Development and Evaluation of a Function-Oriented Display System
Although no clear design philosophy for screen-based HSIs exist, screen-based Human System Interfaces (HSI) are gradually replacing panel-based HSIs. The current paper presents a comprehensive design philosophy where a function-analysis of the plant forms the backbone of the information requirements, information presentation and display organization. The main characteristics of the concept are described as well as the development process behind the first prototype. Finding from the first usability test of the prototype are reported and potential benefits of the HSI are discussed. Ideas and problem areas for a future improved prototype are also described in the paper. The work is part of the OECD Halden Reactor Project’s ongoing research on innovative design for advanced NPP control-rooms and is conducted in close co-operation with Electricité de France.
Development and Evaluation of a Function-Oriented Display System

Gisle Andresen, Helena Broberg, Jon Kvalem

IFE, OECD HRP, Norway, +4769212200, Gisle.Andresen@hrp.no

Abstract – Although no clear design philosophy for screen-based HSIs exist, Screen-based Human System Interfaces (HSI) are gradually replacing the conventional panel-based HSIs. The current paper presents a comprehensive design philosophy where a function-analysis of the plant forms the backbone of the information requirements, information presentation and display organization. The main characteristics of the concept are described as well as the development process behind the first prototype. Findings from the first usability test of the prototype are reported and potential benefits of the HSI are discussed. Ideas and problem areas for a future improved prototype are also described in the paper. The work is part of OECD Halden Reactor Project’s ongoing research on innovative design for advanced NPP control-rooms and is conducted in close cooperation with Electricité de France.

I. INTRODUCTION

Screen-based Human System Interfaces (HSI) are gradually replacing the panel-based HSIs found in most of today’s nuclear power plants. Ageing I&C equipment, cost reduction of maintenance, loss of skilled personnel, and new safety requirements are important factors that drive this trend [1][2]. In addition, several operational benefits provide arguments for making the change: richer and better information presentation, more centralised and task-oriented operation [1][2].

Surprisingly, no clear design philosophy for creating screen-based HSI exists although the technology has been around for more than two decades. Paulsen claims that there seems to be a general lack of strategy for the design of new HSIs [3]. In four modernization projects, she found that the new solutions where based on traditional P&I diagrams and the operators’ experiences from their existing control rooms. Thus, to the extent that there is a strategy for the design, it seems to be heavily influenced by the panel-based control-room concept.

There are several potential problems with applying the reasoning of conventional HSIs on screen-based HSIs. The conventional panel-based control-rooms offer large display areas where a lot of information can be presented simultaneously at fixed positions. The screen-based HSIs have greater flexibility in terms of presentation formats, but the display area is typically much smaller. This may have negative consequences on operator performance. For example, workload may increase due to the need for navigating between displays; situation awareness may decrease due to “key-hole” effects [4].

Guidelines, like the NUREG-0700 Rev.2 [5], have acknowledged these potential problems and the industry has found solutions for mitigating them. A typical way of reducing the navigation load is to create more task-oriented displays. This can be achieved by including task-relevant process information in the system displays; developing menus where displays are organized according to tasks; developing trend displays where parameters are grouped and presented to support particular tasks; or by creating dedicated task-based displays, compiling information from different systems needed to perform specific tasks.

Common ways of dealing with situation awareness problems are to dedicate certain areas of the display page for key plant parameters or by introducing large screen overview displays, ensuring that plant parameters of particular importance always are visible to the operators.

Although not having had a major impact on the industry yet, there are also several lines of research where the technology is utilised for synthesizing and presenting information in more directly perceivable ways for the operators. Today, probably the most influential exponent for this approach is the so-called Ecological Interface Design (EID) [6].

The above design approaches offer ways of compensating for the negative consequences of using the conventional “system-oriented P&I approach” in the design of screen-based HSIs. Still, to use the words of Paulsen, the overall strategy for the HSI design remains vague.

One negative consequence of this vagueness is that there are no principles for integrating the various tools used by operators in the control room. Vicente, summing up the status and challenges of the EID approach admits that this is an unresolved key issue: “Any interface will not realize its full potential unless it is implemented as part of an integrated approach to system design. The interface, decision support, automation, training, selection, alarms, procedures and team collaboration all


need to be designed in a coordinated manner using a common philosophy” (p.74) [6].

