swedish nuclear power plant to demonstrate possible benefits of Ecological Interface Design (EID) for unanticipated power plant events [7]. It was assumed that EID provides higher order information about the nuclear process and reduces cognitive effort by transforming demanding information processing into perceptual tasks.

The study compared three different display types:

- Ecological displays - design solution guided by categorizations of cognitive performance and an analysis of the work domain to determine the system's information requirements.
- Traditional displays - a computerized version of conventional control room boards corresponding to the current industry standard, typical P&ID-inspired design.
- Advanced displays - traditional displays enhanced with some graphical elements.

The experiment concentrated on how the display types affected Situation Awareness (SA) under varying operating conditions [8]. A model of SA for process control was developed, extracting three dimensions of operator problem solving in the control room: (a) process overview - the ability to separate signals from noise by detecting and acting upon unexpected changes in the process, (b) scenario understanding - the ability to diagnose problems correctly and find effective control actions during disturbances, and (c) meta-cognitive accuracy - the ability to correctly monitor your own performance level while engaged in complex tasks, i.e. the degree of realistic operator self-assessment. Measures of SA were developed for each of these dimensions. An indicator of self-rated task complexity (workload) was also included in the experiment.

Ecological displays are conceptually new and were unfamiliar to operators. Effective utilization of ecological displays requires that the operators modify their mental model of the nuclear process, e.g. by forming abstract representations of energy balances. The learnability of the displays may therefore represent a challenge.

The experiment results clearly showed that the ecological displays supported early detection and diagnosis of events, especially under unanticipated operating conditions. Furthermore, findings from the experiment suggest that Ecological Interface Design (EID) supports the situation awareness of power plant operators in the detection phase of beyond design basis scenarios.

3.3 Function-oriented Displays (FOD)

The overall purpose of the function-oriented displays has been to reveal strengths and weaknesses of a design philosophy tentatively called Function-Oriented Design (FOD). FOD uses a function analysis of the plant as the backbone for designing an integrated computerised HSI. It is quite common to use function analysis to define information requirements for HSI design, it is for instance recommended by NUREG-0711, so this is not a unique characteristic of FOD. The uniqueness of FOD is the way functions are explicitly represented through the displays and the way all parts of the HSI are designed from the same functional perspective.

A function-oriented HSI prototype has been implemented on the PWR simulator in HAMMLAB [9]. The prototype covers the feedwater and steam generator functions and includes three display types: process displays, trend displays and computerized procedures. The function-oriented displays differ from traditional process mimic displays in that components and systems are organized according to functions identified through a function analysis.

EDF's function-oriented simulator, called FITNESS, has served as the starting point of the design, and the work has been performed in co-operation with EDF/Septen, France [10]. The function analysis is similar to the approach described in the IEC-61839 standard. The analysis begins with the top-level goals or plant missions and then decomposes the plant into functions and sub-functions. The sub-functions are identified by asking how a function is achieved; functions are identified by asking why a sub-function is performed.

At the highest level of the decomposition, the plant is divided into functional sets. The number of functional sets may vary from plant to plant. In the FOD project, the work initially focused on two functional sets: feedwater function and steam-production function.

Fig. 4 shows to the left the 3-level functional structure and to the right a level 3 FOD display where the "in-service status/function alarm" of the condensate pump function is indicated as well as the in service status/alarm of the 3 pumping groups making up the condensate function.

3.3.1 Evaluation Results

A user test was carried out in 2005. The main objective of the test was to get operator feedback on the usability of the first prototype. Additional objectives were to assess whether the training program for the FOD interfaces was suitable.

Three turbine operators from a Swedish nuclear power plant participated in the test. The operators went through six scenarios lasting approximately ten minutes each. Three scenarios involved start-up and shutdown of functions and three scenarios concerned minor disturbances. After each scenario there was a short interview, and after all scenarios were completed there was a debriefing session comprising an interview and a usability questionnaire. The operator's performance was observed in real-time and recorded.

The operators' impression regarding what they liked and disliked about the FOD HSI was generally positive [11]. For the likes, all operators were positive towards the top-level display, providing an overview of the plant as well as a starting point for navigation. The procedures

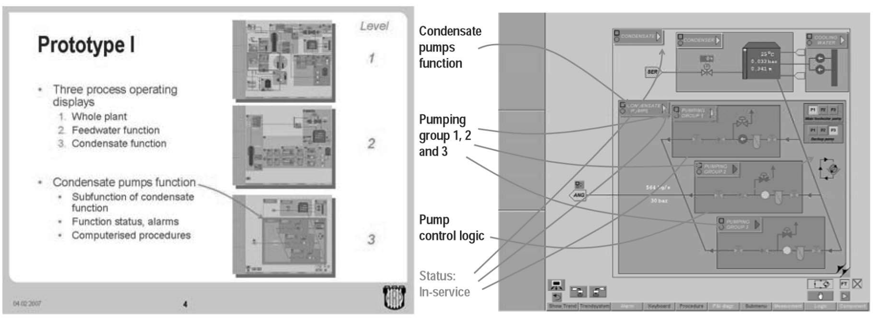

Fig. 4. FOD Functional Structure

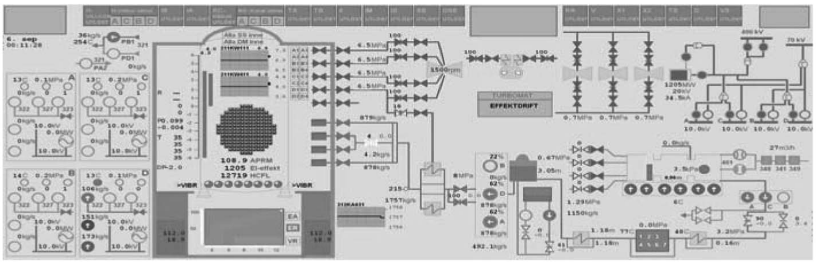

Fig. 5. A Traditional BWR Large Screen Overview Display

were liked for their good structure and organization and the way that control actions could be performed and system responses observed in an efficient manner. The disturbance procedures were appreciated for enabling the operator to quickly deal with disturbances. For the alarms, it was considered beneficial that they were presented in the operating display, showing directly where the problem was located. The prioritization of the alarms was also appreciated.

3.4 Large Screen Displays (LSD) and Information Rich Displays (IRD)

Large screen displays (LSD) can also be referred to as "group view displays", these interfaces are typically designed to support shared situation awareness in the main control room. The Halden Project and its mother institution, The Institute for Energy Technology (IFE), has done extensive work on such displays over a number of years ranging from small overview displays to ultra-large ones. Currently, IFE's experience in this field is put into practice in various industries ranging from the oil & gas industry, to paper manufacturing, power grid operations, as well as the nuclear industry. These industries are all making the shift from traditional analogue control systems to computerized ones, increasingly experiencing the need for shared overview information. Fig. 5 provides an example of a BWR large screen display developed for the BWR simulator used in HRP's experimental facility. The design is inspired by traditional P&ID's, and is a typical representation of today's design scheme.

The different large-screen display concepts that have been explored have many common characteristics:

- *Visual patterns for efficient recognition*. The IRD concept and other "advanced displays" have explored the potential for synthesizing information into visual forms supporting pattern recognition, especially for early detection of deviating plant states.
- *Layered colour scheme*: Colours are chosen to form differentiable layers of information (background/static layer, focus layer and alarm layer) to effectively convey large amounts of information and direct attention.
- *Dedicated zones supporting different tasks*. A large screen display may have a layout supporting different operator tasks in different places, either for different plant states, different type of work or roles. Examples are process overview zone, alarm zone and safety zone, refer Fig. 6.

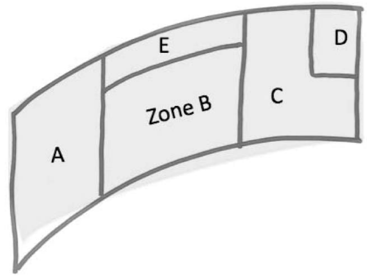

Fig. 6. Different-purpose Zones on a LSD

The IRD concept is so far only realized as large screen displays (LSD). The IRD concept refers to data displays that combine a grayish and low contrast color principle with analogue normalized integrated trends to obtain high data density displays without causing information overload, and at the same time provide a display where abnormal situations with alarm colors are easily detected [12, 13]. The IRD design is patented by IFE, and is currently becoming the reference design standard for Large Screen Displays for Norwegian oil and gas installations. Fig. 7 shows a large-screen overview display for an oil production platform using the IRD concept.

The IRD design differs from traditional design in several aspects; one of the main features is the extensive use of analogue information presentation. With appropriate design, a group of objects with such properties will appear to the visual system as one single object that can be processed reliably and efficiently, avoiding operator

Fig. 7. The Large Screen Overview Display at the Snorre A Oil Platform in the North Sea

Fig. 8. Traditional Design for Three Oil Separators

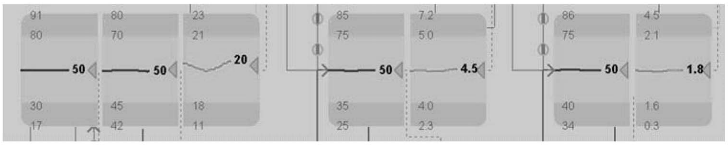

Fig. 9. New IRD Design for the Three Oil Separators

information overload. In the examples below (Figs. 8-9), the traditional old-fashioned oil process separator display is replaced by an IRD separator design. As long as the IRD mini trends are forming one long line (Fig. 9) all parameters are on set point, hence the data interpretation is converted from an internal memory task to an external visual search [12,14].

Based on the IRD success in the oil & gas domain, the Nordic nuclear power plants expressed an interest in seeing whether the IRD principles were possible to utilize for designing large screen displays for nuclear power plant control rooms. A research project was funded by the Nordic utilities with the aim of developing three IRD-based large screen displays for PWRs, BWRs and VVERs.

The first LSD prototype using the IRD design scheme was made for the Loviisa nuclear power plant operated by Fortum in Finland. The prototype implementation was performed at the Fortum development simulator. The new IRD Loviisa LSD design is fundamentally different from the existing Loviisa LSD design. The existing Loviisa LSD is designed using traditional P&ID symbols and digital numbers. Fig. 10 shows the existing LSD's secondary side with alarms on the two turbines and the lower condenser.

The same situation with alarms on the two turbines and the lower condenser for the new IRD-based design is shown in Fig. 11.

The difference in design between the two LSDs, refer Figs. 9-10, is obvious. At the same time, the IRD display consists of approximately 1700 data points, which is approximately three times more than in the original LSD display; hence the name Information Rich Display.

3.4.1 Evaluation Results

A small scale evaluation has been made of the Loviisa IRD prototype [15]. The evaluation was used with a few

operators running a few scenarios. It should be noted that the operators only experienced a short one-day training course on the IRD display prior to the test, while the traditional Loviisa LSD had been used for many years by the participating operators.
The following summarizes a few findings of the evaluation (for more information, refer [15]):

- Presentation of history information and the way dynamic changes were reflected in the display was considered very good.
- The information richness of the IRD display was very much appreciated by operators.
- The measured failure detection time shows promising results for the IRD display. The failure detection time is equal in one scenario and significantly better in another.
- The visual salience of important display elements does not vary, and is a point for improvement.

4. LESSONS LEARNED

Through working with numerous different HSI concepts discussed in section 3 some lessons learned can be compiled and will provide a basis for further research on human system interfaces. Key lessons learned are summarized below.

Helping operators keep the "big picture". The control room crew's process overview and situation understanding must be maintained in a computerized control room. The research performed at the Halden Project shows that the keyhole effect in computerized solutions can be overcome by adding meaningful information to traditional P&ID-based interfaces:

- *Introducing a large screen overview display* (*LSD*). Such a display may provide a complete process overview with status of key equipment and flows as well as spatially distributed alarms and decision support features. It may also be used to increase teamwork transparency, and studies are currently being conducted at the Halden Project to address this issue specifically.
- *Introducing overall information on functional and physical features related to whole or part of the system*. The ecological interface displays (EID) and functional oriented displays (FOD) studies indicate, as do some of the experience with large screen displays, that this kind of aggregated information supports the operators understanding of higher-level functional and/or physical characteristics of the system, and help them discover and diagnose disturbances earlier than in purely P&ID-based interfaces. Displays should be designed to support detection of deviations from a normal situation as early as possible, preferably prior to alarming, allowing operators' ample time to mitigate the situation. See specifically to Figs. 3, 9 and 11.
- *Design interfaces that support pattern recognition*. Pattern recognition should be supported as much as possible, i.e. control room operators should not need to use their mental capacity in reading and interpreting lots of digital numbers or other elements to understand the situation. Utilizing the computers' graphical capabilities when developing animated visualizations may reduce the mental workload and help operators detect anomalies early. Applying a thoughtful colour palette to differentiate between different types of information and to direct

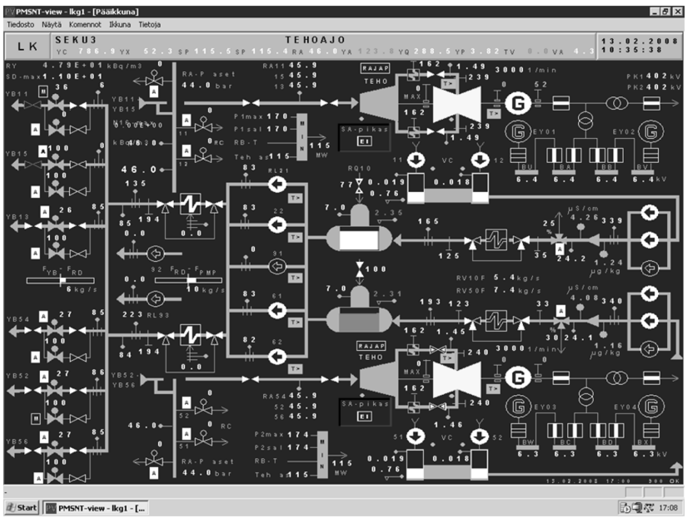

Fig. 10. The Existing Traditionally Designed LSD Secondary Side with Three Alarms

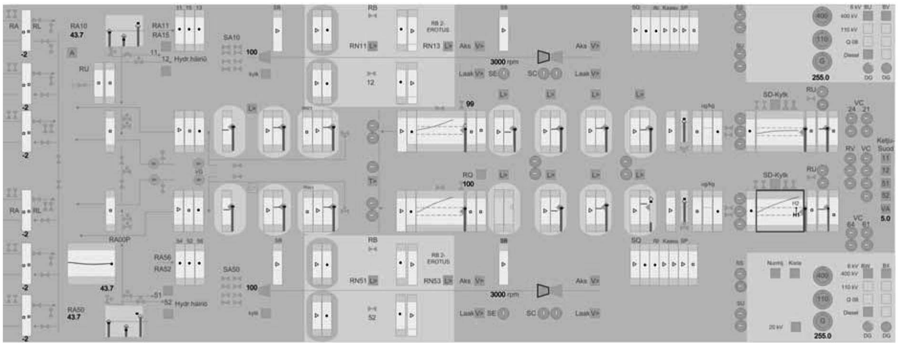

Fig. 11. New IRD Secondary Side with Three Alarms

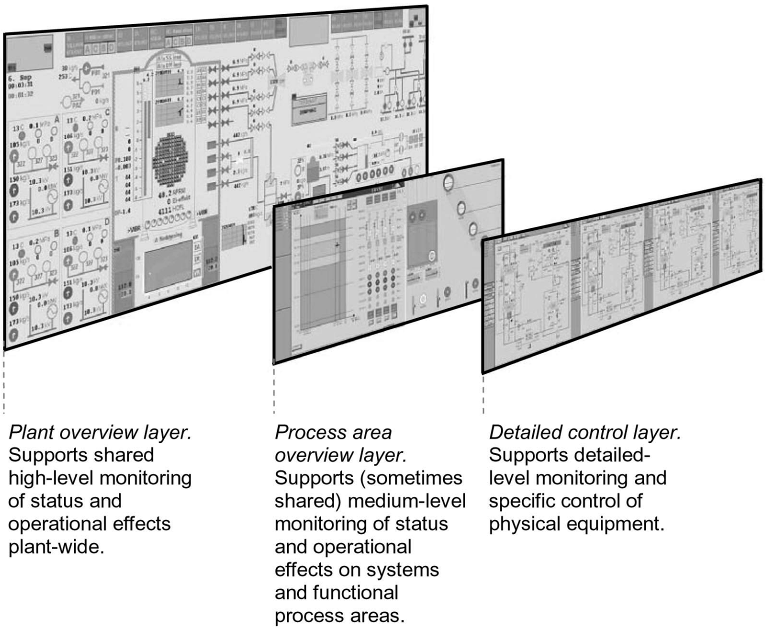

Fig. 12. Characteristics of a Multi-layered HSI

attention is considered effective. Examples are ecological displays (EID) and information rich displays (IRD).

On the basis of the discussion above one may propose a "multi-layered" HSI with different layers supporting different cognitive tasks: From detailed views of physical equipment to more overall, functional or physical views of process areas and work processes. A combination of presentation media, from operator workstations to large screen overview displays, may be used effectively to achieve these layers. One layer need not necessarily be presented on its own media (screen) but can be integrated with others. An illustration of a multi-layered HSI design is provided in Fig. 12.

Integrate procedures with process displays. Usability tests of the task-based displays have provided good results and are a promising path for further work (see Fig. 2). The integration of procedures into the operators' well-known process displays enable procedure execution within their normal operating environment. This philosophy is similar to the one applied when integrating alarms into the process displays. In addition, the task-based approach concept provides opportunities for the whole operating crew to follow procedure execution as visualization of procedure steps are shared among the crew. This is one possibility of rectifying problems with team transparency in computerized control rooms.

5. CONCLUSIONS

A clear trend in many countries is to modernize control rooms, moving from panel-based traditional control rooms to computerized solutions. In order to assist utilities, vendors and regulators in this process, the Halden Project has put emphasis on innovative human system interface research. The aim of this research is to come up with lessons learned and provide technical basis for guidelines. Over the past 5-6 years the Project has designed and evaluated numerous HSI solutions based on a broad variety of different concepts.

This paper has summarized a few of the innovative HSIs, addressing their advantages and drawbacks as experienced through experiments and usability tests within the Halden Project's experimental facility HAMMLAB, and pointed to some important lessons learned.

ACKNOWLEDGEMENTS

The Halden Project has collaborated very closely with various external organizations in the HSI design and evaluation research. The most active ones have been:

- Electricité de France in France (Function-Oriented Design)
- The Universities of Toronto and Waterloo in Canada (Ecological Interface Design)
- The VTT Technical Research Centre in Finland (HSI evaluation methodologies)
- Nuclear Power Plant utilities in Sweden and Finland (participating in user evaluations)

The authors would like to thank all organizations for their contributions, as well as numerous internal Halden Project staff supporting these projects.

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IMPROVING ALARM VIZUALIZATION AND CONSISTENCY FOR A BWR LARGE SCREEN DISPLAY USING THE INFORMATION RICH CONCEPT

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ABSTRACT

The IRD (Information Rich Design) scheme [1] is widely accepted as the state-of-the-art design scheme for LSDs for the Norwegian petroleum industry. The design is used when developing LSDs for both new and older installations in the North Sea. The IRD concept was initially developed for use in oil and gas separation processes, but the concept is gradually being applied also in other domains such as mining and nuclear processes. Nuclear processes are using some of the same type of process equipment as oil & gas processes, such as pumps, valves, turbines etc, and IFE and the Nordic nuclear utilities wanted to see if the IRD concept could be used for a LSD design in the nuclear domain.

It was agreed to develop IRD prototypes for LSDs for both VVER, and BWR type nuclear reactors. The intention was to develop the VVER LSD first, and then, after a user test, develop the next BWR LSD, applying lessons learned from the first implementation.

The first VVER LSD was developed for the Loviisa power plant, and installed on the Fortum development simulator in Helsinki [2]. The VVER display is 5.7m by 1.1m using front projectors. The VTT research centre of Finland performed a user test of the VVER display [5]. Main findings from the user test, and feedback from operators regarding alarms were:

- Alarm consistency and readability should be improved.
- Unacknowledged alarms are not differentiated from old alarms.

The second BWR IRD LSD was developed for the HAMBO (HAMlab BOiling water reactor simulator) simulator and installed in HAMMLAB (HAlden Man-Machine LABoratory). The reactor design is based on the Swedish Forsmark-3 plant. The display was realized using front projectors, creating a seamless display of 6m by 1.5m. The main focus during the development of the HAMBO LSD was to find solutions addressing shortcomings and identified improvement potential from the previous VVER LSD. The main improvements regarding alarm handling implemented on the HAMBO LSD are:

- Alarm consistency and readability are improved by introducing alarm objects of similar shape and appearance for all objects in the LSD.
- Unacknowledged alarms are highlighted by a new dynamic-alarm-spot.

The dynamic alarm-spot appears as a large white bubble surrounding the alarm object when a new unacknowledged alarm occurs in the LSD. The bubble then shrinks into a small white spot within a few seconds. The dynamic appearance of the spot is highly visible for the operator, even without annoying effects like blinking. The spot is turned off when the operator acknowledges the alarm, leaving only the alarm object visible.

This paper is focusing on alarm visualization and consistency issues. The paper describes the new BWR large screen display, and focuses on the design rationale behind the chosen alarm visualization. The dynamic alarm-spot solution is patent pending.

Key Words: Information rich, large screen, alarm

1 INTRODUCTION

The Information Rich Design (IRD) concept, [1], is currently the reference standard for Large Screen Displays (LSD) for the Norwegian petroleum industry. The IRD-based LSDs are currently implemented for Ekofisk, Snøhvit, Statjord A, B and C, Snorre A, Ormen Lange, Troll A, Visund and Gjøa. The IRD concept was initially designed as a process control display with interaction possibilities, but has so far only been applied as non-interactive LSD used for process monitoring. The IRD graphical elements are Design Patented by IFE.

The Nordic Nuclear Power Plants expressed interest in testing whether the IRD concept could be applied for LSDs within the nuclear domain, and initiated a project with IFE. The purpose of the project was to design LSD prototypes for VVERs, PWRs and BWRs. The prototypes should be developed in sequence, with lessons learned integrated from one prototype into the next. The first LSD prototype was developed for the Loviisa nuclear power plant [2]. This report describes the BWR prototype, based on the Swedish Forsmark-3 plant, and implemented in Halden on the HAMBO simulator, using ProcSee [3].

This document describes the main characteristics of the new BWR LSD, with emphasis on alarm visualization, consistency issues and unacknowledged alarms.

