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 thinks 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

Fig. 6. Different-purpose Zones on a LSD

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.

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 has 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.

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- 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)

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