In this paper we will present a design philosophy that we tentatively have called function-oriented design (FOD). The philosophy is not in opposition to any of the above approaches to screen-based HSI design. It does, however, offer something that none of the other approaches have been able to provide: a framework for integrating all the basic tools of control-room operators. Also, the framework is used for organizing the operators’ tasks, providing a coherent operational philosophy.

In function-oriented design a function analysis of the plant is used as the backbone of the information requirements, information presentation and display organization of the HSI. Using a function analysis to identify information requirements is generally recommended for HSI design (e.g., [5]), so this feature is not making the approach unique. What makes the approach distinct is that the state of the plant’s functions is represented through the displays and that the functional hierarchy resulting from the analysis is used for structuring all major elements of the HSI: operating displays, monitoring displays, computerized procedures and alarms.

The purpose of this paper is to describe the main characteristics of the FOD concept as of today. The paper also provides a brief description of the development process of the first prototype and initial results from the usability testing. Finally, it will be discussed how the concept is believed to influence operator performance, how the approach may provide a comprehensive design philosophy (not only HSI design), how the philosophy is related to other approaches and the next steps of the research.

II. MAIN HSI CHARACTERISTICS

In this chapter the main characteristics of the function-oriented design (FOD) concept is outlined. We begin with the function analysis and the information synthesis that forms the backbone of the HSI. Then follows a description of the three display types.

The HSI characteristics and terminology originates from the FITNESS\textsuperscript{1} simulator residing at SEPTEN/EDF Lyon in France. FITNESS is described in Pirus \cite{7,8,9}. Note, however, that the work reported in this paper is still in progress so the presentation shows only the concept as of today\textsuperscript{2}.

II.A. Function Analysis

The function analysis is similar to the approach described in the IEC-61839 standard \cite{10}. 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; for FITNESS there are 12. In the FOD project, the work has so far focused on two functional sets: feedwater function and steam-production function.

The functional sets are aggregates of main functions. For example, the feedwater function is composed of five main functions: feedwater pumping function, condensate pumping function and high, medium and low-pressure pre-heater functions. Functions at the lowest level are called elementary functions. They can be defined directly under a main function or be part of a train or group function.

There is no formal approach for determining the number of levels of the decomposition, but, in addition to the plant’s process functionality and structure, there are typically three aspects involved:

- **Operational complexity.** Tries to minimize the operational complexity and keep it similar across functions at the same level in the analysis.
- **Operational meaningfulness.** Functions are not decomposed unless the resulting sub-functions can be seen as operationally meaningful.
- **Redundancy.** Components/systems that are functionally redundant or may substitute one another functionally are defined as functions.

The functional decomposition of the plant is used as a basis for additional analyses. A task analysis is performed to support the development of procedures. The contents and layout of the procedures are not very different from regular paper-based procedures. The main difference is that they are organized according to the functional decomposition; all functions have their own startup, shutdown and disturbance procedure associated with them.

A separate analysis is needed for determining the functions’ status and level of degradation (alarms). This analysis is performed on the functional decomposition using a bottom-up approach. That is, the status of functions higher up in the hierarchy is determined by the status of their sub-functions. We will describe this analysis next.

II.B. Information synthesis

For all functions, the following status and alarm indicators are defined:

\textsuperscript{1} FITNESS: Functional Integrated Treatments for a Novative Ecological Support System

\textsuperscript{2} The research is conducted by the OECD Halden Reactor Project (HRP) in co-operation with SEPTEN/EDF.
Available/unavailable. A function is “available” when it is usable from the main control room; i.e., all necessary support systems are available and all local actions are completed (e.g., line-ups and maintenance).

In service/out of service. A function is “in service” when it is ready to be used for achieving the current operating objective.

Level of degradation. A function can be in one of four levels of degradation:
- No degradation: the situation is normal.
- Minor degradation: The situation is abnormal, but there is no immediate danger of loosing the function.
- Major degradation: The situation is abnormal, and there is danger of loosing the function if no action is quickly taken.
- Function loss: The situation is abnormal and the function is lost.

The functional status and alarms are calculated and updated dynamically for the whole functional hierarchy. The calculation is done in a bottom-up fashion, aggregating the status conditions from the low-level elementary functions, through the functions at the intermediate level to the top-level functional sets.