1.1 The design process

The IRD-based LSD for HAMBO is developed with the aim of completing a highly advanced and innovative design within strict limitations:

- Limited number of human resources, 2-3 full time persons
- Short time-span, designing and implementing the LSD within a year
- High degree of new and innovative solutions

These three competing factors are difficult to manage within a typical top-down approach following standard industry methods and techniques. Standard approaches typically utilize a highly detailed specification up front, before the design and implementation phase. Instead an action-reflection iterative process [4] was used to develop the HAMBO LSD. The action-reflection iteration process enables designers to evaluate ideas at an early stage, and to modify and improve ideas during both the design and implementation phases.

Figure 1 shows the design process. Note that the “Goals & Requirements” stage at the start is considered flexible, hence new ideas and findings during the “rapid prototyping” process are directly applied into the design. Such ideas and findings do not have to comply with a strict “list” of highly detailed specifications at the beginning of the process.

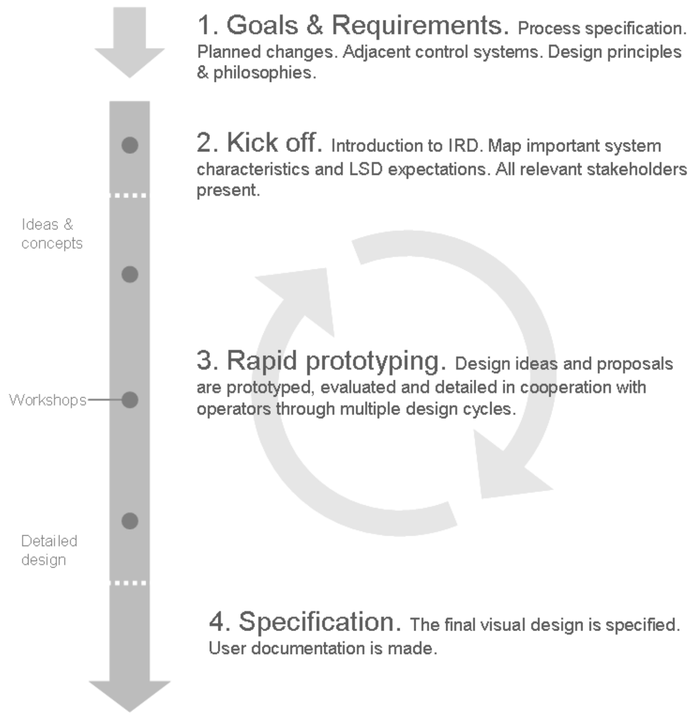

Figure 1 The HAMBO LSD design process

By following this design process, increased flexibility is gained, and the process can move forward at high speed. In the HAMBO LSD project, four workshops were arranged with end-users from the power plants, where new ideas were presented and discussed. Findings from these workshops were thoroughly documented and addressed throughout the design process.

1.2 HAMBO LSD alarm philosophy

The goals and requirements of the HAMBO LSD are based on the goals and requirements of the first IRD prototype for the Loviisa plant; however, additional requirements were introduced due to the feedback from the user test of the Loviisa LSD [5].

The HAMBO LSD is designed according to the IRD principles [1]. These principles refer to displays that combine the use of a dull screen colour concept with analogue data coding, as well as integrating trend and layout techniques to obtain high data density without causing information overload. The dull color principles used are inspired by the work of E.Tufte [6]. Another key feature is that visual forms should be possible to read using different strategies, depending on the user's current preference. A brief glance shall provide essential information, while closer inspection should yield more detail

One of the most important aspects of a LSD is how alarms are visualized. The overall requirements for alarm presentation were:

- Colors and priorities must comply with the alarm list and the operator station displays
- Alarms must give the user enough clues to understand the situation

- It must be easy for operators to spot new unacknowledged alarms
- Group alarms and single variable type alarms must be shown
- Alarms must be visualized at the most intuitive place on the LSD

Generally, alarms on the HAMBO LSD pops up adjacent to the object affected, hence making the display as intuitive as possible. The alarm colors in the HAMBO LSD are consistent with the colors used on the operator stations and alarm-list. The colors and priorities are:

- Red, highest priority
- Yellow, medium priority
- Green, lowest priority

1.2.1 Single type alarms

All alarm priorities are given as filled squares for all process elements in the display. Single type alarms are shown when an object such as pumps, valves and turbines connected to a single type of measurement indicate an alarm. In Figure 2, this can be viewed as filled squares to the right of the green

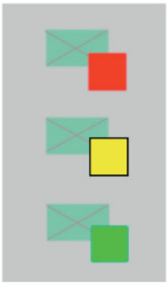

Figure 2 Alarms on valves, example with different alarm priorities

Consistency is further improved compared to the alarm frames given in the Loviisa display. The use of filled squares is easy to apply for all the components used in the HAMBO display, hence the display is consistent both regarding form and function. In Figure 3, an alarm is presented on a mini-trend, using the same filled square as for the valves.

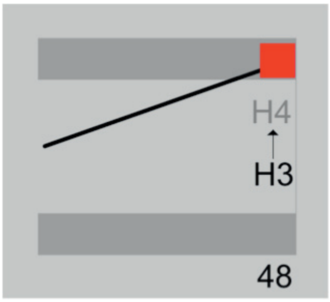

Figure 3 Mini-trend displaying more than just the alarm, H3 is violated moving towards H4

To provide the operator with more clues, some of the objects in the HAMBO display carry more information than just the “single” alarm square. The normalized object provides the user with a specific detailed overview. In the example in Figure 8, the limit “H3” is violated and the “arrow” pointing towards

"H4" appears as the alarm limit is crossed and the value moves towards "H4". In addition, the exact digital value of the variable appears when the objects are in the alarm state

1.2.2 Group alarms

The HAMBO LSD does not contain all alarms of the HAMBO simulator. Expert operators do the selection of single type alarms in the display. To be able to cover as many of the relevant other alarms for the HAMBO process, group alarms are introduced.

The system number shows the group, the active alarm square pops up to the left of the group number. If several alarms are active within the system, the highest alarm color priority is shown. In the example in Figure 4, system 713 (Normal operation cooling water system for priority demands) has at least one acknowledged red alarm.

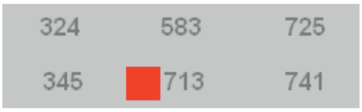

Figure 4 At least one red priority alarm in system 713

1.2.3 Improving visibility of unacknowledged alarm

Identifying new unacknowledged alarms proved to be a problematic area for the Loviisa display. In the Loviisa display new alarms were shown by the use of colored alarm frames, where no distinction could be seen between unacknowledged alarms and acknowledged alarms. In the new HAMBO LSD, a dynamic alarm-spot was developed to enhance the visibility of new alarms. The dynamic alarm-spot appears as a large white "balloon" on new unacknowledged alarms, and within seconds the balloon shrinks to a small white spotlight. The spotlight disappears when the alarm is acknowledged. Figure 5 shows the appearance of this dynamic alarm-spot. Typically, the time frame from t1 to t3 is 2-4 seconds.

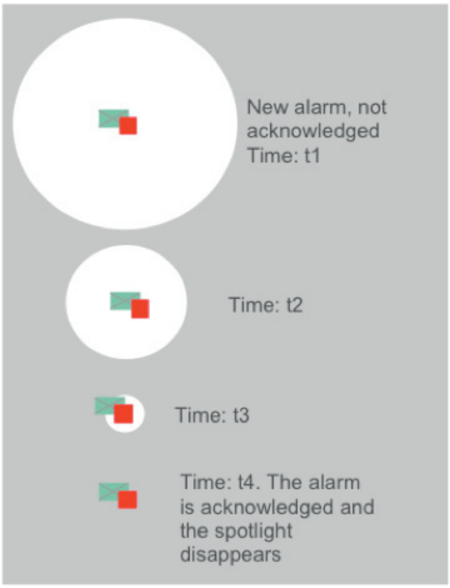

Figure 5 Dynamic alarm-spot on a new unacknowledged alarm

1.2.4 Improving alarm symbol consistency

In the Loviisa display, the alarm frames were shown in different sizes according to the size of the object, hence the same type of alarm, was given different appearances, see Figure 6

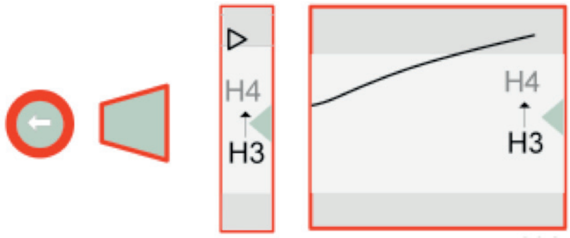

Figure 6 Loviisa LSD; different symbols have different alarm frames

It was found that the yellow color alarm frame was difficult to read, particularly for small-size objects, despite using a black edge on the frame, see Figure 7

Figure 7 Loviisa LSD; yellow alarm frame, not easy to see.

In the new HAMBO LSD, filled square objects proved to be a better solution. The difficult yellow color is more visible when shown as a filled object compared to a yellow frame. But even so, still some tweaking had to be done to the yellow colored squares, a dark frame is added to the object and the yellow color is saturated for enhanced visibility, see figure 8.

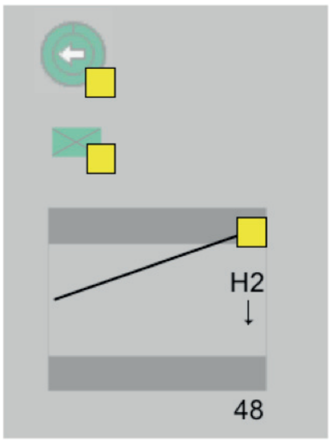

Figure 8 HAMBO LSD with consistent alarm symbols, the yellow color is easy readable

It was also found that using colored squares instead of frames, improved the alarm consistency throughout the whole HAMBO display. In Figure 8 it can be seen that the square alarm object is used consistently for all objects in the HAMBO display, here the pump, valve and mini-trend.

1.3 HAMBO LSD layout and implementation

This chapter describes the layout of the LSD, as well as an overall description on how the display was implemented using the Halden Project's ProcSee graphical tool [3].

1.3.1 Display layout

The HAMBO LSD is shown in Figure 9 below

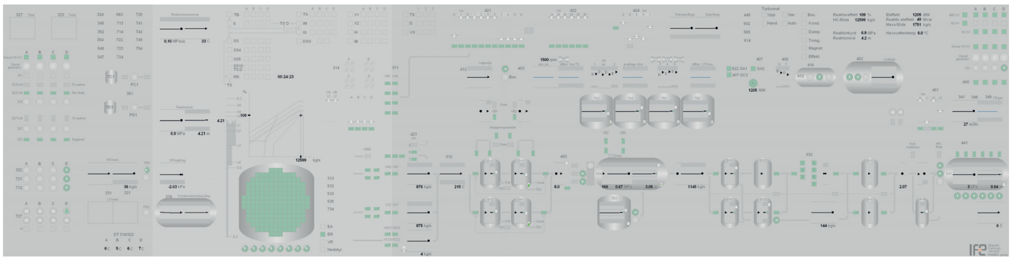

Figure 9 The HAMBO LSD

Four projectors providing a seamless display of 6 x 1.5 m are used to display the HAMBO LSD in HAMMLAB. The display is divided into a right hand turbine side, and a left hand reactor side, see Figure 10

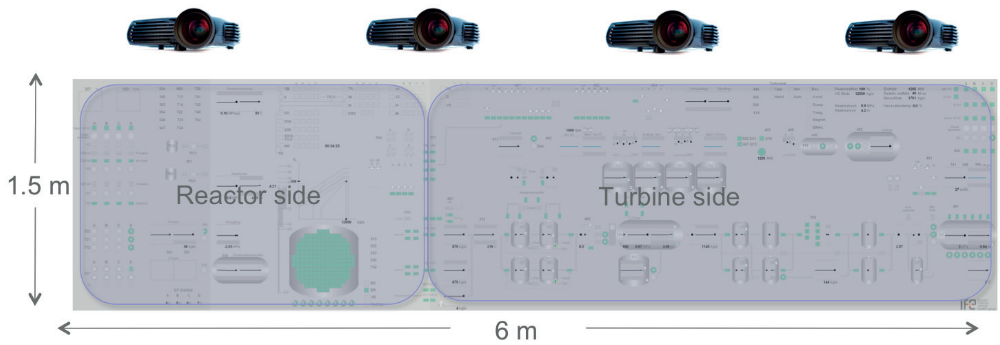

Figure 10 Four projectors are used to display the LSD.

Figure 11 shows the main components of the turbine side of the display. The thick arrows indicate the main process flow.

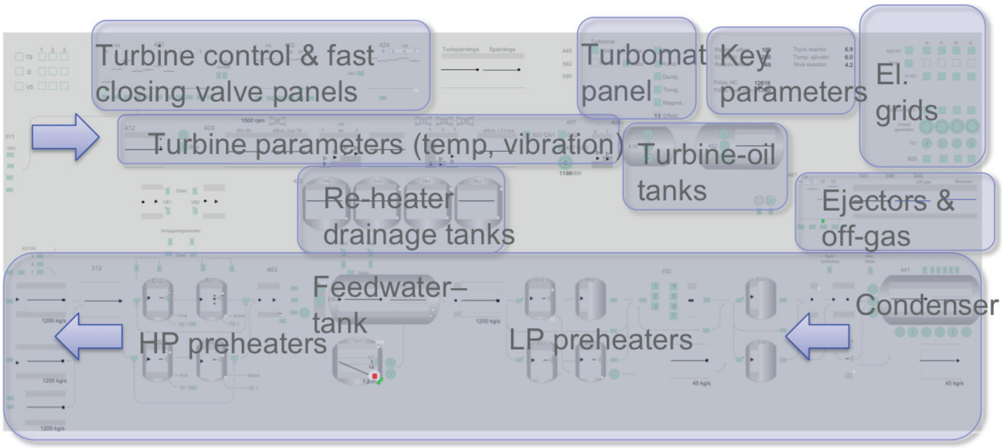

Figure 11 Main functions of the turbine side of the LSD

Figure 12 shows the reactor side of the display.

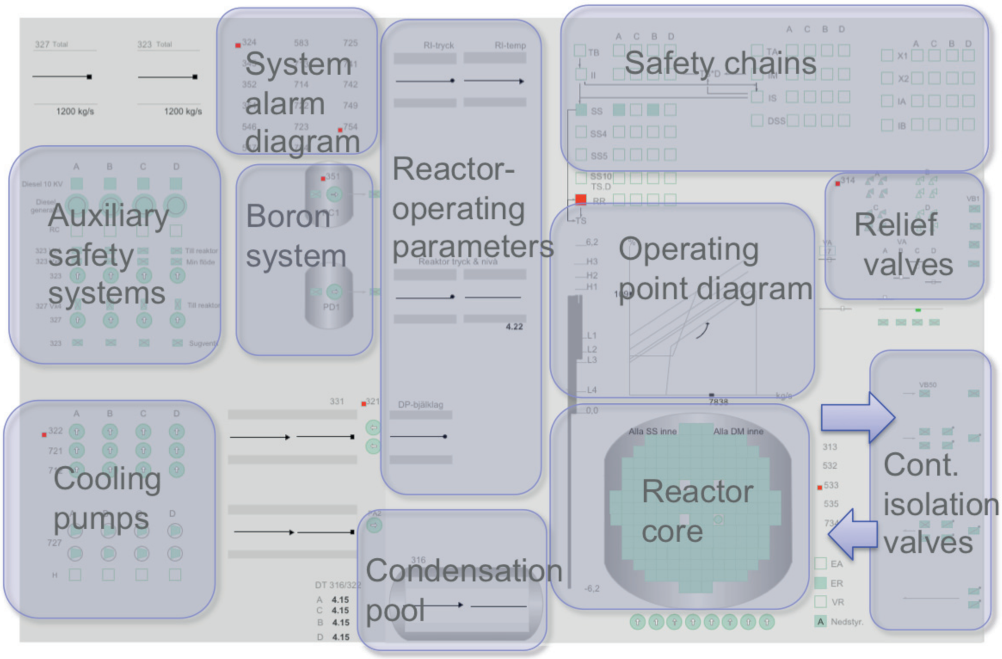

Figure 12 Main functions of the reactor side of the LSD

1.3.2 Implementation using ProcSee

The HAMBO LSD display is implemented in HAMMLAB using ProcSee [3] to realize the graphics. The display is 4200x1050 pixels. The display contains about 560 complex dynamic objects, 120 dynamic pipeline pieces and 330 static objects and texts. The graphics are updated based on new values from the simulator each 300 ms. ProcSee's double buffering refresh algorithm prevents flickering and automatically reduces redrawing to only the dynamic objects that actually changed appearance from the previous cycle. During testing, CPU load of the computer controlling the large screen was below 15% at all times, even during extensive transients.

Generic components from the previous Loviisa LSD were re-used for the HAMBO LSD. However, modifications were required to comply with experiences gained from the evaluation of the Loviisa LSD. Most notably, modifications were required for the visualization of alarms, which was found to be a weak point in the Loviisa LSD. Also, some new components were developed in line with the HAMBO LSD design.

In general, the generic components were assigned individual data structures matching the components' needs for data attributes to enable the dynamic graphics visualization according to the design. Together with the simulator's well-defined naming conventions, this strategy enables a programming approach when connecting the graphic objects to simulator data values, and thereby reduces development time and is less vulnerable to manual errors.

One specific design feature of the HAMBO LSD is the dynamic alarm-spot. The dynamic alarm-spot is a white circle centered on an emerging alarm. Its radius is initially rather big, but decreases towards a stable small size within the first few seconds after the alarm initiated. According to the design specification, the dynamic alarm-spot should never cover important dynamic visualizations for the object containing the dynamic alarm-spot, or for nearby objects. In order to meet this requirement, a new generic feature, the layer, was introduced in ProcSee in parallel with the implementation of the HAMBO LSD. With this feature, ProcSee objects and sub-objects can be assigned individual layers, and the display designer can define the number of layers and their order back-to-front. At run-time, ProcSee will ensure that objects assigned to a background layer never hide objects assigned to a foreground layer. For the HAMBO LSD, four layers were defined (in the back-to-front order):

1. Background layer, containing alarm band sub-objects. This layer also contained individual static background objects
2. Dynamic alarm-spot layer, containing the spotlight sub-objects
3. Default layer, containing most sub-objects
4. Tag layer, containing the tag-text sub-objects. Tag-texts were available during testing to enable manual visual verification to ensure that the graphics was connected to the correct simulator data

Using the layer feature as described here ensured that the dynamic alarm-spot feature was successfully implemented according to the design specification, and in particular prevented the spotlight from covering important parts of nearby objects.

2 CONCLUSIONS

The Information Rich Design concept and the dull screen principle have been used for many years in designing LSDs for the Norwegian petroleum sector. The Nordic Nuclear Power Plants found the IRD concept interesting, and funded a project with the aim of investigating whether IRD could be a viable also in the nuclear domain. Two LSDs have been developed within this project, the first one for Loviisa and the second one for the HAMBO simulator in HAMMLAB. A user test of the first Loviisa LSD, and user feedback is used to improve the HAMBO LSD. With emphasis on alarm consistency and alarm visualization issues, several major improvements to the existing IRD design scheme are made for the HAMBO LSD. A new dynamic alarm-spot is developed to distinguish acknowledged from unacknowledged alarms. New alarm symbols are developed to ensure consistent alarm visualization for all objects in the LSD. A follow-up project evaluating different large screen displays was initiated in 2009 and will be completed towards the end of 2010. The HAMBO IRD-based LSD is one of the LSDs that will be evaluated in this project.

3 ACKNOWLEDGMENTS

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PAPER VII

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Visualizing complex processes on large screen displays: Design principles based on the Information Rich Design concept

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ABSTRACT

Large screen display technology has in recent years become available to industrial control rooms as a supplement to smaller displays. Due to the greater complexity and scale, measured in meters, not inches, it is now a challenge to design for readability and Situation Awareness. Information Rich Design is a design concept for large displays used in many real-life complex processes for almost a decade. The concept simplifies the understanding of large data sets through alignment and Gestalt grouping of process data through a few generic process objects.

This paper describes recent design modifications where new functionality is integrated into existing graphical objects, keeping the original simplicity. This paper proposes design principles for large screen displays based on theoretical discussions of Situation Awareness and a user test using crews of certified operators. The user test shows positive results on pattern recognition of process data and a newly developed animation of unacknowledged alarms; however, the concept still suffers from colour and readability issues.

1. Introduction

Industry control rooms are in a process of change; large hardwired panels displaying information through analogue indicators are being phased out in favour of computerized interfaces. Even in conservative domains such as nuclear power plants, old analogue technology is being replaced with desk mounted operator stations offering great flexibility and low-cost system upgrade potential.

Vicente et al. [1] found however several difficulties by this approach. In a field study of older nuclear power plant control rooms, they pointed particularly to the unfortunate keyhole effect: "*there are not enough CRTs to comprehensively monitor all of the control systems status displays*". This view is supported by a more recent study on conventional and nuclear power plant by Salo et al. [2]. They concluded that it has become more difficult to get the instantaneous process state overview on desktop workstations than through large panels.

More recently, control rooms have begun to take advantage of large screen display (LSD) technology as a supplement to smaller operator stations, having the potential to increase situation awareness (SA) through the big-picture and to reduce keyhole-related problems. Several studies suggest that the use of LSDs is beneficial. Ball et al. [3] found that users prefer physical navigation in visualizing tasks; and that LSDs also improved user performance. Recent work by Endert et al. [4], suggested however that the choice of visual encodings in large displays directly affected users' performance. Andrews et al. [5] found that it is not just a matter of scaling up existing visualizations intended for smaller displays.

The Norwegian Institute for Energy (IFE) in Halden has developed several LSDs for research purposes. The old Halden Boiling Water Reactor (HAMBO) LSD [6] in Fig. 1 is used on a large-scale nuclear reactor simulator. It represents a traditional graphical design approach using a mimic layout with flow-lines, colour layering as described by van Laar [7], and digital numbers representing process values. It has however in addition some more advanced features such as small trends and integrated bar graphs.

As an alternative to digital numbers, Burns and Hajdukiewicz [8] suggested using easy perceivable qualitative indicators for Ecological Interface Design. More recently, the ASM Consortium by Reising and Bullemer [9] has taken an innovative approach on smaller desk-mounted overview displays, using such qualitative direct-perception indicators. On display layout, they suggested using a functional grouping of indicators instead of the traditional mimic type with flow-lines. Tharanathan et al. [10] showed promising results were these overview displays contributed positively on operator's SA.

More advanced than the old HAMBO display is the Information Rich Design (IRD) concept. IRD was developed at IFE for more than

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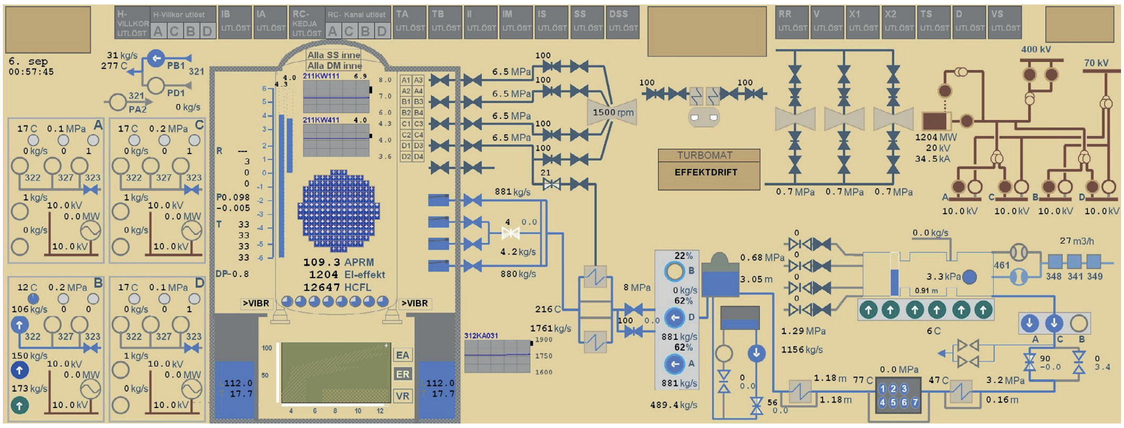

Fig. 1. Traditional LSD approach, 4 × 1.5 m, mimic layout, colour layering and some advanced symbols.

a decade as a scientifically from the ground-up LSD concept for complex processes. It's main objective is to address human capabilities visualizing the big picture, while presenting process information seen at-a-glance. Where the more recent ASM Consortium approach is more comprehensive, combining several graphical elements (dials, horizontal and vertical bars, etc.), the focus of IRD is to simplify larger data-sets through only a few, generic design patented elements visualizing pressure, temperature, liquid levels, etc. The concept combines this with traditional process symbols on valves, compressors etc.

IRD graphical objects simplify larger data sets through alignment and Gestalt grouping. This is enabled through part-wise mathematical normalization of the process variables measuring scale, see Fig. 2.

The IRD approach has proved to work in real-life applications across several domains; it is used in more than 13 LSD applications in Norwegian petroleum industry and later in mining. The concept is realized in two research applications in the nuclear domain, the first generation Loviisa LSD, and second generation HAMBO LSD.

Unfortunately, so far the IRD concept has not formalized design principles usable for others. Since most other concepts for real-life complex processes are developed for smaller displays, we recognize that there is a need to formalize design principles for larger displays:

- Which type of process display objects is suitable?
- How to visualize alarm information?
- What type of display layout is suitable?

This paper first discusses LSDs in context of SA, looking at related work by others, next how the original IRD graphical objects were modified for the second-generation HAMBO LSD. Then a user-test is performed on this LSD to see if modifications were successfully on: Colours, pattern recognition of process data and alarm visualization. Based on this, we propose design principles for large displays and outline some further research topics.

1.1. Earlier work on the IRD concept

Early IRD publications [11,12] discussed the need for a design concept that supports rapid visual perception through Rasmussen's Skills-Rules-Knowledge taxonomy, Tufte on high data/ink ratio and colour layering. More recent publications [13,14] focused on how the IRD concept were realized on LSDs. Laarni et al. [15] provided a user-test of a first generation IRD display.

2. Situation awareness and large screen displays

Endsley et al. [16], described Situation Awareness (SA) as: "*being aware of what is happening around you and understanding what that information means to you now and in the future*". The potential for difficulties in maintaining SA is well established in relation to complex large-scale processes. Durso et al. [17] found problems with SA to be a factor in both aviation and industrial accidents. Reising and Bullemer [9] used the SA concept in relation to overview displays for hydrocarbon processing industry. In the following, we discuss IRD large displays in context of Endsley's description of SA.

2.1. SA level 1

Endsley et al. described the first SA level as: "*perception of the elements in the environment*". For LSDs this suggests that sufficient information should be presented in a way that is easily readable

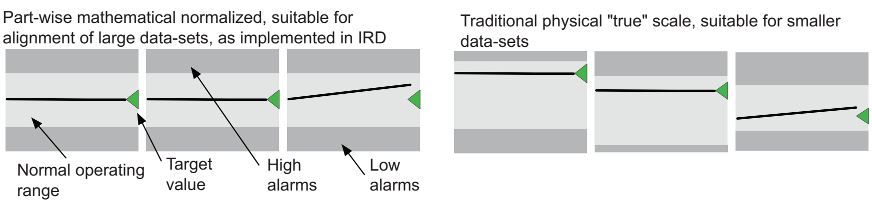

Fig. 2. IRD mini-trends on left side, using traditional scale on right side.

and understandable for the operator, understanding the plant situation. We find Tufte's [18] goal of creating data-rich illustrations to be valuable in this. He advocated the use of a high data-ink ratio, focusing on data, not ornaments or chart-junk. Tufte's work is, however, mostly concerned with data on printed-paper. Gillan and Sorensen [19] applied however Tufte's concepts to computer displays. Their results suggested that indicators and backgrounds should be given distinct different visual features.

Endsley et al. referred to challenges in complex domains due to information that competes for the operator attention. We find this particularly appropriate in context of complex larger scaled displays. To avoid masking primary data, a colour layering technique as described by van Laar [7] can be applied. van Laar and Deshe [20] demonstrated faster search times with these displays than with monochrome or non-layered colour displays.

2.1.1. Design principles

Make the display information-rich, present many cues describing the plant-state. Colour layering is suitable to avoid masking primary data. Visual salience should match the importance of process plant information.

2.2. SA levels 2 and 3

Endsley et al. described the second SA level as: "*comprehension of the current situation*". This can be understood as to integrate the level one SA elements in relation to goals and objectives. For LSDs, this suggests that information such as target values, alarm limits, should be put in an intuitive context, making the operator aware of possible deviations and abnormal situations.

Wickens and Hollands [21] suggested that the operatoŕs mental model of the process is analogue and continuous, rather than discrete and symbolic. From this we find that an analogue presentation of process data is suitable. Tufte [22] suggested the use of small trends, which he calls "*sparklines*", to display data in computer graphics.

Endsley et al. as described the level 3 SA: "*projection of future status*". For process data this can be to indicate in which direction are process values "drifting", toward alarm limits or stabilizing on target values? Yin et al. [23] showed in an empirical study that explicit rate-of-change cues in process control operations improve operator performance. The study does however not conclude on what is best, a trended line or explicit digital information showing the direction of change.

2.2.1. Design principles

Analogue indicators is more in-line with human cognition than digital numbers, small trends are suitable. Visualize process plant goals and objectives explicitly to the operator. Provide rate-of-change cues.

2.3. SA demons

We agree with Reising and Bullemer [9] in their discussion on smaller overview displays that inaccurate mental model, cognitive tunnel vision and data overload are problematic and should be addressed. Due to their size and screen real estate, we find, however, LSDs to have an even greater risk of data overload. For this reason, we find it relevant to simplify visual appearance through Gestalt concepts such as: Closure, good-continuation, Law of prägnanz, proximity, see Lidwell et al. [24].

In addition to the above SA "demons", we find it also relevant to address the "requisite memory trap" in LSDs. In this we find Norman's concept of making data externally available to the process operator interesting, the opposite is described as memory challenging in-the-head information. Display hierarchies are necessary in smaller operator displays, but it can challenge the operator's memory (in-the-head). For this reason we suggest a flat externalized in-the-world layout in larger displays

2.3.1. Design principles

A flat, externalized in-the-world display layout is suitable. Simplify process data by applying Gestalt concepts.

2.4. Other SA considerations

Endsley et al. stated that: "Alternating between bottom-up data-driven and top-down goal-directed processing of information is one of the vital mechanisms supporting SA". LSDs can display thousands of process variables in displays measuring meters, not inches. For this reason we suspect that there is a need to support top-down search for information in these displays. Search in traditional industrial mimic layouts is aided by visualizing process flow-lines and larger objects such as vessels. We agree however with Reising and Bullemer [9] using a more abstract functional tabular layout, that such static information takes away valuable space for dynamic process information. In larger displays, we suggest however that some sort of aids for top-down search should be included.

Other means that is suitable aiding top-down search is the use of negative-space, that is open areas in the display, avoiding a too information dense display. Hornof and Halverson [25] found that people effectively ignore negative space searching in computer displays, suggesting that it is not harmful.

Means to be properly alerted on bottom-up data driven situations such as alarms and process deviations must included in design through sufficient pop-out effects.

2.4.1. Design principles

Display design should aid in top-down search for information, consider using visual landmarks, lines and negative space. Apply strong pop-out effects supporting data-driven situations such as, key-alarms, new unacknowledged alarms and process deviations.

3. Modifications for the HAMBO large screen display

In this section, we first look at issues reported from a user test of the first generation Loviisa LSD. Based on these findings, we describe how the IRD concept was modified for the follow-up second generation HAMBO LSD.

The user test of the Loviisa LSD by Laarni et al. [15] reported several problem areas, in the following we look at three major issues and how we have modified the original design concept to overcome these:

- The value of pattern recognition through part-wise normalization of set-point and alarm limits was questioned.
- Poor alarm visualization.
- Too glary and tiring display, difficult to differentiate between grey and green. The LSD looked crowded and too abstract.

3.1. Pattern recognition, modifying basic elements

Fig. 3 shows the three original generic indicators developed for IRD, the mini-trend, bar type and polar diagram. All three objects use part-wise mathematical normalization of the measuring range to create visual bands of values and alarm limits. In this approach, the measuring range is divided into several segments; each segment is compressed or stretched. The result is that all process variables regardless of type or measuring range fit into the same graphical elements. In normal plant state, the process value should

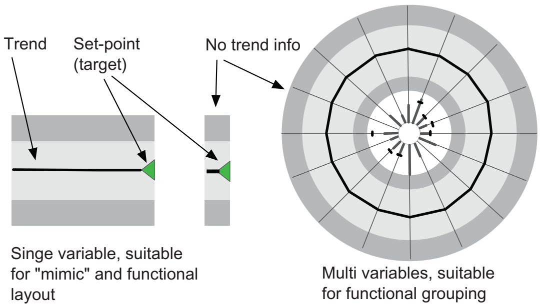

Fig. 3. The three original IRD objects used in LSDs.

be positioned in the middle of the object; alarms are always at the same position. It should however be noted that using such unphysical scale can lead to inaccurate mental models.

For the new HAMBO LSD, it was decided not to abandon the concept of part-wise mathematical normalization of the measuring scale, as we suspected it could result in a complex and difficult to read display, illustrated in Fig. 2.

The narrower bar-type object in Fig. 3 saves valuable space but is less information rich, as it carries no time-information. The polar diagram excels however by grouping many variables into a more condensed package. In the example in Fig. 3 and 16 variables form a circle in the middle of the light grey area, each spoke representing a process variable. If values are at their target point, they form a circle. The inner thicker spokes are controller output and ticks represent valve (controller organ) position. The diagram is suited for integrating functional related variables, but carry no time-information. It is also quite abstract and not particularly well suited in mimic type layouts. For the HAMBO LSD, we chose the two left process objects in Fig. 3, suitable for a more familiar mimic-layout.

In the following we show examples through the mini-trend, but the same principles apply for the narrower bar type. A weakness in the Loviisa display, and by the original IRD objects was that they lacked intuitive information related to controller and controller organ position. This is valuable, as it can alert the operator of potential problems such as "no more regulation margin" or "stuck valve".

For the HAMBO LSD we increased information richness by integrating intuitive visualization of controller and controller organ (valve) on the right side of the IRD-mini-trend, keeping the operator "in-the-loop" on plant-automation, see Fig. 4.

Ideally the controller output (square) and valve position (line) should be aligned on top of each other. If not, it can indicate automation abnormalities. The range from closed (bottom) to fully open (top) supports natural use of metaphors.

3.2. Improving alarm visualization

Traditionally, alarms are displayed as alarm-lists providing alarm identification, description and time stamp. However, this

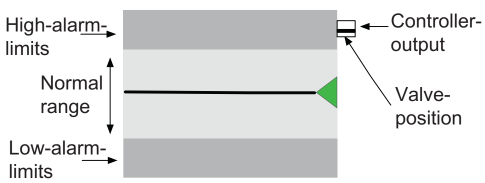

Fig. 4. Integrating intuitive cues on plant-automation.

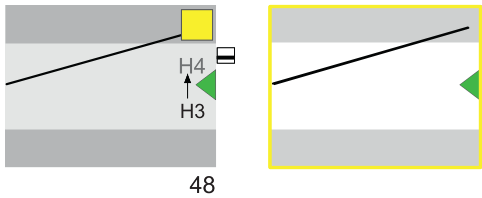

Fig. 5. HAMBO to the left, stronger alarm pop-out, better consistency, more alarm cues.

challenges human cognition in faster-paced situations, as alarms must be read and understood line by line. LSDs can serve as a useful supplement to lists in displaying key-alarms through easy to spot pop-out effects.

Unfortunately, the alarm frames used in the Loviisa LSD did not have enough pop-out effect; they were also inconsistent in size, as the alarm frame follows the size of the process object. Neither did the Loviisa alarm visualization inform on which alarm was active, or whether it was a high or low alarm. In addition to this, some operators suggested that the qualitative indicator did not offer sufficient reading accuracy.

To increase pop-out and improve consistency, alarm frames were replaced with filled squares, having the same size and shape for all process objects. In addition, we integrated explicit alarm information, and rate-of-change cues, see Fig. 5. The position of the alarm square is also in-line with common use of metaphors, on top (high alarm), at bottom (low-alarm). For increased accuracy, the digital value was added on key components, and always popping up in alarm condition. In Fig. 5, the H3 alarm limit is violated, moving toward H4, the process value is 48.

It was noted as a weakness that the Loviisa display did not distinguish new incoming alarms from old standing alarms. In smaller displays, it is quite common to use blinking/flashing to notify the operator on such events. This can be intrusive and tiring to look at over longer time periods of time, particularly on larger displays.

For the HAMBO display we developed an alternative: the dynamic alarm-spot. It works as a gentler animation on top of the new alarm, creating a strong pop-out effect. Fig. 6 shows how it is implemented on a red alarm on green open valve. The dynamic alarm-spot works consistently for all alarms on all display process objects.

3.3. Improving colours and display layout

The general concept of a flat, in-the-world display for monitoring (not interaction) was kept for the HAMBO LSD. However, more negative space was added to reduce the crowded and dense look of the Loviisa display. To reduce the feeling of a too abstract and unfamiliar display and to improve top-down search, we added some mimic-type features (flow-lines) and visual landmarks (large vessels), see Fig. 8.

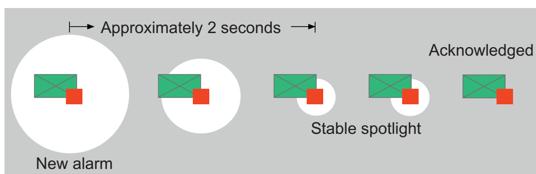

Fig. 6. The new dynamic alarm-spot visualizing new incoming alarms.

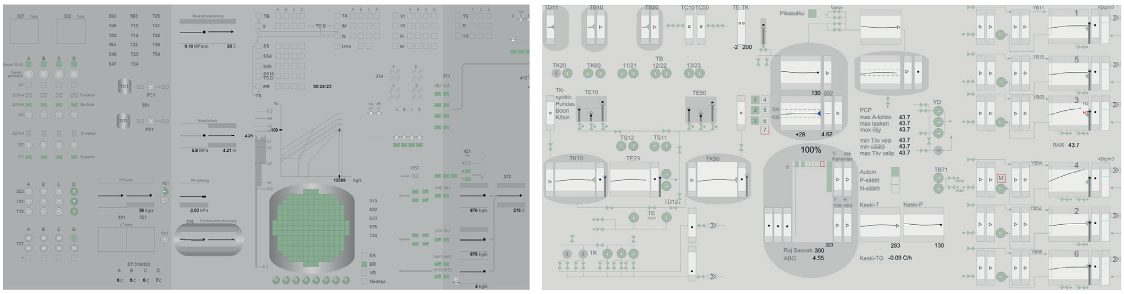

Fig. 7. The darker HAMBO to the left, brighter Loviisa to the right (reactor side of LSDs).

A darker flat grey background was used avoiding a garish and tiring display, the downside is a loss of contrast, (see Fig. 7). For improved readability of grey–green, a more saturated green colour was chosen to indicate active states (running, open, etc.).

It could also be possible to increase readability in the display by introducing other colours instead of the extensive use of grey-scale. This could, however, result in masking signal colours reserved for abnormal plant conditions.

4. User-test of the hambo large screen display

The analysis in this section is based on: (i) Rated data collected from a larger study [26]. (ii) Operator statements from the larger study. Kaarstad and Strand [26] at IFE Halden studied three large screen displays, only one of these, the second generation HAMBO display is discussed in this paper, see Fig. 8:

Four projectors provided a seamless display measuring 6 m × 1.5 m, with a typical seated viewing distance of 3.5–4.0 m. The display was divided (zoned) into a right hand turbine side, and a left hand reactor side. The display was implemented with ProcSee [27]. Colours were adjusted for projectors not for printed-paper. The display was 4200 × 1050 pixel resolution and contained about 560 complex dynamic objects, 120 dynamic pipeline pieces and 330 static objects and texts.

Key-data for the larger study is:

- Seven crews from five different Nordic power plants participated in this study.
- The mean age across all operators was 43, 1 (ranging from 29 to 56).
- The operators generally rated their amount of experience with large screen displays as intermediate, mean value of 2, 4 on a 5-point rating scale where 1 represents little experience and 5 represents much experience.
- The crews were introduced to the large screen displays and the digital screen based control room before the test scenarios. The operators were provided a couple of hours' training before the test.
- Test-scenarios were performed on the HAMBO large-scale nuclear simulator [6].
- The requirements for the test-scenarios were that they should cover a diverse set of situations that the large screen display was intended for: normal operation with tasks (like periodical tests and shifting equipment), load-changes, disturbances and emergency operation.
- The goal was that the crews could use as many of the specific features of the displays as possible, and that information was collected for both the crews overall impression of the display in different situations, and on specific graphical elements.

4.1. Purpose

The purpose of the user test in this paper was to see if issues reported on the first-generation Loviisa LSD were solved on the second-generation HAMBO LSD. "*Are colours, the concept of pattern-recognition and the new dynamic alarm-spot working satisfactorily*?"

4.2. Data collection

Data were collected from written operator statements from the larger study. Four research scientists at the Institute for Energy Technology (IFE) assigned data with positive or negative affect on the following three categories:

- The colour layering concept
- Pattern recognition through normalization of variables
- The dynamic alarm-spot

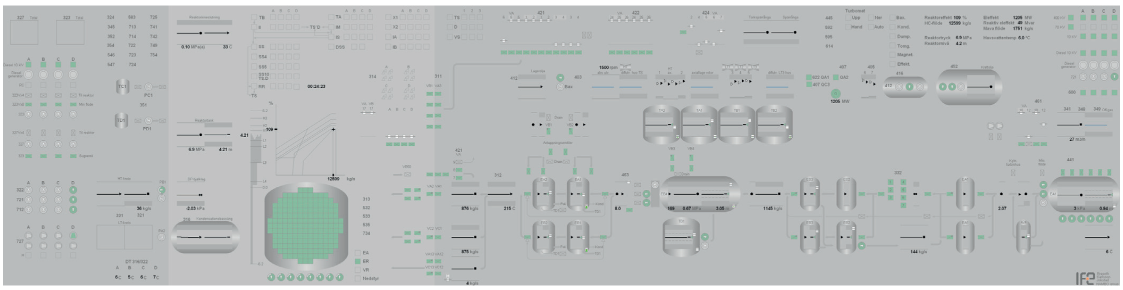

Fig. 8. The HAMBO LSD, 6 m × 1.5 m.

Table 1
Collected data for the three categories.

	1		2		3		4	
	+	–	+	–	+	–	+	–
Colours	41	117	27	124	16	46	33	62
Pattern	79	9	88	20	33	10	33	3
Alarm-spot	45	12	31	10	28	6	24	4
Colours %	14	39	9	41	12	33	21	39
Pattern %	26	3	29	7	24	7	21	2
Alarm-spot %	15	4	10	3	20	4	15	3

The rating was done according to a set of written rules. All four participants had knowledge of the IRD concept, and participated in a short briefing before rating data. Each participant did the rating independently.

4.3. Results from rating

Table 1 shows the collected data, positive (+) and negative (–) affect.

Persons 1 and 2 reported approximately twice as many entries (303 and 300) as persons 3 and 4 (139 and 159). This indicates that persons 1 and 2 have set the bar significantly lower when applying the selection criteria. The largest difference in distribution is that person 3 reported more positive feedback for the dynamic alarm spot, and person 4 reported more positive feedbacks for the colour scheme than the others. The distributions are however quite similar, indicating that the studied categories and selection criteria were well defined:

- The colour concept: consistently more negative than positive.
- Pattern recognition through normalization of variables: consistently more positive than negative.
- The dynamic alarm-spot: consistently more positive than negative.

From this we suggest that the mean result is valid. Fig. 9 shows the average percentage distribution all data (901):

4.4. Results from rating and operator statements from the larger study

The colour concept has more negative than positive statements, approximately 3 to 1 ratio. This is consistent with operator statements that colours and contrast are too diffuse, and do not provide sufficient readability. The result suggests that colour modifications for the HAMBO display were not successful. Operators were however generally positive to the background colour, and that they found the display calm enough: "*Pleasant background colour, but*

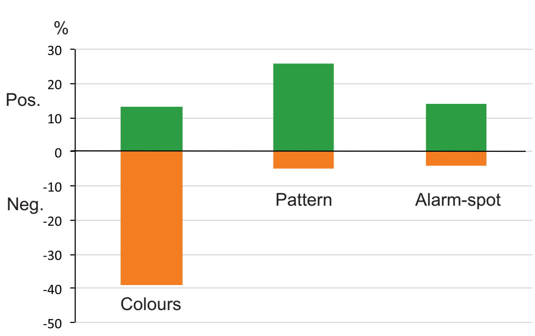

Fig. 9. Averaged data (901): colour concept, pattern recognition and alarm-spot.

the contrast generally toolow", *and* "*Thebackground colour is comfortable to watch*". This suggests that the HAMBO display has better background colour than the Loviisa display.

A problem from the Loviisa display - how to distinguish between grey (not running) and green (running) – does not seem to be solved: "*The green valve symbols are tooanonymous*". In sum, this suggests that the contrast and readability of dynamic entries in the display must be further improved. It should be noted that the use of front projectors and ambient lighting in the room might also cause problems on colour readability, affecting contrast ratio and saturation. Both adjustments to the colour concept, calibration of projectors and ambient lighting should be further investigated.

Pattern recognition through normalization of variables is given more positive than negative feedback, approximately 5 to 1 ratio. This suggest that this concept is well understood, and appreciated by the operators. Operator statements are backing up with positive feedback: "*Like the straight lines throughout thedisplay*. *It is easy to see when something differs*". The results are therefore not supporting the more negative attitude on this from the evaluation of the first Loviisa display. Several operators stated however that the "bar-type" normalized IRD object without trended information has less value, see Fig. 3.