II.C. Display types

Three display types have been designed to support the operators in performing their main tasks: operation, monitoring and procedure execution.

The displays are organized according to the same functional decomposition, but there is not a one-to-one correspondence between the display network and the functional hierarchy. This is because it is common to present more than one function on each display.

There are several ways of navigating through the display network:
- Through the functional hierarchy from top-level function displays to low-level function displays and vice versa.
- Between displays showing functions at the same level.
- Between different display types representing the same function.
- From menus, shortcuts and history buttons.

II.C.I. Operating Displays

The operating displays use a process mimic format. Functions are represented as grey rectangular areas superimposed on the process mimic. Sub-functions are located within the boundaries of the functions they are subordinate to and are represented by a darker grey color. The display in the upper left corner of Figure 1 shows the operating display of the high-pressure heater function. This function consists of two trains, which are further decomposed into two pre-heaters, and a bypass.

![Example displays for the high-pressure heater function: Operation and procedure displays](image-url)

In the upper-left corner of the function area is a label containing the function name, status information and alarms. The in service signal is shown as an arrow on the right-hand side of the label. Alarms or “level of degradation” are signaled through the square icon in the upper-left corner of the function label. When a function is unavailable, this is indicated by a red cross superimposed on the label. Conversely, when the function is available, there is no red cross.
II.C.II. Procedure displays

The procedure displays use a flowchart format, indicating in which order the procedure steps should be executed (see Figure 1). For each function there are three kinds of procedures: 1) startup of function, 2) shutdown of function, and 3) disturbance handling.

II.C.III. Monitoring displays

The monitoring displays show historical trends of parameters of significance for the function. The number of parameters trended on one display depends on how many parameters are considered relevant. Parameters can be presented in the same or in separate diagrams.

III. DEVELOPMENT PROCESS

Since the design concept originates from FITNESS, the project did not begin with a conceptual design phase. Instead, the work began by finding technical solutions for implementing the display types and signals. The solution was to use two tools developed by the Halden Project: ProcSee [11] for implementing the displays, and COAST [12] for implementing the functional status and alarm signals. The condensate main function was used as a test case. It consisted of four sub-functions: the three condensate pumps and the water source (condensate pool).

Being reasonably confident in the technical implementation, the scope was increased further to cover the main feedwater function. While the functional decomposition used in the test case was identical to that of FITNESS, the team now made the function analysis from scratch so as to represent the simulated PWR in the best possible way. It was clear that alternative decompositions were possible, and when the alternatives seemed to be equally good, the decomposition differing from FITNESS was chosen.

At this point in the development process, the prototype was considered having sufficient scope and interaction possibilities for being investigated in a usability test. Selected findings from this test are described next.

IV. USABILITY TESTING

IV.A. Approach

Three turbine operators participated individually in the test. They went through six scenarios designed to engage them into using the different features of the prototype while performing realistic tasks. Three scenarios involved tasks typical for normal plant transitions such as starting a second feedwater pump or aligning the valves of the pre-heaters. The operators would have to use the normal startup and shutdown procedures to perform these tasks.

The other three scenarios involved minor disturbances such as a leakage in one of the pre-heaters or a deviation in the level of one of the steam generators. To handle these events, the operator should use the disturbance procedures.

Test data were collected by means of observations, interviews and questionnaires. The observations were made in real-time by a human-factors person positioned behind the operator. The observer tried to capture instances of interaction breakdowns, i.e., situations where the operator’s interaction with the HSI came to a halt. The operators were encouraged to “think aloud.”

Immediately after a trial was completed, the operator was interviewed about problems she experienced during the trial and interaction breakdowns noted by the observer. After all trials were completed there was a debriefing session. Here the operator was interviewed about how tasks are performed at the home plant compared to how they are performed on the prototype. The operator was also interviewed about what he liked and disliked about the prototype.

The rating-questionnaire was administered during the debriefing as well. It contained 12-items tapping into various aspects of usability presumed to be of relevance for advanced HSI.

The main purpose of the test was to provide input to the design team on the usability of the prototype. Secondary purposes were to provide input to the training program for the HSI and to explore various methods for testing innovative design concepts. In this paper we will only address the main purpose.