However, some statements on pattern recognition are also negative: "*The mini trends are not always easy tosee*, *as they have noframes*". Again the problem might be traced back to the colour/contrast readability issues. The results are however in general encouraging, suggesting that this concept is suitable for process monitoring on LSDs.

The results for the dynamic alarm-spot shows a positive result, approximately 3 to 1 ratio. This indicates that the problems from the Loviisa display with poor readability of alarms, and difficulty in differentiating between acknowledged/unacknowledged alarms are solved more satisfactorily in the HAMBO display. Statements given in the user test are backing this up: "*The dynamic alarm spot was very good in displaying what is wrong*".

Some operators are, however, pointing out problems during larger upsets with alarm flooding: "*Wouldbe more useful during disturbances if alarms were suppressed*". This indicates that the dynamic alarm-spot would benefit from alarm suppression and in general a well-managed alarm system. The concept is however promising for LSDs, this suggest that the dynamic alarm-spot should be kept and used as a part of the IRD concept.

4.5. Considerations and limitations

There are limitations in this study. It is difficult to draw definitive conclusions on the three studied categories, since they are extracted from the source material from the larger study [26]. It has also to be emphasized that the operator crews were not familiar with the HAMBO process. Their lack of familiarity with the details of the process and system numbers might have influenced their perceptions and evaluations. IRD is in addition more features rich and abstract compared with what they are used to, and might therefore require more training to acquire a comparable level of skills than other designs.

It can also be argued that the three studied categories are not independent variables. As an example, the dynamic alarm-spot uses the concept of colour layering to display a new unacknowledged alarm.

5. Design principles and further work

The poor readability of IRD larger displays using a grey colour scheme has been a surprise to us. During design phase, prototypes seemed to have sufficient readability on smaller LCD displays, but as the user test shows, they look either: garish and too bright, or washed out and too dark, and they generally have poor readability. Extensive use of grey-scale colour layering seems to be difficult on larger displays using front mounted video projector technology in well-lit rooms.

In visualization of process alarms, it is quite common to use coloured frames surrounding process objects, also in modern approaches [9]. We have, however, struggled with readability of frames. Our work suggests that filled objects work better on LSDs. They create stronger pop-out effects on key-alarms, and they improve consistency. We cannot see problems with this approach, as it supports the underlying principles on alarm-colours, prioritizing, consistency, etc. The most recent addition, the design-patented animation to visualize unacknowledged alarm is, however, particular to our IRD concept, and the user-test suggest that this is an attractive alternative to blinking/flashing in larger displays.

In our opinion, the use of graphical objects supporting pattern recognition is in line with general principles on information presentation. Well-known guidelines for nuclear domain, NUREG-0700 [28] Section 6: Group-view display system states: ''*An overview display should provide a characterization of the situation as a whole in a concise form that can be recognized at a glance*''. Others [9] also use qualitative direct-perception indicators as an alternative to traditional process data visualization in real-life applications, combining dial-gauges, horizontal and vertical bars etc.

There are many ways to design direct-perception indicators supporting human cognition, our work suggests however to design for simplification than accurate reading in larger more complex displays. For this reason, our recent design-modifications as described in this paper, are integrated within the context of these objects, keeping the original simplicity, avoiding extra add-on graphical objects. The user test suggests that this is a promising way of visualizing process information in larger displays. IRDs simplicity has also made it possible to be used in many real-life processes in several domains through industrial vendors tools by, ABB, Siemens and Kongsberg Offshore.

We propose the following design principles:

- Display graphics should be information rich, describing the plant situation through many cues. Visual salience should match data importance. Colour layering is suitable, but extensive use of grey-scale has given readability problems in well-lit rooms using front-projected technology.
- Qualitative direct perception indicators are suitable in displaying process data. Rather trended information than not. Integrate, target values, rate-of-change cues and automation keeping the operator ''in-the-loop''. Reduce visual complexity through a limited number of display objects, support Gestalt simplification of data and alignment.
- Visualize key-alarms through strong pop-out effects; equally sized filled objects are better than alarm-frames. Integrate alarm information within a natural context of graphical objects. Highlight new unacknowledged alarms, a gentle animation is an alternative to protrusive flashing/blinking.
- An externalized explicit flat in-the-world layout is suitable. Improve top-down search through visual landmarks and negative space. We suspect that a physical recognizable mimic layout including some process flow-lines helps in top-down search.

In our opinion, the principles on general display layout are inline with others; NUREG-0700 refers to the advantages of long shot view, perceptual landmarks, and spatial representation in retrieval of information in the total display space. Even if design principles are developed for IRD displays, we suggest that they are of interest for others in designing for complex large-scale processes. We find them not in conflict with existing guidelines, but are modified and extend on what others have found for smaller displays.

More work must be done with the colour-layering concept, the use of front mounted projectors and with ambient light conditions. As our theory foundation mostly is influenced by information visualization theory for a static state, such as printed-paper, there is also a need to expand the theoretical foundation of the IRD concept, creating a stronger relation to dynamic process plant behavior.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.displa.2013.05.002.

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PAPER VIII

Seeing the Big Picture: Principles for dynamic process data visualization on Large Screen Displays

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ABSTRACT

Control room operators in time-constrained situations easily lose track of what is happening in complex large-scale processes, coping with thousands of variables and control-loops. Information-Rich Design (IRD) is an industry-tested approach to Large Screen Display (LSD) design that aims to close the gap through an easy perceivable big picture. This paper develops a theoretical basis and proposes design principles for IRD, focusing on visualization of dynamic behaviour of complex large-scale processes.

The theoretical basis is discussed in light of initial evaluations of the IRD concept, other display concepts for complex processes, scientific findings on visualization and perception of displays, and psychological literature on rapid, intuitive, information perception. Design principles are discussed using the case of an on-going installation of a third generation IRD large screen display for a nuclear research reactor.

Keywords: Large Screen Display, Complex Processes, fast Visual Perception

1. INTRODUCTION & MOTIVATION

Control room operators face a huge challenge in monitoring thousands of variables and control-loops in large industrial processes. They may experience difficulty in seeing the greater picture if complexity goes too far. Endsley [1] noted that operators have difficulties developing satisfactory Situation Awareness (SA) in complex processes because of the necessity to perceive critical factors, comprehend them in a meaningful context in relation to goals and to support projection of future status.

Display technology suitable for control room installations has evolved rapidly in recent years. High-definition video projectors and flat screen power-walls have enabled the display of process information on much larger surfaces than in the past. Andrews et al. [2] refer to studies showing that high-resolution Large Screen Displays (LSDs) can positively affect user performance for spatial visualizations. Thus it is plausible that LSDs can contribute to improving the operator´s SA, presenting much more information than on smaller desktop displays.

Unfortunately, larger scale displays in control rooms are often only up-scaled traditional schematic process and instrumentation type pictures, using traditional process symbols, numbers and bar graphs. Andrews et al. [2] suggest, however, that designing effective large displays is not a matter of scaling up existing visualizations; designers should adopt a human-centric perspective on these matters, taking limited human capabilities into consideration.

Endsley [1] refer to studies showing that experts use pattern-matching mechanisms to draw upon long-term memory structures, enabling them to quickly understand a given situation. This mechanism is recognized by the US nuclear regulator, which has worked with issues related to information presentation in control rooms for many years. For example, NUREG-0700 [3] section 6: Group-view display system states that: "*An overview display should provide a characterization of the situation as a whole in a concise form that can be recognized at a glance*", it is also referring to object categorization schemes and pattern matching cues to reduce demands on attention. There is, however, a scarcity of scientific literature or design approaches that attempt to answer the question: "How should one display process information on LSDs to support fast information perception for complex large-scale processes?"

The IRD approach discussed in this paper is a scientifically based LSD concept developed at the Norwegian Institute for Energy Technology. It has been applied for industrial and research purposes so far through 13 live applications in the petroleum, mining and nuclear domains. Its objective is to give the big picture of the process state, and to support rapid visual perception of data.

Figure 1 illustrates qualitatively how the process operator experiences reduction in information acquisition capacity in increasingly faster-paced, data-driven situations. IRD addresses fast information acquisition, inspired by Rasmussen's Skills-Rules-Knowledge (SRK) model [4].

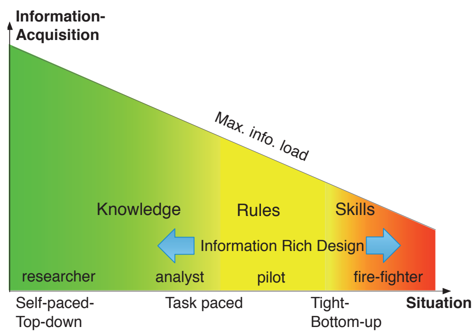

Figure 1*: Positioning IRD, modified from [9]*

The IRD approach incorporates graphical process objects inspired by Tufte´s concepts of high data-ink ratio and colour layering [5, 6]. The objective is to reduce cognitive workload through explicit information visualization inspired by Norman´s [7] concept of *information is in the world*, rather than *in the head*. Gestalt grouping principles are used to reduce complexity in larger data sets, see Lidwell, Holden and Butler [8].

The left side of Figure 2 shows an example of three process variables visualized through horizontally aligned IRD generic mini-trends, using mathematical normalization of the measuring scale. This generic objects are used to visualize process data such as liquid level, pressure, temperature and flow. The green arrow represents the target value (set-point), darker areas indicate high and low alarm limits. The IRD mini-trend can also integrate controller output, valve position and explicit alarm information.

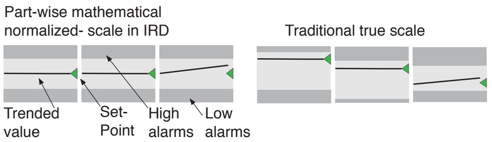

Figure 2: *IRD mini-trends on left side, a traditional true scale on the right side*

With the exception of the SRK model, the IRD theoretical framework is, however, mostly influenced by information visualization theory for a static state, such as printed-paper. For this reason, there is a need to expand the theoretical foundation of the concept, most notably by creating a stronger relation to dynamic process plant behavior, and findings from studies focused on display-based visualization. Typical questions are:

- Which means are suitable to support rapid-search attention to dynamic data in LSDs?
- How can one visualize dynamic process plant behavior in LSDs?

Outline: We examine first what others have accomplished on display concepts for large complex processes, before introducing some recent findings on visualization and perception on displays. We then discuss psychological literature on an ecological approach to interface design. This is applied to extend the IRD theoretical foundation, focusing on dynamic behaviour of complex processes. From this, design principles are proposed.

An example of applying the design principles, and earlier findings on IRD displays are discussed through the case of a third generation IRD display implemented for a live nuclear research reactor process. Finally, relevant issues for further research are described.

Earlier work: This paper extend on our earlier work discussing the need for a design concept that supports rapid visual perception through Rasmussen´s SRK model and Tufte on high data ink ratio and colour layering; see Braseth et al. [9]. More recent publications focus on realizing the concept on LSDs, see Braseth et al. [10, 11]. Two user-tests have been done on for the nuclear domain; see Laarni et al. [12] and Braseth et al. [13, in press].

2. DISPLAY CONCEPTS FOR COMPLEX PROCESSES

Even though not much has been done on visualization concepts for LSDs, we find it relevant to look at related concepts intended for smaller desktop displays. Well-known approaches regarded as state-of-the-art are discussed: the ASM Honeywell approach, Function-Oriented Design (FOD), Parallel Coordinates concept, grid control displays and Ecological Interface Design (EID).

Reising & Bullemer [14] suggest that direct perception displays are needed to provide an overview at a glance supporting SA. The Abnormal Situation Management (ASM) consortium explores the concept on smaller desktop overview displays in the petroleum industry. They suggest displaying process data through generic qualitative indicators such as normalized dials, and vertical and horizontal bars. These overview displays use a functional tabular layout instead of the more common schematic layout with lines to connect process objects.

A user-test by Tharanathan et al. [15] found an ASM functional overview display more effective in supporting SA than ordinary schematic displays with traditional data coding. The results suggested that a transition to a functional display is not overly problematic. In an ASM-sponsored paper, Bullemer et al. [16] discuss the advantage of new technology not restricted by colour limitations, recommending a grey background, considering situation awareness, alertness, eyestrain and fatigue.

FOD is an innovative approach to human-system interfaces intended for use in large complex nuclear systems on a display system called FITNESS (not specific to LSDs). The concept originates from work by Pirus [17] and his colleagues at Electricité de France. The objective is to *"control the complexity of the plants and their operation by introducing structuring elements"*. FOD reduces plant complexity; applying a hierarchical display structure, see Figure 3.

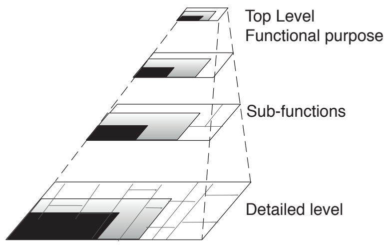

Figure 3: *FOD reduces complexity through display hierarchy, based on Pirus [17]*

In a large-scale user test by Andresen et al. [18], the FOD concept was given positive feedback by the test subjects on process-overview, disturbances, and alarm visualization. On the negative side, there was an extensive need for button pushing and navigation in the display hierarchy.

The Parallel Coordinates concept excels in displaying high-density graphics, visualizing large data sets on a single display. Lines are drawn as patterns of values for variables at different instances of time, where deviation from normal plant modes can be spotted as lines falling outside earlier clusters of lines. Inselberg [19] popularized the concept; a later paper by Wegman [20] initiated computerized applications of parallel coordinates. The concept is used in industrial applications as demonstrated by Brooks et al. [21], illustrated in Figure 4.

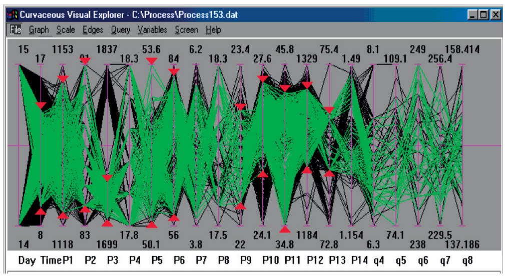

Figure 4: *Parallel Coordinates data in PPCL software (Brooks pers. communication 2012)*

Comfort et al. [22] performed a case study determining the effectiveness of parallel coordinates for supporting operators in mitigating hazard events through historical process data. They found the concept excellent for general explorative data analysis.

Hoff and Hauser [23] presented a new design approach to improve display interfaces of grid control in energy management systems. They argued that traditional display approaches are not tuned to our natural ecological perceptual system. They suggested an approach that supports rapid information pick-up in-line with ecological psychology and Rasmussen´s SRK model. They offered some display examples of easy to perceive analogue diagrams. Hoff and Ødegård [24] outlined eight properties referring to the degree of directness in display interfaces in a taxonomy named Ecological Interaction Properties.

EID is a theoretical framework that covers the work domain description, and how to assign information to displays according to Rasmussen's SRK taxonomy, see Vicente and Rasmussen [25, 26]. The main objective of EID is to support operators in unfamiliar, unanticipated, events. The concept is well described in the scientific literature, but has had few industrial applications. The concept does not focus on a specific display size or type. A more recent book by Burns and Hajdukiewicz [27] describes suitable EID graphical objects; some are quite similar to the generic qualitative objects used in the ASM consortium approach.

Applicable for IRD: Even though these concepts are not designed specifically for LSDs, ASM consortium, grid-control, EID, and the Parallel Coordinates approaches suggest that generic qualitative process objects are suitable for fast visual perception of complex processes. The results from FOD suggest that a hierarchical display structure might result in extensive and time-consuming navigation. The work by Hoff and Hauser and EID suggests that Ecological Psychology is a suitable approach for describing a complex dynamic work-domain.

3. VISUALIZATION & PERCEPTION IN DISPLAYS

The following section focuses on rapid visual perception in computer displays.

Ware [28] focused on how to create displays that support human pattern recognition skills through efficient top-down search strategies, and bottom-up data driven pop-out effects. He suggested relying on external visual aids in the process of visual thinking due to limited human visual memory, and that the real power rests in pattern finding. Ware explained that it is better to re-establish visual cognitive operations through rapid fast eye movements than to remember or navigate for information. He identified the strongest pop-out effects, or features, to be: Color, orientation, size and motion (omitting depth here). Motion is extremely powerful, and a gentler motion can be used instead of abrupt flashing and blinking, which can overly irritate the user. He suggested as a rule of thumb that the most important, and common queries in displays should be given most weight, *"if all the world is grey, a patch of vivid color pops out"*. Ware suggests visualizing large and small-scale structures to support efficient visual top-down search. Lines and connectors are suitable to describe relationship between concepts.

Healey & Enns [29] have written a comprehensive article on attention and visual memory in visualization and computer graphics, see also Healey´s web page [30]. They described how seeing is done through a dynamic fixation-saccade cycle 3-4 times each second through bottom-up data-driven, and top-down search processes. Only a limited number of visual features can be detected within a single glance in a saccade cycle.

They suggested that visual features should be suited to the viewers' needs and not produce interference effects that mask information, referring to Duncan and Humphreys' [31] similarity theory. To avoid masking primary data, the most important information should be given the most salient features (feature hierarchies). In their discussion on change blindness, on how people miss information due to limited visual memory, Healey and Enns [29] noted that larger format displays increase this problem in comparison to smaller computer screens. They suggested reducing the problem by designing displays that support both top-down and bottom-up processes.

Applicable for IRD: Although this work is not specifically focused on the issue of visualization of dynamic process plant data on LSDs, it indicates that a dynamic process display should allow rapid visual scans for information due to limitations in visual memory. LSDs should support effective means for top-down search, including large and small-scaled structures. Lines are appropriate to connect concepts. Data-driven processes should be visualized through pop-out effects. Feature hierarchies can help avoid masking of primary data.

4. AN ECOLOGICAL APPROACH TO INTERFACE DESIGN

Gibson [32] is one of the founders of ecological psychology, and in this approach he sees humans and other animals from an organism-environment reciprocity perspective. Gibson described how the values and meaning of things in the physical environment are directly perceivable for humans and animals, contrary to a sensation-based perception triggered by stimuli, and approaches describing cognition through mental models.

Gibson described the world and its behavior through: *Substances*, *mediums*, *surfaces*, *events* and their *affordances*. *Substance* is described as persistent to outer forces. Bodies can move through *mediums*. They are homogenous, without sharp transitions, examples are air and water. *Events* are described as changes in our environment as a result of shock or force, ripples on water, evaporation, etc. *Events* are typically observed on the *surfaces* that divide *substances* and *mediums*. *Affordance* describes how the physical environment provides immediate actionable properties, such as: walking on a floor, sitting on a chair, *constraints* describe limitations.

Ecological psychology aims in general to address human behaviour in our complex multisensory, dynamic, physical world, not for abstract displays visualizing process plant´s behaviour. It offers, however, several useful concepts when considering the process control operator as an integral, mutual, part of a complex process plant. Most notably, it enables us to explore direct perception of a complex domain.

Direct perception suggests that information should be presented in a manner appropriate for rapid visual perception, for intuitive pick-up, in-line with: *substances*, *mediums*, *surfaces*, *events* and *affordances*.

Figure 5 suggests that only the left vessel visualizes process plant disturbances in a manner directly perceivable through *surface* movement. The number, bar and dial to the right only afford an immediate description of the actual value and *constraints* (measuring-scale bar & dial). The *events* happen inside a physical structure of unchangeable *substance*.

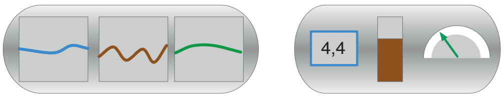

Figure 5: *Vessels with three variables. Dynamic events directly perceivable through left side trend-lines, surfaces*

The use of *affordance* in HCI is, however, debated. Norman [33], stated that the concept has taken on a life far beyond its original meaning. He suggested instead *perceived affordance* when applied to screen-based interfaces. Hartson [34] extended this further for use in context of interaction design and evaluation, and proposed: *cognitive affordance, physical affordance, sensory affordance*, and *functional affordance*.

Applicable for IRD: We conclude that LSDs should be rich in *perceived affordances*, providing many clues to the complex process plant, enabling the operator to detect and see the big-picture with enough detail to comprehend the whole situation. Dynamic process disturbances can be described through *events*, directly perceived through trended *surfaces* and their *constraints*. Physical vessels and structures in the process plant can be visualized as *substances*.

5. DISCUSSION

Due to the large scale and high complexity of LSDs, we find the approach of attempting to address our limited visual memory to be particularly interesting. That work gives us further insights and support on how to support fast top-down search in large displays. It suggests including both large and small-scale structures in a process display, for which we have earlier used the term landmarks. However, we had not previously considered that they should be given different size and shape (typically large vessels) to better support rapid top-down search. This is somewhat contradictory to our intention of creating displays that focus on dynamic information, reducing static clutter. The problem can, however, be minimized through the use of colour layering to avoid masking primary dynamic information.

Furthermore, it is interesting that the use of lines to connect shapes is encouraged. We have in earlier displays been very cautious in the use of lines, only using grey colours for fear of generating unnecessary clutter. This could be a reason why it has proven challenging to make IRD displays easily interpretable. On the whole, this suggests that we need to focus more on connecting process objects in the display to enhance top-down search.

Early IRD displays were found overly information dense, so introducing more space, as open areas, might also be beneficial. More research is needed to determine the right balance for fast top-down search between static large- and small-scale structures, lines and information density.

Attention to dynamic data-driven processes is a challenge in LSDs, and we find the work on pop-out effects to be particularly appropriate to this. In many ways, our earlier work on colour layering supports this, but we have given limited attention to masking issues. This work suggests that we must introduce greater differences in features between information classes in the display than we have done in the past. Users have also complained that IRD displays are too dim, with too little contrast - "*everything is grey, nothing stands out*". Ware [28] suggested, however, being cautious of blinking, applying a gentler motion instead. This indicates that the IRD dynamic alarm-spot is an appropriate solution to visualize new, unacknowledged alarms, see Figure 6.

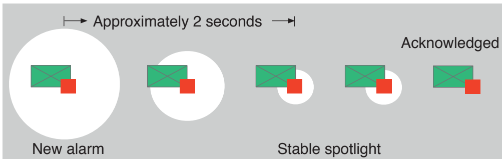

Figure 6*: Pop-out effect: incoming unacknowledged alarm visualized through dynamic alarm-spot on green valve*

There seems to be a consensus that qualitative indicators as process objects are suitable for rapid visual perception. In IRD displays, we have used mathematically normalized bar graphs, polar diagrams and mini-trends to make them even easier to perceive also in LSDs. The ecological *surfaces* and *events* suggest, however, that the mini-trend is probably best suited to visualize dynamic process plant behaviour.

In summary, we find the theory and approaches described here relevant for the IRD concept, and we propose the following design principles for dynamic process data on LSDs:

- Display graphics should support direct perception of the system situation. One should design dynamic graphics rather than lists and numbers. Data should be rich in *perceived affordances*, presented as graphics designed to visualize *substances*, *mediums*, *surfaces*, and their *constraints*.
- The design should include large- and small-scale structuring elements that support top-down visual search. One should layout the system using lines, grouping, and open space.
- Data should be given lower level pop-out effects, to provide cognitive support through rapid eye movements. One should apply graphics orientation, colour, size, and motion and substitute blinking for a gentler animation. A grey background is suitable for pop-out effects.
- Colour layering should be used for a visual hierarchy rather than display hierarchies, avoiding too low contrast.

In our opinion, what separates IRD from smaller desktop oriented concepts is: firstly, a stronger focus on simplification of visual complexity, secondly, its use of animated objects (dynamic alarm-spot), and finally, its focus on visual search in larger displays, retaining a relatively traditional schematic layout.

6. A THIRD GENERATION IRD DISPLAY

Figure 7 illustrates how we have applied the proposed design principles to a new third-generation IRD display. The display is installed in the Halden research reactor control room, using two rear-mounted projectors and mirrors. It is designed by expert operators and the first author, and replaced older hardwired panels during 2012.

The objective is to address some of the problems encountered in our earlier first [10] and second-generation [11] LSDs. The first generation display succeeded well in comparison with a traditional overview display, but it had significant potential for improvement in readability: it was too dense, abstract, and was inconsistent in alarm visualization. A follow-up second-generation display had improved alarm visualization. However, it still suffered readability problems, as it was too dim with low contrast. Both were reported to be unfamiliar and abstract.

The largest structure in the new display is the reactor tank with nuclear control rods; other liquid filled vessels are using a 3D shaded background. The brown lines are primary radioactive coolant circuits. The green and blue are the second and third outer non-radioactive coolant circuits. Mini-trends at the lower right are monitoring experimental loops.

To avoid challenging limited human visual memory, the display layout is flat without any hierarchy, in accordance with the last design principle. Instead, a colour hierarchy is used, and dynamic data-driven events as alarms are visualized through salient pop-out effects. Saturated red is reserved for alarms, avoiding masking problems. To limit visual clutter, we have used the grey background colour on equipment that is not running or is closed. Green is used on active running equipment.

Early in the development phase we used a functional tabular layout of display elements, but it was considered too unfamiliar and abstract by process operators. The final display combines a traditional schematic layout of large process elements, and a functional tabular layout of other monitored process variables (right and upper left). The central section of the display is quite similar to the replaced older analogue panels. This might contribute to a display that is not too unfamiliar and abstract.

To ease top-down navigation, large and small-scale structures (*substances*) are visualized. Examples are the large reactor tank, and other liquid-filled vessels. Space, in the form of open areas, has been introduced to avoid the earlier overly dense appearance. Major flow-lines visualizing medium colour are included to connect related objects through a livelier colour palette than in earlier displays, avoiding the "*everything is grey*" appearance.

We have used aligned and grouped IRD mini-trend objects to display pressures, temperatures and liquid levels (*surfaces*). Alarm-limits (*constraints*) are visualized where applicable as darker areas in the mini-trends. Unfortunately, the mini-trends are quite abstract looking. Using physical structures (*substances*) as a background might help putting them into a context.

To keep the display rich in cues (*perceived affordances*), graphical objects are kept dynamic. Examples are the use of thick flow lines when valves are open, thin lines when closed. A circle indicates pump speed, full speed is full circle, and half circle is half speed. A problem reported from earlier IRD displays is that analogue data presentation does not afford high enough accuracy. This has encouraged us to include digital numbers on key parameters in the new display.

7. CONCLUSIONS & FURTHER WORK

This paper approaches complex processes through effective LSD design, the IRD concept described here has a human-centric perspective; resulting in graphical process objects and design principles. We have found the mini-trend object suited to display dynamic process response in a natural way. To our knowledge, IRD is positioned quite uniquely as a LSD concept. User tests from earlier nuclear research displays indicate, however, that the concept has not yet achieved an acceptable level of user experience. From this and our initial discussions, we suggest focusing on the following in further research work:

- Measure Situation Awareness levels; does IRD increase levels and reduce information overload problems through easily perceivable process objects and their layout?
- Measure user experience; is IRD acceptable for real-world installations?

Other issues include consistency problems between the IRD LSDs and other control room information sources.

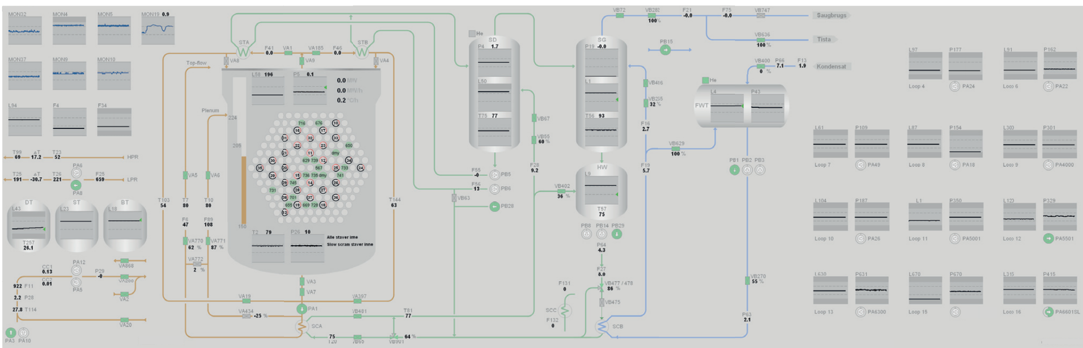

Figure 7: *Third generation nuclear IRD large screen display, 1.4m x 4.5 m*

8. ACKNOWLEDGEMENT

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PAPER IX

Evaluating usability of the Halden Reactor Large Screen Display: Is the Information Rich Design concept suitable for real-world installations?

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Abstract: Large Screen Displays (LSDs) are beginning to supplement desktop displays in modern control rooms, having the potential to display the big picture of complex processes. Information Rich Design (IRD) is a LSD concept used in many real-life installations in the petroleum domain, and more recently in nuclear research applications. The objectives of IRD are to provide the big picture, avoiding keyhole related problems while supporting fast visual perception of larger data sets. Two LSDs based on the IRD concept have been developed for large-scale nuclear simulators for research purposes; they have however suffered from unsatisfying user experience. The new Halden Reactor LSD, used to monitor a nuclear research reactor, was designed according to recent proposed Design Principles compiled in this paper to mitigate previously experienced problems. This paper evaluates the usability of the Halden Reactor LSD, comparing usability data with the replaced analogue panel, and data for an older IRD large screen display. The results suggest that the IRD concept is suitable for use in real-life applications from a user experience point of view, and that the recently proposed Design Principles have had a positive effect on usability.

Keywords: Large Screen Display; Information Rich Design

1 Introduction

This paper first presents two challenges: i) challenges in cognition of large data sets, and ii) the fragmented keyhole view of complex processes. Next it describes how Large Screen Display (LSD) design can help maintain the greater picture of large-scale processes, followed by this papers' research questions. The objectives of Information Rich Design (IRD), the Design Principles used, and a description of the Halden Reactor LSD are presented. Followed by the usability evaluation method, results and discussion. Lastly, topics for further work are outlined.

1.1 Large data sets & keyhole effects

In the aftermath of the Three Mile Island and Chernobyl disasters, there has been an increased focus on control rooms' user interfaces, and how large data sets with thousands of variables and control loops challenge human capacity. Endsley [1] described how *"current technologies have left human operators extremely challenged in this process"*.

In addition to the great complexity of large data sets, there are challenges associated with applying new technology, as analogue hardwired panels are replaced with flexible low-cost desktop displays. Vicente, Roth & Mumaw [2], and Salo, Laarni & Savioja [3] pointed to possible keyhole effects, and highlighted how it can be more difficult to obtain an immediate overview of the process situation on smaller desktop displays than on larger panels. This unfortunate fragmented view is often referred to as the keyhole effect; see Woods [4].

One possible solution to such challenges is to use LSD technology to display the big picture, supplementing desktop displays. Andrews *et al.* [5] suggested however that it is not sufficient to up-scale pictures intended for smaller desktop displays. This is also in line with Endert *et al.* [6], who found that the choice of visual encodings in Large Displays directly affected users' performance.

The U.S. Nuclear Regulatory Commission's well-known guidelines for the nuclear domain, NUREG-0700 [7], provide some objectives for overview displays (of which LSDs are one of several possible formats): "*An overview display should provide a characterization of the situation as a whole in a concise form that can be recognized at a*

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glance", suggesting that graphics and layout must be taken into consideration for visualization of such large data sets.

In sum, this suggests that LSDs should be designed for this purpose from the ground-up to allow for fast visual perception, and to avoid keyhole effects.

1.2 Research questions

Skjerve and Bye [8] described how the Norwegian Institute for Energy Technology (IFE) in Halden has performed research activities on display concepts for nuclear and other complex environments over many years; one of its outcomes is the IRD concept.

IRD has previously been applied in LSDs for commercial use in the petroleum domain, and more recently in two research applications for large-scale nuclear simulators (1st and 2nd generation displays). It is however necessary to evaluate whether the newly developed IRD Halden Reactor LSD has improved on the previously unsatisfying user experience with the 1st and 2nd generation LSDs. For this reason, this paper explores the following two research questions:

- Is usability of the IRD concept satisfying for real-life industrial installations?
- Have the recently proposed IRD Design Principles improved perceived usability of the LSD concept?

The IRD concept is not domain specific, and for this reason, the first research question is asked broadly, not specifically for nuclear. The second research question is explored through the Halden Reactor LSD designed accordingly to modifications reflected in recent proposed Design Principles (compiled in this paper).

1.3 Earlier work on IRD

This paper extends on earlier work, which discussed the need for a design concept that supports fast visual perception [9]. More recent publications focused on realizing the concept on nuclear LSDs; a 1st generation LSD in Finland [10]; and a 2nd generation LSD in the Halden Man-Machine Laboratory (HAMMLAB) Boiling Water Reactor Simulator (HAMBO) [11]. Two user tests have been done on for the nuclear domain; see Laarni *et al.* [12, 13]. Theoretical foundation and design principles are recently published [13, 14].

2 Information Rich Design

2.1 IRD design objective

The objective of IRD is to present the big picture of the complex information space in-line with human cognitive capacity. For this reason graphical elements and their layout are designed to simplify larger data sets through Gestalt principles such as alignment and grouping.

This is illustrated in the left side of Fig. 1, where three process variables are visualized through horizontally aligned IRD generic mini-trends, using part-wise mathematical normalization of the measuring scale, the right side is not normalized (traditional approach). This generic qualitative indicator is used to visualize process data such as liquid level, pressure, temperature, and flow. The green arrow represents the target value (set point), while darker areas indicate high and low alarm limits.

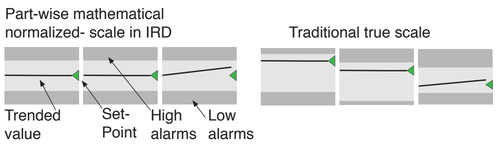

Fig. 1 IRD mini-trends on left side, a traditional true scale on the right side.

The IRD concept has also used animation effects to draw attention to new unacknowledged alarms, creating strong visual pop-out effects on key alarms; see Fig. 2.

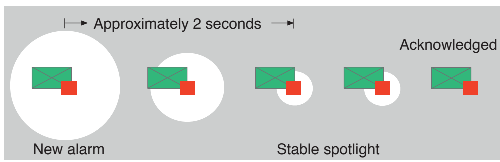

Fig. 2 Pop-out effect: incoming unacknowledged alarm visualized through dynamic alarm spot on green open valve.

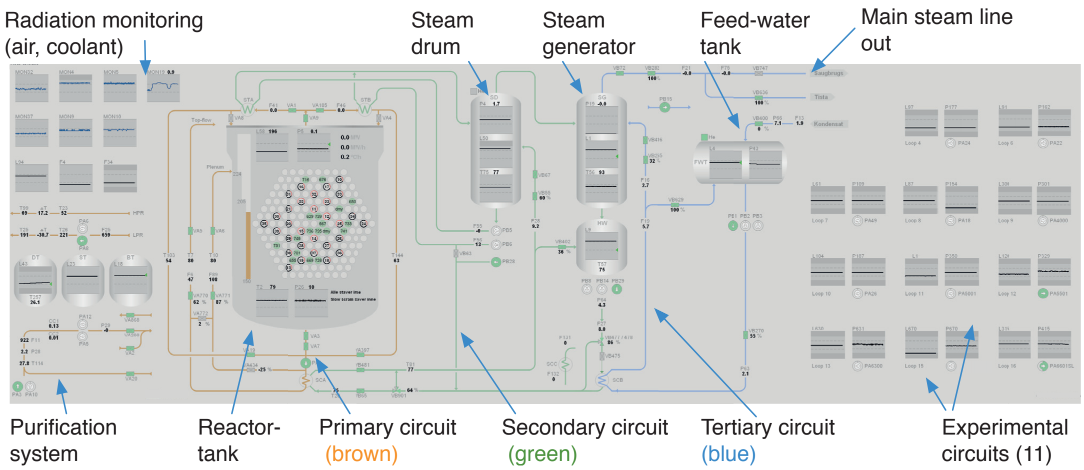

Fig. 3 The Halden Reactor LSD (4.5**m** x 1.4**m**) installed in the research reactor control room, main functionality.

2.2 Functionality of the Halden Reactor Display

The main functionality of the Halden Reactor LSD is illustrated in Fig. 3. It is designed to be complimentary to control room operators' desktop workstations, where the big picture is visualized on the LSD, while in-depth details and process interaction are reserved for desktop displays.

The LSD is designed to support process operators in a wide range of operational activities:

- Understanding the reactor circuits and the experimental loops.
- Supporting normal and safety-critical operation of the plant.
- Running the process up and down.
- Early detection of disturbances and abnormalities.
- Detection of unacknowledged alarms and key alarms.

2.3 Proposed IRD design principles

The IRD concept builds on well-established scientific theory on information visualization and human cognition. Findings from user tests and commercial IRD applications have been used to improve the concept iteratively during the last ten years.

The following principles (1) – (8) are compiled from two recent publications [13, 14], key references are included. The Halden Reactor LSD is designed according to these principles (1) - (8).

Display Graphics (1) – (3):

(1) Gibson [15] inspired the use of ecological psychology as a theoretical foundation for fast visual "pick-up" of data. How display graphics should be rich in *perceived affordances*, visualizing *substances, mediums, surfaces*, as well as their *constraints*. Tufte [16] explained how to focus on high data-ink ratio and dynamic data.

(2) Burns & Hajdukiewicz [17], and Tharanathan [18] suggested to use qualitative direct perception indicators to display data. We have however found trended indicators best in displaying plants´ dynamic response. Endsley *et al.* [19] inspired us to integrate target values, rate-of-change cues, and to visualize automation to keep operators in the loop.

(3) Ware [20] and Healey & Enns [21] explained how data should be given lower level pop-out effects through a visual feature hierarchy, providing cognitive support through rapid eye movements, achieved through graphics orientation, colour, size, and motion. We have found equally sized filled objects better than frames for alarm visualization and how to integrate alarm information within a natural context of graphical objects. Ware [20] described how a gentle animation is a preferred alternative to protrusive flashing or blinking in displays; we have used this to highlight new alarms.

Display Colours (4) – (5):

(4) Van Laar [22] described colour layering for displays. We have found that grey-scale has given readability problems in well-lit rooms using front-projected technology.

(5) Bullemer *et al.* [23] suggested a grey background colour in process displays, considering situation awareness, alertness, eyestrain and fatigue.

Display layout (6) – (8):

(6) Lidwell, Holden and Butler [24] described how Gestalt Principles reduce visual complexity through alignment and grouping. Duncan & Humphreys [25] showed how to avoid masking problems by limiting the number of different display objects.

(7) Ware [20], Healey & Enns [21] described mechanisms supporting fast top-down visual search in displays. Suitable means are lines, multi-scaled structuring elements, grouping, and open space, see Horn of & Halverson [26].

(8) Norman [27] inspired the use of a flat, externalized display layout (externalized visible elements).

2.4 Applying design principles (1) – (8) on the Halden Reactor LSD, Fig 3

In the following, numbers (1), (2), *etc.* refer to the applied principle from the previous section.

The main difference from the earlier 1st and 2nd generation LSD designs is a stronger focus on supporting fast top-down visual search, and to display the plant's dynamic response through trended data representation.

For improved top-down search, open space is used (7), including familiar large- and small-scaled physical structures (7) as *substances* (1) and grey backgrounds (5) for dynamic data. Major flow-lines (7) are used to visualize fluid *medium* (1) connecting process objects. The display uses no display hierarchy (8).

Visual simplicity (6) is achieved by alignment and grouping of variables. Dynamic process response is displayed through generic indicators (2) with trended *surfaces* (1) and its *constraints* (1) (alarm limits). Graphical symbols focus on dynamic data, *perceived affordances* (1). Key alarms are shown as filled objects and animation (3) as strong pop-outs on the top level of a visual colour layering hierarchy (4).

2.5 Removing the panel, implementing the LSD

The design process started in 2007, and the graphical design was developed through 14 iterations by a design team including the author (designer), expert operators, and a computer expert (implementing the graphical design). A prototype was installed on two 30" displays early in 2012, followed by correction of major flaws prior to final installation in the spring of 2012. The design team met regularly during the first months after the installation to further correct errors.

Figure 4 shows the dismantling and removal of the analogue Panels. IFE engineering, electro and maintenance competence were used in planning this process, which was challenging while running the research reactor. Disconnecting and reconnecting were done according to scheduled reactor stops.

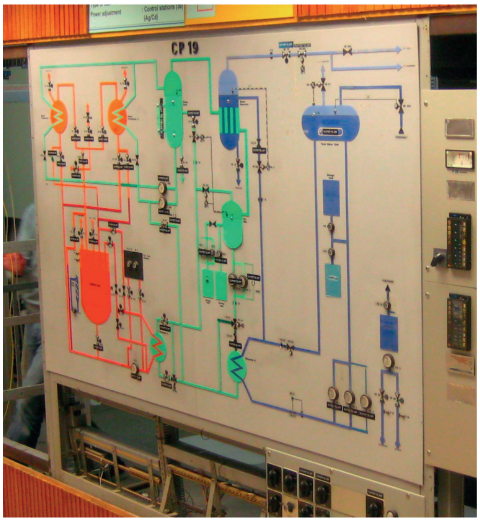

Fig. 4 The Panel (CP 19) is dismantled, preparing for the new Halden Reactor LSD.

Figure 5 shows a part of the new LSD from the control room operator's normal seated position.

Fig. 5 The Halden Reactor LSD.

A black frame surrounding the LSD was installed to enhance contrast. The LSD is displayed on a StarGlas 60 matte glass screen mounted in an aluminium frame with dimensions 4.5**m** x 1.4**m**. A new ceiling with adjustable lighting was installed during the process.

3 Method

This paper's evaluation of the IRD concept compares: i) the Halden Reactor LSD, Fig. 3 & 5, ii) the replaced analogue Panel, Fig. 4, iii) the earlier 2nd generation HAMBO LSD, Fig. 6.

The usability data reported in this paper for both LSDs and the replaced Panel is based on the System Usability Scale (SUS) [28] questionnaire data. Additional data for operators' subjective perceived support is collected for the Halden Reactor LSD and the replaced Panel.

3.1 Two questionnaires

The SUS used in this paper was developed as part of the usability-engineering programme at Digital Equipment Co. Ltd., Reading, UK, and has been made freely available for evaluations in usability assessment [28]. Ten items are rated on a five-point scale. Ratings are then calculated into a final usability score (0-100).

A questionnaire addressing the operators' subjective opinion of perceived support was also used for the Halden Reactor LSD and the replaced Panels. Five items were scored (0-7): detecting alarms, detecting disturbances, perform process actions, obtain a shared awareness, and perform tasks without high mental workload.

3.2 SUS scores as percentile rank

SUS has become an industry standard with references in over 600 publications. Sauro [29] has reviewed existing research on SUS and analysed data from over 5000 users across 500 different evaluations. The average SUS score from all 500 studies is 68 (0-100).

Sauro suggests interpreting the SUS score by transforming this to a percentile rank. For example, a SUS score of a 74 converts to a percentile rank of 70%, meaning that the system tested has a higher perceived usability than 70% of all products tested. Similarly a score above 80.3 represents the top 10% of scores.

3.3 SUS reliability and validity

Reliability refers to how consistently users respond to the items (the repeatability of the responses). The SUS has been shown to be reliable and to detect differences at smaller sample sizes than other commercially available questionnaires [29]. SUS has

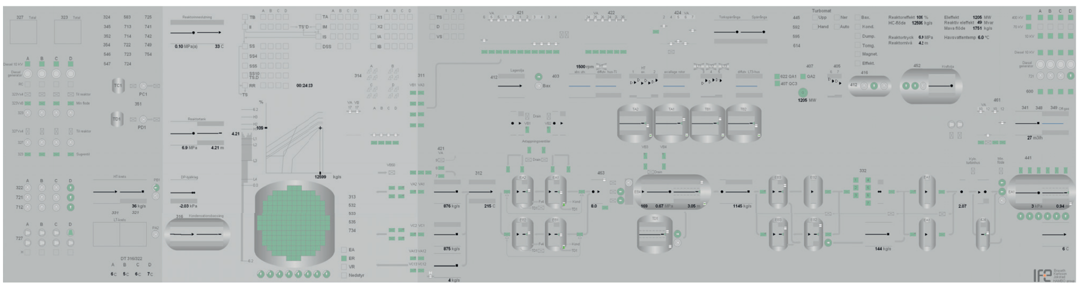

Fig. 6 The 2nd generation HAMBO LSD, installed on nuclear simulator in Halden, 6**m** x 1.5 **m**.

also shown to effectively distinguish between unusable and usable systems as well as or better than proprietary questionnaires; correlating highly with other questionnaire-based measurements of usability [29]. This suggests that SUS results have sufficient validity in measuring perceived usability.

3.4 Evaluation of the Halden Reactor LSD

All crews working at the Halden Reactor participated in this study, except persons involved in designing the Halden Reactor LSD, with a total of 22 operators. Two researchers at IFE interviewed the operators; neither had participated in designing the LSD. Both SUS scores and data from operators' subjective opinion of perceived support were collected. This was carried out in early autumn 2012, approximately 1-2 months after implementing the LSD. It was an objective to assess operators' early impressions of the LSD.

3.5 Evaluation of the replaced Panel

The evaluation of the replaced Panel was carried out simultaneously with the evaluation of the Halden Reactor LSD; the Panel was used to control the same process in the same control room as the Halden Reactor LSD. The same control room operators participated in this evaluation, using the same questionnaires.