The test was not oriented towards task performance but focused on the operator’s interaction with the interface and their experiences using the system. This, in addition to the low number of participants and general uncertainty regarding the robustness of the prototype, implied that the data did not allow us to draw general conclusions about the strengths or weaknesses of the design concept. This would have to be investigated at a later stage of the development process.

IV.B. Results

The results showed that the operators’ general impression of the HSI was positive. This was confirmed from the results of the rating questionnaire and the interviews. Some parts of the display system were given favorable remarks from all participants. For example, the way the displays were organized according to the functional decomposition of the plant was appreciated; the top-level display provided a good overview of the plant while more detailed information could easily be retrieved from the displays presenting the lower level functions.

Another part of the HSI the operators liked very much was the computerized procedures. They had generally few problems with interpreting their contents and appreciated
getting information about whether a procedure step was completed.

Although the general feedback on the HSI was positive, several usability issues were identified. The findings were categorized in three: bugs (minor implementation errors), conceptual (related to the design concept) and training (related to the training program). This division made it easier to determine how the findings should be funneled into the development process. Typically, bugs were easy to fix and involved little controversy. The conceptual and training issues, on the other hand, were more difficult to deal with and needed to be analyzed further; i.e., the following questions had to be explored: a) is the design solution satisfactory and the problems observed primarily due to too little training, and b) what are the consequences of redesigning the concept — how much effort is needed and are there adversary side-effects on operator performance? The main conclusions from these explorations were that the training should be improved, but that it also was necessary to make changes to the design. For instance, both the navigation mechanism and structure of the disturbance procedures had to be redesigned.

IV.C. Conclusion

The usability testing showed that the HSI was generally well received by the participants. This is consistent with tests performed internally to EDF on the FITNESS simulator, and strengthens our confidence in the feasibility of the concept.

Several usability issues were identified. They served to illustrate the trade-offs that need to be made when redesigning the HSI, striking a balance between various usability dimensions (e.g., consistency versus efficiency). Also, the test showed that usability testing is a useful vehicle for informing the design team on issues related to integration. It is not reasonable to expect inspections or expert judgment to be sufficient for identifying detrimental interaction breakdowns when so many factors are involved.

Because the main purpose of the FOD project is to reveal strengths and weaknesses of the concept, the test also served as a pilot for identifying possible biases that may reduce the value of a future summative usability test (validation test). The following general implications can be derived from the findings:

- Bugs may interfere with the operator’s performance, so it is important to make the prototype more robust. The best way to accomplish this is through a more formalized verification process of the individual displays.
- Training/Experience on the HSI is a factor that interacts with most of the conceptual usability issues, so to reduce the number of alternative interpretations the training program should be improved. In particular, the operators should receive more training on the display management features.

V. NEXT STEPS

A comprehensive HSI design philosophy for a Pressurised Water Reactor needs to include the primary side and emergency procedures. Extending the scope to cover these elements will pose several new challenges. For example, the relationships between components, systems and functions are generally more complex on the primary side than on the secondary side. Also, on the primary side, both production and safety missions will have to be considered.

When creating displays for the primary side we are so far addressing the following challenges:

- sub-functions that are present in several functions
- supporting functions or cross-functions (e.g., electricity)
- safety functions and engineered safety features
- implementation of emergency operating procedures

Figure 2 below shows an extract of the goals-means analysis for the primary side, and we clearly see that several functions are present in each of the top functions “Control RC volume” and “Control RC water quality”. How should this be visualised? Would it be correct to show the full sub-function at several places, or should the function be placed only at one place and represented only by an icon at the other place in the hierarchy. Would this jeopardise the clean-cut functional decomposition? How would the navigation issue be influenced by different design solutions?

![Figure 2 An extract of the analysis of the primary side](image.png)

Functions supporting one or several other functions, named cross-functions, also constitute a design problem.
Should they be linked to other functions as icons, or being accessed through higher-level functions? Maybe separate cross-function displays would enhance understanding of relative placement in the display hierarchy?

How to address safety functions and engineered safety features, and properly integrate such with the function-oriented display philosophy, is still an area of discussion in the project. The same goes for implementation of emergency operating procedures.

ACKNOWLEDGEMENTS

In addition to the authors of this paper, the members of the development team are: Dominique Pirus (EDF), Mårten Friberg and Arild Teigen (IFE).

REFERENCES