At the time of data collection, the Panel was dismantled and not in use. However, operators were interviewed in an environment with the Panel present.

3.6 Evaluation of the 2nd gen. HAMBO LSD

The evaluation of the 2nd generation HAMBO LSD (Fig. 6) was done in an earlier usability study performed in a laboratory (HAMMLAB) on a large-scale nuclear simulator (HAMBO) in 2011. Seven crews from different Nordic nuclear plants participated, in total 20 operators; see Kaarstad and Strand [30] for a full description of this study.

The participants were interviewed and responded to the same SUS questionnaires as for the Halden Reactor LSD and Panels, after running through a set of scenarios. Data were however not collected for operators' subjective opinion of perceived support.

3.7 Limitations

We recognize that there are weaknesses and limitations in this paper´s usability data comparison. Most notably, the SUS score for the recent study (Halden Reactor LSD + Panels) and older study (2nd generation HAMBO LSD) are not directly comparable. The data were collected in different conditions, from different nuclear processes and by different participants.

The Halden Reactor Display and Panels are evaluated in a real life operative control room, after 1-2 months of use, while the older 2nd generation HAMBO LSD was evaluated in a simulator setting, with only a limited (one day) familiarization. The replaced Panels were however obsolete and taken out of operation at time of evaluation.

In addition, we emphasize that SUS is not designed for testing LSDs in particular, but for system usability in general. In sum, this suggests to use SUS scores only as indications, and not as directly comparable data.

4 Results

Individual SUS scores are presented, (Fig. 7), and then the total calculated SUS score is converted to a percentile rank, (Fig 8). The perceived support questionnaire results are presented at the end, (Fig. 9).

4.1 Individual and percentile SUS scores

Figure 7 shows the individual SUS scores of the Halden Reactor Display (total 83), the replaced Panels (total 77) and the HAMBO LSD (total 59). Figure 8 shows the percentile rank (%) for the Halden Reactor LSD (95 %) red line, representing a top 5% score. The replaced Panels (77 %) blue line, and the HAMBO LSD (30 %) green line.

4.2 Operators subjective perception of support

Figure 9 shows the perceived degree of support, comparing the Halden Reactor LSD with the replaced Panel. These data were not included in the study of the HAMBO LSD.

The operators rated the Halden Reactor LSD significantly better on perceived support than the Panels with respect to alarm detection [F(1,38)=206,13, p=.000)]; disturbance detection [F(1,38)=229,23, p=.000)]; performing process actions [F(1,38)=64,80, p=.000)]; shared awareness [F(1,38)=21,87, p=.000)] and workload reduction [F(1,38)=16,10, p=.000)].

5 Discussion

The first research question - *Is usability of the IRD concept satisfying for real-life industrial installations?* - Is discussed by looking at System

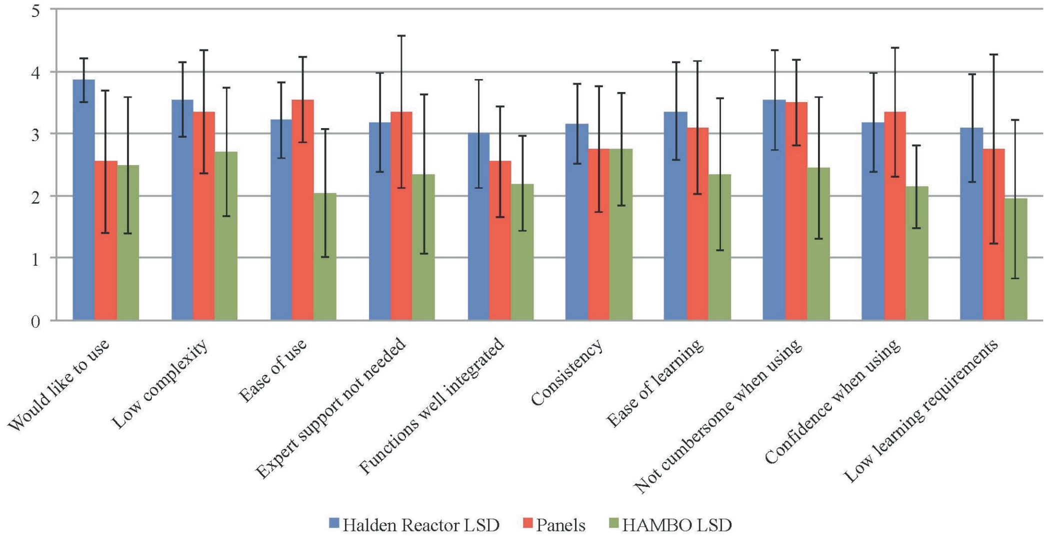

Fig 7 Individual SUS scores. (1: Strongly disagree; 5: Strongly agree)

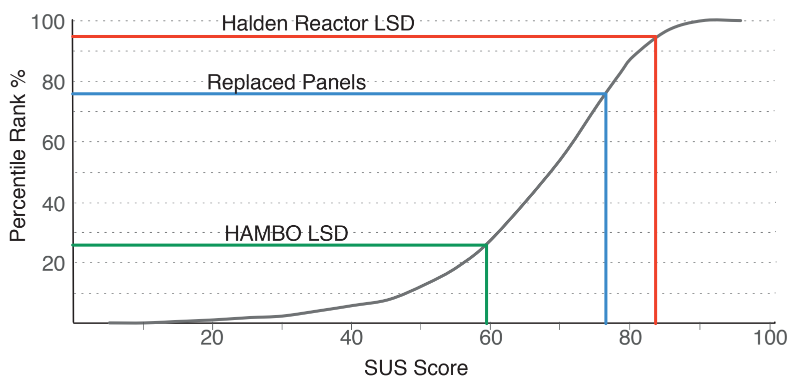

Fig. 8 SUS scores converted to percentile rank, based on Sauro [29].

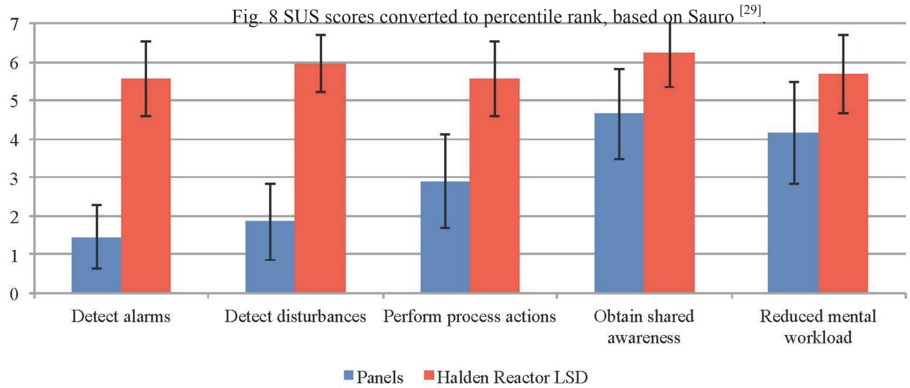

Fig. 9 Perceived support. (1: Low degree, 7: High degree)

Usability Scale (SUS) data and the perceived support for the new Halden Reactor Display and Panel. In addition we look at historical SUS data (percentile rank).

For the second research question - *Have the recently proposed IRD Design Principles improved perceived usability of the LSD concept?* - We draw comparisons between SUS data for the new Halden Reactor LSD and the earlier 2nd generation HAMBO LSD.

5.1 Is usability satisfying?

The SUS data (Fig. 8) indicates that the Halden Reactor LSD has a high level of user satisfaction, being among the top 5% of SUS scores. By comparison, the replaced Panels have also a high score, being among the 25% highest SUS scores. From the individual SUS data (Fig 7), we can see particularly that the item “would like to use” seems to be quite high for the Halden Reactor LSD.

The operators’ ratings of perceived support (Fig. 9) in different tasks have no particularly low rating for the Halden Reactor LSD, with a higher score than the old Panels for each task. The biggest difference is found in detection of disturbances and alarms. This indication seems to be in accordance with the general design objective of IRD: helping operators to spot deviations at a glance. The item “shared awareness” obtained the smallest difference in perceived support between the Halden Reactor LSD and Panels. This suggests that older Panels are also suited to facilitate a shared awareness, which is in line with work by others, *e.g.* Vicente *et al.* [1] and Salo *et al.* [2].

The data analysed so far, suggests that the IRD Design Principles as used in designing the Halden Reactor LSD has become more mature and suitable for use in real-life nuclear processes from a user experience point of view. It should also be noted that the Halden Reactor LSD is actually being used in a “real-life” operational control room, which strengthens these findings. We stress however that the current data is not representing operator performance, only usability.

5.2 Have the Design Principles improved perceived usability?

The overall SUS score for the 2nd generation HAMBO LSD was 59 in the former study, and 83 for the new Halden Reactor LSD in the current study (Fig. 8). These numbers are however not directly comparable, as data was collected from two different user groups in two different operational contexts. However, the same scale was used for evaluating usability, and the results indicate a significant increase in usability for the Halden Reactor LSD. One reason for this result can be a stronger focus on a more familiar “mimic” display type layout, focusing on top-down visual search, as outlined in this paper´s Design Principles, displaying coloured lines and familiar background shapes.

We are however cautious to draw definitive conclusions on our second research question, since the two displays were tested under different conditions. The results are however in general promising, suggesting that the recent proposed design principles should be kept.

5.3 Reflections & Further work

Though the usability results in this paper are promising for the Halden Reactor LSD, both real performance data, and display technology should be further studied.

As a first step, in-depth discussions with control room operators using the Halden Reactor LSD would be beneficial in finding out what works well and what should be further improved. Performance data for the IRD concept would also be beneficial, particularly measuring Situation Awareness levels, comparing IRD to other display concepts to see if the design concept really increases Situation Awareness levels in complex scenarios.

The concept of part-wise mathematical normalization of the measuring scale as used in IRD introduces non-physical visualization of process variable behaviour (Fig. 1). This can however result in operators building errant mental models of processes, as described by Endsley *et al.* [19]. The effect of this should be further studied.

We suspect further that the choice of display technology affects the usability results. The 2nd generation HAMBO LSD used front mounted video projectors, while the Halden Reactor LSD represents an advance in rear-projection technology, increasing the contrast ratio considerably, which might have positively influenced the SUS score.

We have designed LSDs using other technologies, such as high-resolution display cubes in some commercial applications for the petroleum domain; see eyevis technology [31]. Even if this type of technology introduces unfortunate visible frames, which appear as thin lines in the LSD, it further increases the contrast ratio, and the picture is much brighter than the rear projection technology used in the Halden Reactor LSD. Such technology appears to us as an advantage, particularly on grey-scale colour layering LSDs, suggesting that this technology should be investigated also for use in the nuclear domain.

Technology is however evolving rapidly, and there is much to explore in emerging display technologies. Touch technology is particularly interesting. Can operators interact directly with the process through touch technology on larger high-definition surfaces? What opportunities exist for the use of haptic feedback from the display surface?

Acknowledgements

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Part III: Magazine Article (paper 10)

A magazine article, paper 10 of this thesis:

Paper 10: Braseth A.O. (2014). Information-rich design for large-screen displays: A new approach to human-machine interfaces has produced a radically different design of control room displays. Nuclear Engineering International, special issue Instrumentation & control, February 2014, pp. 22-24.

PAPER X

NUCLEAR ENGINEERING INTERNATIONAL

www.neimagazine.com February 2014

New visions for I&C

Large-screen displays: starting from scratch at Halden (below) page 22

An acoustic thermometer as thermocouple alternative page 26

Power market developments

World nuclear capacity up by 50% in 2030—WNA page 30

D&D market growing too—Roland Berger page 15

Enel tops PWR fleets in utility load factor league tables page 36

Information-rich design for large-screen displays

A new approach to human-machine interfaces has produced a radically different design of control room displays. The first of these has now been installed at the Halden research reactor in Norway. By Alf Ove Braseth

In the aftermath of Three Mile Island, Chernobyl and other high-profile accidents, there has been focus on control rooms' user interfaces, how our complex plants challenge human capacities, and the challenge of presenting the big picture of a plant's status. One solution is using Large Screen Displays (LSDs). Unfortunately, LSDs are often just up-scaled versions of desktop workstation displays. Recent research and industry standards such as IEC 61772 (2009) suggest that this is not sufficient.

To mitigate this, the Norwegian Institute for Energy Technology (IFE) in Halden has developed a from-the-ground-up LSD concept named Information Rich Design (IRD), where the objective is to display the greater picture of plant status in a rapidly perceptible manner on a LSD, while leaving in-depth details and process interaction for desktop workstation displays. The concept consists of graphic display objects and design principles for LSD graphics. IRD is grounded in a broad research perspective, combining scientific theory, user tests and feedback from industrial applications. It has been applied commercially in the petroleum domain by IFE's design team, used in research applications for full-scope nuclear simulators, and used for IFE´s research reactor in Halden.

Figure 1: Comparison of user utility of three types of displays: trendline (left), graph (centre) or number (right).

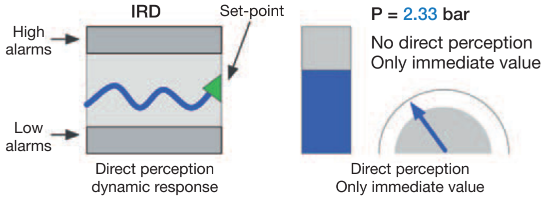
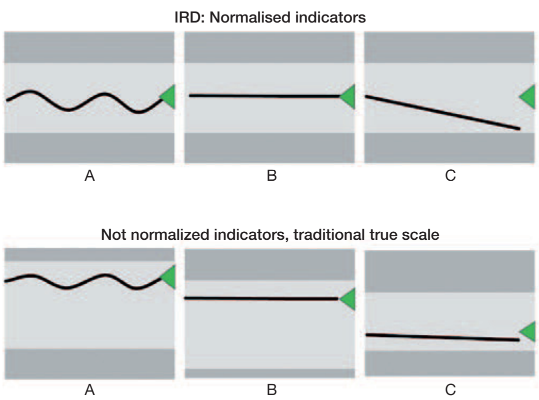


Figure 2: The so-called 'mini-trend object' summarises current and past data, their relationship (the trend), operational parameters, and the target value.



Direct perception of process dynamics

Situation Awareness (SA) is a concept used in analysis of decision-making in complex systems; it incorporates how operators perceive the situation. One challenge in LSD design is how to visualize the greater picture of process dynamics, showing how processes variables behave dynamically: pressures fluctuate, liquid levels move up and down, etc. Standards and guidelines stress the importance of visualizing time variance: NUREG-0700 explains how large group-view displays (LSDs) should support overall assessment at a glance, indicating both major changes in plant condition, such as alarms, and minor disturbances.

We have focused on indicators that visualize process variable fluctuations in an intuitive way; this is sometimes referred to as "direct perception". Figure 1 illustrates how different visual objects can represent the same process data.

For this reason, we have focused on rapidly-perceivable trended graphics, offering direct perception of dynamic process behaviour. Below, we will describe how these trended objects have been further developed to reduce visual complexity for industry scale data sets by applying part-wise mathematical normalization, and how we have integrated alarm and automation data for increased information richness.

Reduced visual complexity

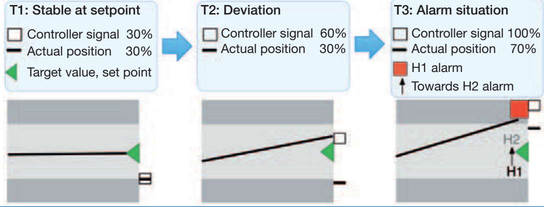
First, we use generic indicators for simplifying graphics, using the same objects for liquid level, pressure, temperature and flow. Second, to further reduce visual complexity, IRD uses indicators that can be arranged to create visual patterns, where process values and alarm limits align in horizontal bands in the LSD.

To achieve this, we apply part-wise mathematical normalization of process variables measuring range; indicators do not re-scale during plant operation. Normalization of indicators is calibrated from alarm limits and process target values for plant's normal operational state. A situation for three process variables: A, B, and C is illustrated in Figure 2.

In Figure 2, variable A fluctuates around its set-point. Although its behaviour is qualitatively the same for both normalized and un-normalized graphics, it is typically distorted for the normalized variant. Variable B is stable at set-point. Variable C is moving toward low alarm limits; although its value is typically distorted for a normalized object, it behaviour remains qualitatively true.

The downside of normalized graphics is how they distort reality. They might not be aligned in situations such as start-up, shut-down,

Figure 3: Example of variable exceeding its operational parameter



and major upsets, and are less helpful for identifying how far alarm limits are exceeded, or how far process values are off target values. On the positive side, such graphics reduce visual complexity for industry-scale data sets. Normalized graphics are generally more suitable for spotting deviations qualitatively in LSDs, than for detailed readings. Feedback from operational LSDs suggests, however, that this is an acceptable trade-off when LSDs are used to complement desktop workstations, which present detailed information.

Using a similar trend-time on the x-axis for all types of variables on mini-trend displays is a problem. Typically, pressures can fluctuate rapidly within seconds, while liquid levels change within minutes, and temperatures react even more slowly. We found a typical trend-time on the x-axis of 10 minutes to be a reasonable approach for mini-trends; however, this is not ideal for all types of process variables. We have found it necessary to add long-term trends showing hours on the x-axis for key variables for some LSD applications.

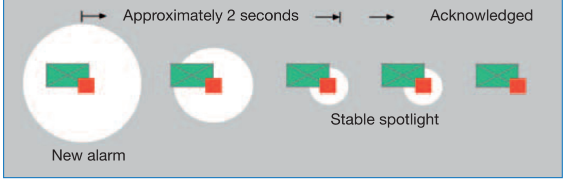
Keyhole effects

Human factors review guidelines from NUREG-0700 in the group-view (LSDs) section explain how it is difficult to maintain awareness of plant status through desktop workstations since they only display a portion of the total plant information (keyhole view), and how navigation through display hierarchies causes delays in operator responses.

We have approached the problem of keyhole effects and visual memory limitations firstly through larger display surfaces, secondly through a 'flat' layout without display hierarchies, and thirdly through data-rich graphics. One example of the latter is how we have integrated automation and alarm data within generic indicators; this is illustrated in Figure 3 .

In this example, from left to right, we can see the effect of an increasing process value on the signal to a controller, and the valve position, both of which are plotted on the right-hand side of the box (vertical position represents extent of system response: top represents 100% controller signal or 100% open valve). T1 shows a stable situation where process value is at set point, and where controller signal is relatively low and the valve is mostly closed. At T2, the system automatically reacts to an increasing process value by ramping up the controller signal, but since it typically takes a longer time for the actual position of a valve or pump to respond, a vertical gap opens between the controller square and valve position line. At T3, the parameter has continued to increase, exceeding an alarm limit. Both controller signal and valve position have continued to respond: controller signal has also increased to its full value, and the valve has mostly opened. In a situation where the system does not respond to a process variable, this design makes it possible to distinguish whether the problem lies with the controller signal, or whether the actual valve/pump is not reacting properly, which might indicate a stuck valve. The graphic also shows violated alarm limits, and a small arrow indicates predicted development. The objective of this design is to avoid the need to visit different parts of a display hierarchy to mentally construct an overview of the situation. It should, however, be noted that this design is better suited for qualitative data perception than for accurate readings.

Figure 4: Dynamic alarm spot for a new incoming alarm (red square) on a green open valve

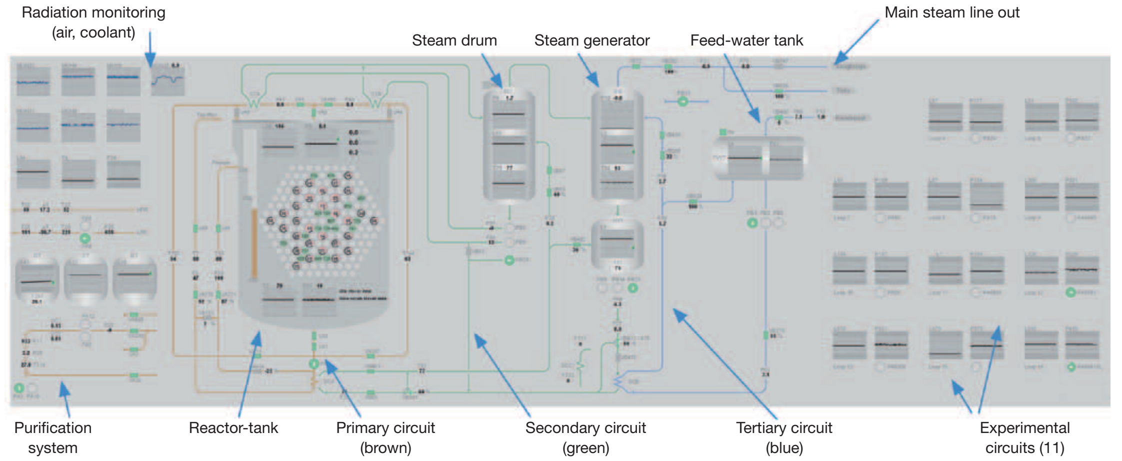


Alarm visualization

Recent research has shown how change-blindness (being unable to detect changes because visual processing capacity is already stretched to its limit) is of particular concern for large displays, since users need to look around for information ('Attention and Visual Memory in Visualization and Computer Graphics' by Healey C. G, Enns J. T., *IEEE Trans. On Visualization and Computer Graphics*, vol. 18, no. 7, 2002, pp. 1170-1188). It described how design should take advantage of our built-in apparatus for fast pattern finding and should use perceptual salience to direct attention. Visually salient graphics are often referred to as pop-out effects.

We find this particularly interesting for visualization of alarms. We have found that equally-sized filled alarm squares create stronger, more consistent, visual pop-out effects than alarm frames, (which can vary in size with process objects' sizes). A neutral background (such as grey) is suitable to facilitate pop-out effects. Furthermore, it is quite common to use blinking/flashing effects for new alarms. However, on large displays this can create unfortunate tiring visual effects. For this reason, we have developed a gentler animation effect to draw attention to new alarms, illustrated in Figure 4. This dynamic alarm-spot can be used for alarms on all types of process values and equipment.

Figure 5: Halden reactor LSD (4.5m by 1.4m) after user testing, featuring few indicators, mini-trend objects and open space.



Design principles

Based on our industry practice, and LSD research, we propose the following design principles as applied for the Halden Reactor LSD:

- Design for fast visual perception. Create visual patterns from process values and alarm limits. Qualitative indicators based on part-wise mathematical normalization are suitable. Reduce masking problems by limiting number of different display objects.
- Design for limited visual memory. Avoid keyhole problems through a flat display layout rather than display hierarchy. Explicitly show target values, alarm information, rate-of-change cues and automation data.
- Visualize a plant's dynamic response through qualitative trended indicators; focus on dynamic data through high data/ink ratio (display as little ornament as possible around data; with clever design the real data itself provides the necessary context).
- Support top-down search through lines, multi-scaled structuring elements, grouping, and open space.
- Support bottom-up, data-driven awareness through strong visual pop-out effects: graphics orientation, colour, size, and motion. Equally-sized filled objects are better than frames for visual effect. Highlight new alarms through gentle animation rather than flashing or blinking. Use a neutral background (such as gray) to facilitate visual pop-out effects, with the caveat that gray-scale graphics can cause readability problems in well-lit rooms using front-projected displays.

IRD in user-centered design

Endsley et al. (2003) describes how a user-centered system approach is desirable for complex systems. They described how designs should start with user needs and capabilities, rather than being moulded around technologies. We find Information-Rich Design to be a reasonable approach to LSD design from this perspective, but what is needed to accomplish industrial projects using the IRD approach? The standard for human/user-centered design for interactive systems, ISO-9241 (2010), suggests the following principles:

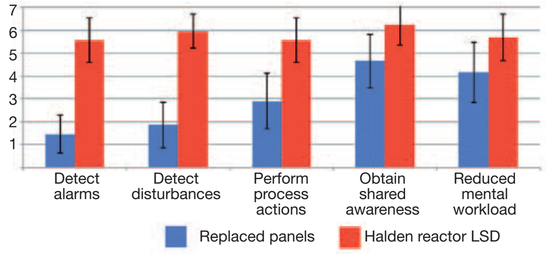
- Base design upon an understanding of users, tasks and environments
- Involve users throughout design and development
- Refine and drive design through user-centred evaluation, using an iterative design process
- Address the whole user experience
- Include multidisciplinary design team including skills and perspectives.

From this we see that IRD does not ensure that a user-centered design process is followed. IRD graphics and design principles should therefore be part of a larger systems perspective for control room design. This design process should include the formation of a focused design team with a broad skills profile including designers, process experts and industrial vendors. Design should reflect work-domain analysis findings, which could imply the need to harmonize colours and graphics with a control room's other display interfaces, and the inclusion of other graphic elements, such as long-term trends for key variables, and displays of a plant's safety and integrity functions. The design process should be iterative. (We have used Microsoft Visio, Concept Draw and OmniGraffle for rapid iterative prototyping of LSD graphics).

We also need to address the user experience by investigating the effects of display technology, comparing, for example, front-projection displays, rear-projection displays, and LCD panels. This is particularly interesting for well-lit control rooms. We have recently designed LSDs for the petroleum industry using high-resolution display cubes. Even though this type of technology introduces unfortunate visible frames as thin lines, it increases the contrast ratio and brightness. Such technology appears to us to be advantageous, particularly on grey-scale colour-layering LSDs.

The IRD concept for LSD graphics has similarities with other display approaches, both industrial- and research-oriented concepts; one is the ASM Honeywell approach for overview displays for petroleum industry (Tharanathan et al. 2012). The differences stem mainly from how IRD is targeted for larger display surfaces. In sum, we feel that IRD is not a radical or revolutionary development; rather, it extends well-known principles of display design for LSDs. We have found IRD graphics to be realizable through industrial vendors, using Siemens, ABB, and Honeywell systems.

Figure 6: Results of user testing of Halden reactor large-screen display (red) compared with replaced analogue panels (blue), where 7 is a high, and 1 is a low, degree of support.



Information search

Other research describes how people must be able to quickly switch between goal (top-down search) and data-driven (bottom-up, typically alarms) processing to achieve adequate situation awareness (*Designing for Situation Awareness, An Approach to User-Centered Design*, by M.R. Endsley, B. Bolté, & D.G. Jones (2003)). To design for this, we examined research in human-computer interaction that described the process of how people perceive information. Healey and Enns (2012) describe how seeing is done through a fast dynamic cycle of short stops (fixations) and rapid movements (saccades), where only a limited number of visual features can be detected within a single cycle. Other research suggests organizing data through large- and small-scale structures to support efficient visual top-down search (C. Ware, *Visual Thinking for Design* (2008)) . He describes further how relationship between concepts could be established through: proximity grouping, enclosing contour, common colour region, alignment and lines and connectors, inspired by Gestalt psychology.

From this, we have designed LSDs to support search by positioning process data in a familiar context of different-sized backgrounds, by grouping related data, and by connecting them with medium-colored lines and open space. This has resulted in a graphical design that is relatively familiar to operators, while at the same time supporting search for, and rapid overview of, information. Figure 5 shows the Halden reactor LSD designed by IFE's expert operators and the author, which was recently implemented along the IRD design principles presented in this article.

User tests

IRD is being explored for the nuclear domain through iterative research on three LSDs. This research is partly a joint project for Nordic nuclear power plants using crews of certified operators. The two first LSDs were implemented on large-scale nuclear simulators: the first at the Finnish Loviisa NPP, and the second in IFE's simulator for Swedish Forsmark-type NPPs (HAMBO LSD). The last user test was done for a live control room installation for the Halden reactor LSD.

Based on user feedback, improvements were made for the Halden reactor LSD. This LSD was compared with the analogue panels it replaced in a user test. The LSD received good system usability scores for subjective perceived support in operational use (Figure 6).

In sum, the results show how the IRD concept has improved through the research process of designing and testing whole LSDs. ■

About the author

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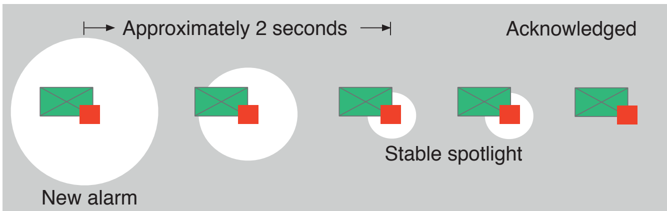
Part IV: Design Patented Graphics

The design patented graphical objects for this thesis Information-Rich Design concept.

Design patented graphical display objects

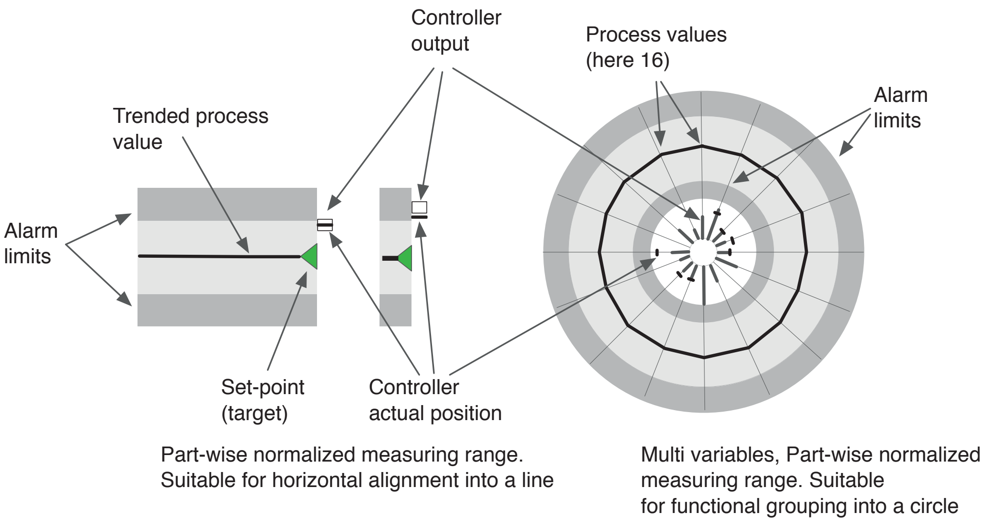
The following figures illustrate appearance and functionality of design patented graphics for Information-Rich Designed LSDs, these figures are for illustrative use only, and not exact reproduction of actual design patents:

The dynamic alarm spot registered on Alf Ove Braseth. Design patents and Design reg. In EU and Norway: No 001654765-0001, 082551.



Dynamic alarm-spot: visualizing incoming alarms in LSDs, here a red alarm on a green open valve.

The qualitative mathematical normalized indicators (mini-trend, polar-star & bar type) are registered on Alf Ove Braseth, Øystein Veland and Robin Welch. Design patents and Designreg. USA, EU and Norway: US D549, 870 S, No 000632740-0002, No 000633466-001, No 000633458-0001, No 000633458-0002, No 000633458-0003, 080686, 079695.



Qualitative mathematical normalized indicators: visualizing process data and automation data in LSDs

Appendix A

A literature review of industrial Standards and Guidelines. The following are reviewed in this appendix for this thesis:

- IEC 60964 (2009)
- IEC 61772 (2009)
- NUREG-0700 (2002)
- ISO 11064-5 (2008)
- ASM Consortium guidelines (2013)
- ANSI/HFES 200 (2008)

A literature review of industrial Standards and Guidelines

This section contains new material not presented in the thesis papers. The material is written for the purpose of discussing industry best practice (chapter 7), and outlines an overview of some well-known industry standards and guidelines used for control room display design. The focus is on principles relevant for LSDs and for overview purposes, it should, however, be noted that standards and guidelines are in general cautious of giving direct recipes on display design, they are rather oriented toward general principles and underlying problems. The standards and guidelines are intended for wide range of use: the ASM Consortium guidelines (2013) was oriented toward petrochemical processes, ISO 11064-5 (2008) and ANSI/HFES 200 (2008) were not domain specific, while NUREG-0700 (2002) and IEC 60964/61772 (2009) were intended for nuclear control centres. The following material is given separately for each standard/guideline to avoid misunderstandings. The content is mostly written chronologically in the same order as they can be found in the standard/guideline.

Control room design and application of VDUs: IEC 60964/61772 (2009)

According to their homepage (www.iec.ch, accessed Aug. 2013); the International Electrotechnical Commission (IEC) is a leading organization that prepares and publishes International Standards for all electrical, electronic and related technologies. They wrote that experts from industry, commerce, government, test and research labs, academia and consumer groups participate in IEC Standardization work. They described further, when appropriate, IEC cooperates with ISO (International Organization for Standardization) or ITU (International Telecommunication Union) to ensure that international standards fit together. For this literature review, the following two IEC standards were found relevant:

- IEC 60964, Edition 2.0, 2009-02. Nuclear power plants - Control rooms – Design. IEC 60964 focused on the functional design of new main control room in nuclear power plants; intended audience were described as vendors, utilities and licensors (p. 6).
- IEC 61772, Edition 2.0, 2009-04. Nuclear power plants – Control rooms – Application of visual display units (VDUs). IEC 61772 supplements IEC 60964, presenting design requirements for the application of VDUs in the main control room of nuclear power plants (p. 8). The intended use was described as to assist the designer on both individual workstations and larger displays (p. 8).

The following section gives first a short review from IEC 60964 on general human-machine interface issues in control room design, followed by IEC 61772 which described principles for display design and specific guidance on LSD design. IEC 60964 described how the display system should be designed considering human capabilities and characteristics (p. 30). They described how the display system should inform operators of actions on reactor protection systems, and the state of automatic systems, supporting analysis of cause of disturbances, and to support counteractions (p. 30). Further, they suggested that display types should be selected in accordance with their purpose (p. 30). For alarm system functionality, they suggested to display alarm information enabling operators to understand the fault situation, removing irrelevant information and avoiding information overload (p. 31).

IEC 61772 described how visual display unit (VDU) design should minimize the workload contribution from monitoring, operation and problem solving, and to avoid information overload (p. 11). The standard described how the display system should inform of: logic control algorithms, trip set points alarm thresholds and input assignments (pp. 13). Further, how design in general should include analogue coding in addition to numerical values, bar graphs, trends etc. (p. 20). The standard also brought up problems by using smaller VDU displays; how VDU-based information does not support the human capabilities of spatial information coding and information catching to the same extent as conventional panels (p. 31). Further, how VDUs have a disadvantage since information will not always be presented at the same location, referring the keyhole effect (p. 31).

On LSD design, IEC 61772 described how LSDs could function to maintain Situation Awareness and group cooperation. They suggested that a more concentrated and abstract information display could be suitable for this, exploiting and supporting the mental capacity and expert knowledge of the operator (p. 13). The standard explained how LSD pictures should be specifically developed for it´s purpose, and not copies of workstation/overview pictures. They suggested further how LSD pictures should supplement individual computer displays (p. 25), and how LSD pictures should support at-a-glance information perception, avoiding the need for mental calculations and processing of numerical data (p. 26).

More specifically, IEC 61772 wrote that LSDs should allow for comparative overview with: normal, presets, alarm limits and visual comparisons for similar components (p. 26). The LSD should leave details for individual workstations (p. 26). Further, how LSDs should use visual layering, highlighting alarms and alerts, support attention getting of warning signals, using faded colours for less important or shut down systems (pp. 26-27). The standard provided guidance on how LSDs critical information should not be modifiable or erasable (p. 28), and that LSDs has reduced need for text and labels since they are always present, and such information tend to create clutter (p. 27).

On the use of colours in LSDs, IEC 61772 suggested to use as few colour codes as possible (p. 28). Further, they described how LSDs using lighter backgrounds are less prone to loss of contrast by scattered light (p. 27), and that LSDs using unsaturated colours could be difficult to read from longer distances with some background colour combinations (p. 27). They also brought up issues with control room´s lighting conditions, they suggested that the major lighting problem is to have enough illumination for written material, without illuminating VDUs and LSDs and undesirably reducing screen contrast. They gave advice to use indirect and diffuse lighting, suggesting that front projectors should not cause glare or reflections on workstation displays (pp. 12-13).

Human-System Interface Design Review Guidelines: NUREG-0700 (2002)

The guidelines (intro. p. iii) were developed for reviewing human factors engineering aspects of nuclear power plants. They described the objective as to review and evaluate the interfaces between plant personnel and plant systems and components. The intended audience were U.S. Nuclear Regulatory Commission staff, reviewing nuclear power plants. NUREG-0700 (rev. 2) Human System Interface Design Review Guidelines was prepared by: J.M. O´Hara, W.S. Brown, P.M. Lewis and J.J. Persensky. The following section first provides some general objectives for display design from the guidelines Part 1: Basic HSI Elements; followed by specific guidance on group-view display system, design from Part II: HIS Systems: Group-view Display System. NUREG use the term group-view display system for displays applicable for overview purposes used simultaneously by operators to see the greater picture, they also mention large screen displays for this functionality. However, NUREG´s definition does not state that this represented a LSD.

The guidelines described how the objective of information displays is to ensure human performance through suitable information representation: "*Information is at the center of human performance in complex systems"* (p. 1). They described how formats should be chosen appropriate for supporting operator´s tasks: Text or flowcharts for instructions, tables for comparing text or numbers, mimics or diagrams for comparing functional relationships, diagrams or maps to show spatial relationships, bars, pie charts or graphs for interpreting patterns in numerical data (p. 9). Further, how interfaces should follow consistent conventions, offering explicit mapping between characteristics and system functions (p. 10). They described how global Situation Awareness should be supported as well as projection of future status, typically by trends. The guidelines suggested that information displays should offer status at-a-glance (p. 11).

The guidelines used the term group-view display systems for larger displays, and described how they are important for supporting team performance. Further, describing how some of the characteristics of conventional control rooms using analogue technology might be lost in with computer-based workstations, among problems, they listed the following (p. 309):

- Difficulty maintaining awareness of overall plant status; narrowing of attention to local problems at the expense overall awareness since workstations only display a portion of the total plant information.
- Problems through navigation of the computer display space, causing time delays.
- Difficulty maintaining awareness of crewmembers actions through an isolated view.
- Difficulty communication and to express face-to-face ideas.

The guidelines described how group-view display functionality could include overview and high-level plant status; give cues for directing operator's attention (p. 310), further how information should be relevant to the task requirements (p. 313). They described how the overview display should indicate both major changes in plant condition, such as alarms, in addition to minor changes that not yet have gone beyond alarm conditions (p. 315). They described how the group-view display should direct the user to relevant detailed information (p. 318), further, how data driven information should be informed to the operator (typically alarms) and knowledge driven search for information should be supported (p. 315).

The guidelines described how group-view displays must pay attention to interaction (typically through keyboard or mouse), incorporate features to minimize potential conflict from several users and with other input devices (p. 310). They suggested that one way to do this is to develop administrative procedures for changes in group-view systems (pp. 313). However, the guidelines informed that critical information should not be modified or deleted inadvertently or arbitrarily (pp. 329). They wrote further that consistency and compatibility with other human system interfaces should be addressed for operator performance (p. 311). They explained how inconsistency issues might include using different units and coding schemes (p. 313). The guidelines advised that personal additional information should be presented on individual view displays (p. 314).

They described how group view displays in general should support overall assessment at-a-glance (p. 316). Means might be: coding schemes making important information salient, group related information with symbols for major plant components, reduce the number of components for reduced demands on short term memory, define object categorization and pattern-matching cues to reduce demands on attention (p. 316). The guidelines described further how mimic format should be included if it increases personnel performance, through communication of functional relationships between components, or providing means of organizing information for plant monitoring (p. 316). Lastly, how perceptual landmarks are suitable providing a frame of reference for long shot views of the structure of the display space (p. 318).

Ergonomic Design of Control Centres, Displays and Controls: ISO 11064-5 (2008)

ISO (the International Organization for Standardization) is a worldwide federation of national standard bodies carried out through technical committees. The purpose of 11064-5 was described to maximize the safe, reliable, efficient and comfortable use of displays and controls in control centre applications, identifying general principles of good practice (p. vi). These principles were intended for use in systems design, one section was written specifically for larger off-workstation displays (p. vi). The intended audience were described as: operators and companies, equipment purchasers, interface designers, manufacturers end engineering firms (p. vii). The following section is organized as follows: first is general design guidance for display design, followed by specific guidance for LSD design.

General design principles (p. 5-7) addressed main topics for: operator in charge, information for solving tasks, efficiency, human-centred design, ergonomic principles, mental models and known memory limitations. Display related principles (p. 10-11) focused on efficient operator performance. They described how display design should be intuitive through use of metaphors, minimizing use of characters and superfluous elements (logos etc.). The standard described how known design principles should be used on; size, shape and grouping, and means for highlighting safety critical information should be visualized through redundancy (typically colour size and shape). Further, how dynamic and priority information should be highlighted. Display design should strive for consistency across different display types and within display hierarchies. More specific guidance for display design was provided in Annex A 1-2 (pp. 25-29). The standard suggested how it is beneficial to use information layering through: background, static data layer, Information layer, and priority layer. Further, how spatial orientation of data in predetermined locations can help faster search and recognition in displays. The standard explained how it is beneficial for trend curves to show data for different time lengths.

Annex A 5.2 (pp. 36-37) provided some specific guidance for LSDs; named off-workstation shared displays (OSD). They described LSDs, as displays were a number of individuals simultaneously could view information for increased team performance, facilitating status overviews. The standard suggested focusing on the following aspects for LSD design:

- Information allocation between LSD and workstations.
- Information structuring.
- User system interaction.
- Consistency and capability issues with workstations.

The standard recommended using overview displays for general monitoring, and that control tasks should be conducted from individual displays.

Effective Operator Display Design: the ASM Consortium guidelines, second edition (2013)

The ASM (Abnormal Situation Management) Consortium guidelines communicated recommendations for designing information displays and devices for console operator workstations, (p. 1). The Effective Operator Display Design Guidelines is prepared by: P.T. Bullemer and D.V. Reising, ASM Joint R&D Consortium. The guidelines described the audience as individuals who establish or assist in establishing company standards for information displays in console operator workstations (p.1); although the guidelines are intended for workstations, these principles are applicable to other operator applications (p. 1). For this reason, some of the sections for design of overview displays, and sections describing general display functionality and principles are quite relevant for LSD design and included in this literature review.

The guidelines (p. 16) suggested how overview displays should show key-variables, safety critical information and in general supporting a monitoring function of key variables. Multiple trend displays or dashboard style graphics was suggested for this. The guidelines described how a shallow broad flat display hierarchy is a better choice for navigation than a deep one, avoiding unnecessary strain on short-term memory (pp. 55-56). The guidelines described how process overview displays could help operator´s perceive the big picture, maintaining Situation Awareness, while other lower level displays can be used for details (pp. 20-23). They suggested for this purpose using easy perceivable qualitative analogue type indicators, displaying: alarms, key process parameters and equipment status. They suggested further how trend displays is one of the most useful visualizations, particularly supporting decisions about the performance of variables over time (p. 38-43).

On display style and layout, they recommended generally using colour layering, reserving high contrast and animation (blinking) for safety critical activities, and lower contrast grey scales for normal content and plant´s physical structures (pp. 78-86). Process equipment should be shown without excessive detailing for rapid perception (pp. 83, 86). Display layout should be consistent and follow expected conventions (p. 84, flow direction and true to physics). Minimize visual complexity; avoid visual clutter, and present related information in a single view (pp. 87-88). Further, to group related information for better memory retention (p. 99).

Colours were described as having particular strong impact on human visual attention (p. 101). They suggested using a limited colour palette, reserving signal colours such as red, orange and yellow for abnormal states (pp. 102-106). Advising to use colour combinations ensuring acceptable and sufficient contrast (pp. 107-108). They suggested avoiding colour combinations leading to colour-blind perception (p. 109). A muted background such as light grey (not darker colours) was suggested as appropriate considering eyestrain, fatigue, and glare. This type of background is suitable for visually salient foreground colours (pp. 111-113). The guidelines advised to use brightness with care, design should support alarm pop-outs (p. 109).

Human Factors Engineering Of Software User Interfaces: ANSI/HFES 200 (2008)

The American Standard (ANSI/HFES 200) is positioned for Human Computer Interaction and published by The Human Factors and Ergonomics Society Human Factors Engineering of Software User Interfaces (p. 1), editors were: G. Vanderheiden, A. Bangor, D. Gaardner-Bonneau and J. Williams. They described how the material was based on human-computer interaction research findings, established best practices, and consensus of international experts with references to the background material (p. 1.).

ANSI/HFES 200 was primarily focused on user interaction with software for personal business, educational use such as desktop PC or terminal (p. 9). Although the standard do not address high-risk applications such as nuclear power plant control room environments, alarm/security applications and process control, they stated that many of the recommendations could be used to improve the quality of such software applications (pp. 9). They wrote that the intended audience were: designers of user interfaces, buyers, evaluators and end users (pp. 13). They described that HFES 200 were harmonized with some of the ISO standards chapters: "*Interaction techniques*" and "*Visual Presentation and Use of Color*" were harmonized with ISO 9241-210 (p. 8).

ANSI/HFES 200 covered however not larger displays, but some general guidance for display design is found relevant, and for this reason listed in the following section.

In Part 2; Accessibility designing for effectiveness, efficiency and satisfaction for a wide range of people; they wrote that there is a great variety of psychological functioning for people, and of particular concern for accessibility were the area of cognitive functioning that relates to the handling of information. The major elements were describes as: receiving information, processing it and making appropriate responses (p. 102). They explained how it is beneficial to support strategies to identify the required focus of attention involving formatting and presentation of information. Further, how interactive software should enable recognition rather than demanding recall to avoid strain on long and short-term memory (p. 102). They stated that flash/blinking must be less than three flashes in any second period (p. 79), and should be considered for user attention on important tasks, (particularly in periphery of field view, also in p. 407), however, they wrote that other means should be considered for readability (p. 402). ANSI/HFES 200 stated that warning or error messages should persist in displays until dismissed or not active.

In Part 5; Visual Presentation and Use of Color; ANSI/HFES 200 wrote that the user should be enabled to perform perceptual tasks effectively, efficiently, and with satisfaction, based on knowledge from: human physiology (sensory), psychology (mental workload), ergonomics (context of use), typography and graphical design (p. 371). They wrote that information density should not be perceived as overly cluttered by the user (p. 375); and that information can be grouped by spacing; location that naturally follows tasks sequences; arranged to follow common formats and conventions (pp. 376-377). Grouping can be done through Gestalt principles: proximity of related data, similarity, closure, chunking for rapid visual perception (pp. 377-379).

Part 5 followed up with more guidance on both graphical coding and appropriate use of colours; they wrote that graphical coding should be used conservatively, limiting the number of perceptible levels. Further, to limit different graphical objects sizes (p. 402), geometrical shapes etc. 3D coding techniques were described as appropriate (p. 394). They suggested how colour in general should be used to achieve design goals: meaning, grouping, reducing complexity, guide user´s attention, signal state, show relationships, and to create a pleasant environment (p. 403).

The standard described further how colour coding should be used redundant together with other coding techniques, and applied conservatively, clutter if overused (pp. 395-396, 400, 404); preferable no more than six colours in addition to black and white for visual search (p. 405). They suggested mapping colour to meaning or context through familiar conventions (red – alarm), and to use and to restrict high contrast colours for special states (pp. 397-398, 414). ANSI/HFES 200 wrote that colour readability is best within users central field of view (pp. 407-408). The standard stated that colours for foreground should be warmer, more saturated and lighter (p. 408), and that colours for background should be more neutral or cool, less saturated, and darker (p. 408). On the use of colour combinations, they suggested choices to maximize readability, spectrally extreme blue and red on dark background gives poor readability (pp. 408-410). Finally, how colours for real-world physical objects should be used realistically (p. 413).

Appendix B

Declarations of co-authorship for the research papers of this thesis

Declarations from co-authors are given in chronological order for the following papers:

Paper 1: Braseth A.O., **Welch R., Veland Ø.** (2003). A Building Block for Information Rich Displays. Paper at IFEA conference, Gardermoen, Norway.

Paper 2: Braseth A.O., **Veland Ø., Welch R.** (2004). Information Rich Display Design, paper in Proceedings, Forth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Controls and Human-Machine Interface Technologies NPIC&HMIT, Columbus, Ohio.

Paper 3: Braseth A.O., **Nurmilaukas V., Laarni J.** (2009). Realizing the Information Rich Design for the Loviisa Nuclear Power Plant. Paper in Proceedings, Sixth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies NPIC&HMIT, Knoxville Tennessee.

Paper 4: Laarni J., Koskinen H., Salo L., Norros L., A.O. Braseth, **Nurmilaukas V.** (2009). Evaluation of the Fortum IRD Pilot. Paper in Proceedings, Sixth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies NPIC&HMIT, Knoxville Tennessee.

Paper 5: Braseth A.O., **Nihlwing C., Svengren H., Veland Ø., Hurlen L., Kvalem J.** (2009). Lessons learned from Halden Project research on human system interfaces, Nuclear Engineering and Technology, An International Journal of the Korean Nuclear Society, Vol. 41, No. 3, pp. 215-224.

Paper 6: Braseth A.O., **Karlsson T., Jokstad H.**, (2010). Improving alarm visualization and consistency for a BWR large screen display using the Information Rich Concept. Paper in Proceedings, Seventh American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies NPIC&HMIT, Las Vegas.

Paper 7: Braseth A.O., **Øritsland T.A.** (2013). Visualizing Complex Processes On Large Screen Displays: Design Principles Based On The Information Rich Design Concept, Elsevier Displays, No 34, pp. 215-222.

Paper 8: Braseth A.O., **Øritsland T.A.** (2013). Seeing the Big Picture: Principles for dynamic process data visualization on Large Screen Displays, in Proceedings of Complexity, Cybernetics, and Informing Science and Engineering, Porto, Portugal, pp. 16-21.

NTNU

Vedlegg til søknad om å få avhandlingen bedømt

MEDFORFATTERERKLÆRING

(jfr. § 10.1 i ph.d.-forskriften)

Alf Ove Braseth søker om å få følgende avhandling bedømt:

Information-Rich Design: A concept for large-screen display graphics
Design principles and graphic elements for real-word complex processes

*)Erklæringen skal beskrive arbeidsprosessen og arbeidsdelingen samt inneholde samtykke til at artikkelen kan benyttes i avhandlingen.

*)
Erklæring fra medforfatter på følgende artikkel: A.O. Braseth, R. Welch, Ø. Veland (2003), A Building Block for Information Rich Displays. Paper at IFEA conference, Gardermoen, Norway.

The paper presents early Information Rich Design graphical symbols and discusses challenges in monitoring and understanding large-scale processes.

Alf Ove Braseth is the main author and writer of this paper. Alf Ove Braseth has contributed with writing in all sections through this paper. The paper's written content and graphics is produced through feedback and discussions with co-authors Robin Welch and Øystein Veland.

The original idea and concept of this paper is from Alf Ove Braseth. He is responsible for about 70 % of the work.

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* *Separat underskrift for Robin Welch

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Erklæring fra medforfatter på følgende artikkel: A.O. Braseth, R. Welch, Ø. Veland (2003), A Building Block for Information Rich Displays. Paper at IFEA conference, Gardermoen, Norway.

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The original idea and concept of this paper is from Alf Ove Braseth. He is responsible for about 70 % of the work.

FREDRIKSTAD, 10.01.14 ....
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Robin Welch ....
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Erklæring fra medforfatter på følgende artikkel: A.O. Braseth, Ø. Veland, R. Welch (2004), Information Rich Display Design, paper in Proceedings, *Forth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Controls and Human-Machine Interface Technologies NPIC&HMIT*, Columbus, Ohio.

The paper discusses how to support control room operators different roles, from self-paced (researcher) to tight (fire-fighter), how to free mental resources needed for problem solving in faster paced situations. The paper present proposes Information Rich Designed graphical objects and demonstrates alignment of several objects.

Alf Ove Braseth is the main author and writer of this paper. Alf Ove Braseth has contributed with writing in all sections through this paper. The paper´s written content and graphics is produced through feedback and discussions with co-authors Robin Welch and Øystein Veland.

The original idea and concept of this paper is from Alf Ove Braseth. He is responsible for about 70 % of the work.

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Øystein Veland ....
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Erklæring fra medforfatter på følgende artikkel: A.O. Braseth, Ø. Veland, R. Welch (2004), Information Rich Display Design, paper in Proceedings, *Forth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Controls and Human-Machine Interface Technologies NPIC&HMIT*, Columbus, Ohio.

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The original idea and concept of this paper is from Alf Ove Braseth. He is responsible for about 70 % of the work.

FREDRIKSTAD, 10.02.14
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Robin Welch
Underskrift medforfatter

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Underskrift medforfatter

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Declaration of co-authorship for paper: A.O. Braseth, V. Nurmilaukas, J. Laarni (2009), Realizing the Information Rich Design for the Loviisa Nuclear Power Plant. Paper in Proceedings, *Sixth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies NPIC&HMIT*, Knoxville Tennessee.

The paper discusses how to provide a shared information space for operator cooperation, communication, coordination of tasks and increased awareness. Which plant operational states should the 1st generation Loviisa LSD support? The paper present the first Nuclear IRD Large Screen Display

Alf Ove Braseth is the main author and writer of this paper. Alf Ove Braseth has contributed with writing in all sections through this paper except chapter two, which is the technical description of the Loviisa Nuclear Power Plant, this is written by co-author Ville Nurmilaukas. Alf Ove Braseth has been responsible for producing graphics and pictures for this paper, exception is Figure 7 (by Lars Hurlen) and Figure 17 (by Fortum). The entire paper was thoroughly reviewed and revised by co-authors Ville Nurmilaukas and Jari Laarni.

The original idea and concept of this paper is from Alf Ove Braseth. He is responsible for about 80 % of the work.

Espoo, 6/2/2014 .... Place, date

.... Sign co-author
Jari Laarni, VTT

* *Separat underskrift for Ville Nurmilaukas

.... Place, date

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Declaration of co-authorship for paper: A.O. Braseth, V. Nurmilaukas, J. Laarni (2009), Realizing the Information Rich Design for the Loviisa Nuclear Power Plant. Paper in Proceedings, *Sixth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies NPIC&HMIT*, Knoxville Tennessee.

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The original idea and concept of this paper is from Alf Ove Braseth. He is responsible for about 80 % of the work.

4.2.2014 Espoo, Finland
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Ville Nurmilaukas

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Declaration of co-authorship for paper: J. Laarni, H. Koskinen, L. Salo, L. Norros, A.O. Braseth, V. Nurmilaukas (2009), Evaluation of the Fortum IRD Pilot. Paper in Proceedings, *Sixth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies NPIC&HMIT*, Knoxville Tennessee.

The paper evaluates the 1st generation Nuclear Large Screen Display based on the Information Rich Design concept. The paper discusses the usefulness of the display using feedback from control room operators.

Alf Ove Braseth has contributed with writing some text in the Introduction, describing the technical aspects of Information Rich Design. Alf Ove Braseth has produced Figure 1 and Figure 2, and the large screen display shown in Figure 3, which is evaluated in this paper. Alf Ove Braseth has thoroughly reviewed and revised the paper.

Alf Ove Braseth has played a minor role in this paper as co-author, not more than 15 % of the work

Espoo, 05/03/2014 Place, date	…………………………… Sign co-author Jari Laarni
Helsinki, 21/03/2014 Place, date	…………………………… Sign co-author
Espoo, February 10 2014 Place, date	Leena Salo Sign co-author
Espoo, March 17, 2014 Place, date	…………………………… Sign co-author

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Declaration of co-authorship for paper: J. Laarni, H. Koskinen, L. Salo, L. Norros, A.O. Braseth, V. Nurmilaukas (2009), Evaluation of the Fortum IRD Pilot. Paper in Proceedings, *Sixth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies NPIC&HMIT*, Knoxville Tennessee.

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Alf Ove Braseth has played a minor role in this paper as co-author, not more than 15 % of the work

4.2.2014 Espoo, Finland
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Ville Nurmilaukas

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Erklæring fra medforfatter på følgende artikkel: A.O. Braseth, C. Nihlwing, H. Svengren, Ø. Veland, L. Hurlen, J. Kvalem (2009), Lessons learned from Halden Project research on human system interfaces, *Nuclear Engineering and Technology, An International Journal of the Korean Nuclear Society,* vol. 41, no. 3, pp. 215-224.

The paper discusses and summarizes results for control room displays, focusing on the following: the keyhole effect, interface management issues, visual patterns and teamwork transparency.

The idea and concept of this paper is a joint venture from IFE research scientists Alf Ove Braseth, Christer Nihlwing, Håkan Svengren, Øystein Veland, Lars Hurlen, Jon Kvalem.

Alf Ove Braseth was responsible for writing text for section 3.4 "Large Screen Displays (LSD) and Information Rich Displays (IRD)". Alf Ove Braseth wrote text also for section 2 "Challenges and opportunities in computerized human system interfaces", 3.2 "Ecological interface design (EID)", and 4 "Lessons learned" and 5 "Conclusions". Alf Ove Braseth has produced Figure 3, Figure 8, Figure 9 and Figure 11.

Alf Ove Braseth has thoroughly reviewed and revised the whole paper; he is responsible for about 30 % of the work.

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The paper discusses how the Information Rich Design concept be improved from issues found in the 1st generation display to the 2nd generation display, most notably on alarm readability and visual consistency. The paper describes the dynamic alarm-spot used to differentiate unacknowledged alarms from old alarms.

Alf Ove Braseth is the main author and writer of this paper. Alf Ove Braseth has contributed with writing in all sections through this paper. Alf Ove Braseth has been responsible for producing all graphics and pictures for this paper; exception is Figure 1 (by Lars Hurlen). The entire paper was thoroughly reviewed and revised by co-authors Tommy Karlsson and Håkon Jokstad.

The original idea and concept of this paper is from Alf Ove Braseth. He is responsible for about 80 % of the work.

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Löddeköpinge 2014-02-11 | Tommy Karlsson
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Erklæring fra medforfatter på følgende artikkel: A.O. Braseth, T. Karlsson, H. Jokstad, (2010), Improving alarm visualization and consistency for a BWR large screen display using the Information Rich Concept. Paper in Proceedings, *Seventh American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies NPIC&HMIT*, Las Vegas.

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The original idea and concept of this paper is from Alf Ove Braseth. He is responsible for about 80 % of the work.

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Erklæring fra medforfatter på følgende artikkel: A.O. Braseth, T.A. Øritsland (2013), Visualizing Complex Processes On Large Screen Displays: Design Principles Based On The Information Rich Design Concept, *Elsevier Displays*, No 34, pp. 215-222.

The paper discusses three questions on LSDs: i) Which type of process display objects is suitable? ii) How to visualize alarm information? iii) What type of display layout is suitable? In addition, the paper seeks to answer the question "Was modifications of the display concept from the 1st to the 2nd generation HAMBO display successful? The paper positions the Information Rich Design concept looking at related industrial approaches. The paper proposes design principles.

Alf Ove Braseth is the main author and writer of this paper. Alf Ove Braseth has contributed with writing all sections through this paper. Alf Ove Braseth has been responsible for producing all graphics and pictures for this paper; exception is Figure 1 (the "old-HAMBO display). The entire paper was thoroughly reviewed and revised by co-author Trond Are Øritsland.

The original idea and concept of this paper is from Alf Ove Braseth. He is responsible for about 90 % of the work.

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Erklæring fra medforfatter på følgende artikkel: A.O. Braseth, T.A. Øritsland (2013), Seeing the Big Picture: Principles for dynamic process data visualization on Large Screen Displays, in *Proceedings of Complexity, Cybernetics, and Informing Science and Engineering, Porto, Portugal*

The paper discusses two questions: i) Which means are suitable to support rapid-search attention to dynamic data in Large Screen Displays? ii) How can we represent dynamic process plant behaviour in LSDs? In addition, the paper discusses the research contribution of the Information Rich Design concept and positions the concept by looking at other scientific display approaches. The paper proposes design principles.

Alf Ove Braseth is the main author and writer of this paper. Alf Ove Braseth has contributed with writing all sections through this paper. Alf Ove Braseth has been responsible for producing all graphics and pictures for this paper, except Figure 4 (by Brooks). The entire paper was thoroughly reviewed and revised by co-author Trond Are Øritsland.

The original idea and concept of this paper is from Alf Ove Braseth. He is responsible for about 90 % of the work.

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Trondheim 28/3-14 .... Sted, dato

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Appendix C

Declarations of co-authorship for design-patented graphics, and the author´s contribution in designing this thesis research-oriented Large-Screen Displays.

Declarations from co-researchers Øystein Veland and Robin Welch for the design-patented graphics.

Declarations for author´s contribution in Large-Screen Display design for the following three Large-Screen Displays in this thesis:

The Loviisa Large-Screen Display.

The HAMBO Large-Screen Display.

The Halden Reactor Large-Screen Display.

NTNU

Vedlegg til søknad om å få avhandlingen bedømt

MEDFORFATTERERKLÆRING

(jfr. § 10.1 i ph.d.-forskriften)

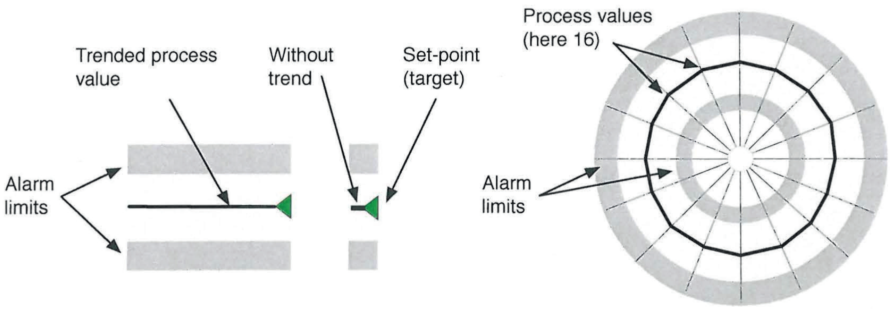
Alf Ove Braseth søker om å få følgende avhandling bedømt:

Information-Rich Design: A concept for large-screen display graphics
Design principles and graphic elements for real-word complex processes

*)Erklæringen skal beskrive arbeidsprosessen og arbeidsdelingen samt inneholde samtykke til at artikkelen kan benyttes i avhandlingen.

*)
Erklæring fra medforfatter på følgende grafikk: Alf Ove Braseth, Øystein Veland and Robin Welch. Design patents & Designreg. in USA, EU & Norway: US D549,870 S, No 000632740-0002, No 000633466-001, No 000633458-0001, No 000633458-0002, No 000633458-0003, 080686, 079695 This concerns the original graphics, not later graphics that is entirely contribution from Alf Ove Braseth (modified with automation, rate of change, explicit alarm text, dynamic alarm-spot).

The idea is using generic graphical indicator, using with part-wise normalized measuring range calibrated at set point and alarm-limits for process data, se illustration.



Part-wise normalized measuring range. Suitable for horizontal alignment into a line

Multi variables, Part-wise normalized measuring range. Suitable for functional grouping into a circle

The original idea and concept of this normalized graphics was entirely a contribution from Alf Ove Braseth. The colour-layering concept was inspired from earlier work by fellow scientists Øystein Veland, Hanne Haukenes and Lars Åge Seim at IFE. Detail design of graphics was a joint effort from Alf Ove Braseth, Øystein Veland and Robin Welch. Alf Ove Braseth has at least 1/3 contribution in detail design.

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Øystein Veland ……………………
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Erklæring fra medforfatter på følgende grafikk: Alf Ove Braseth, Øystein Veland and Robin Welch.
Design patents & Designreg. in USA, EU & Norway: US D549,870 S, No 000632740-0002, No 000633466-001, No 000633458-0001, No 000633458-0002, No 000633458-0003, 080686, 079695
This concerns the original graphics, not later graphics that is entirely contribution from Alf Ove Braseth (modified with automation, rate of change, explicit alarm text, dynamic alarm-spot).

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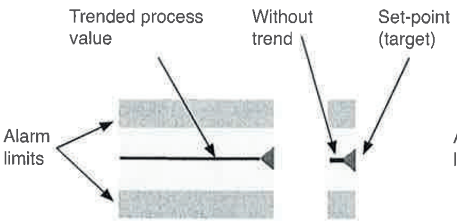
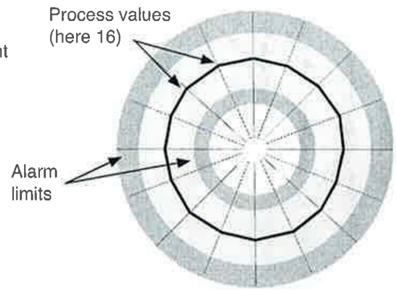


Part-wise normalized measuring range.
Suitable for horizontal alignment into a line



Multi variables, Part-wise normalized measuring range. Suitable for functional grouping into a circle

The original idea and concept of this normalized graphics was entirely a contribution from Alf Ove Braseth. The colour-layering concept was inspired from earlier work by fellow scientists Øystein Veland, Hanne Haukenes and Lars Åge Seim at IFE. Detail design of graphics was a joint effort from Alf Ove Braseth, Øystein Veland and Robin Welch. Alf Ove Braseth has at least 1/3 contribution in detail design.

FREDRIKSTAD, 10.01.14
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Robin Welch
Underskrift medforfatter

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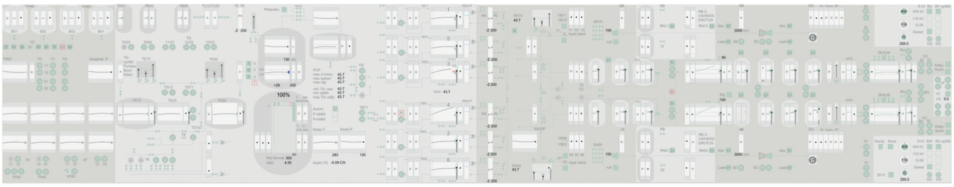
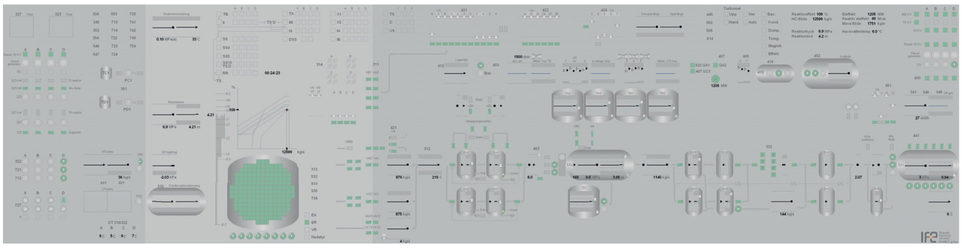
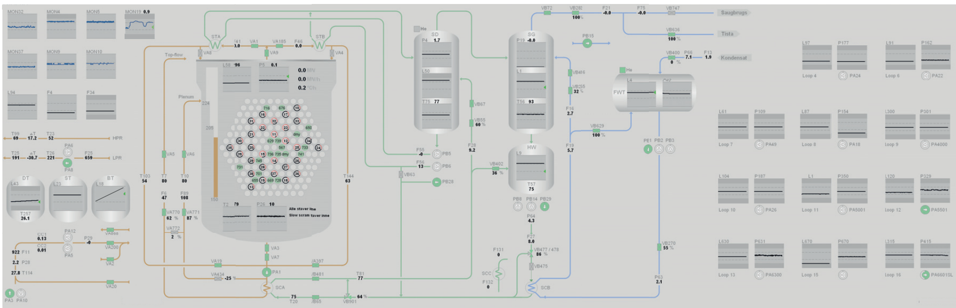
Erklæring for medvirkning til følgende grafikk: Three Large Screen Displays (LSDs), described in both thesis and research papers. The LSDs are: Loviisa (top figure), HAMBO (middle) and Halden Reactor LSD (bottom).







The idea and concept of these three LSDs is entirely contribution from Alf Ove Braseth. All graphics and layout is prototyped by Alf Ove Braseth on an Apple Mac, using Concept Draw and OmniGraffle. Expert process operators and Alf Ove Braseth produced detailed graphic design through an iterative design process. Others did implementation.

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