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A Human-Machine Interface Evaluation Method Based on Balancing Principles

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Abstract

Human factors principles provide foundation for guidelines of various codes and standards in designing Human-Machine Interfaces (HMIs). Also in Nuclear Power Plants (NPPs), a lot of guidelines from various codes and standard and derived from various research and development projects are available for designing Main Control Room (MCR) HMIs. However it is not easy to optimize and balance a great deal of information sources provided in NPP MCRs in a systematic manner. In this study, a balancing principle for HMI design optimization is proposed to be used in the HMI design of complex supervisory tasks in NPPs. The balancing principle is that a HMI element (e.g., an indicator or a push button) should be designed according to its importance. Design and importance attributes in the HMI design are recognized to apply the balancing principle, respectively. Two measures, Design preference to Importance Ratio (DIR) and Balancing Index (BI), based on the balancing principle are developed. The proposed principle and measures are then successfully applied to an HMI design evaluation. By using the proposed measures, unbalanced design features could be found out and reasonable recommendation could be made based on the evaluation results. As a further study, more extensive attention should be paid to considerations on how to find out and apply various design and importance attributes in the HMI design.

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1. Introduction

As the design of instrumentation and control (I&C) systems for various plant systems including nuclear power plants (NPPs) is rapidly moving toward fully digitalized I&C, much attention has been paid to human factors studies

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[1-2]. The authors have developed an evaluation system of human performance in NPP Main Control Rooms (MCRs) which was named as “HUPESS (HUman Performance Evaluation Support System)” [3]. Human performance aspects such as plant performance, personnel task performance, situation awareness, cognitive workload, teamwork, and anthropometric/physiological factor are evaluated with the HUPESS. Even though the HUPESS provides evaluation results in each of the performance aspects for the integrated system validation (ISV), additional researches have been needed to develop methods on how to find out design deficiency leading to poor performance and give a solution for design improvement in HMI. The authors have developed a method of HMI design improvement for the monitoring and detection tasks which was named as “DEMIS (Difficulty Evaluation Method in Information Searching)” [4]. The DEMIS is a HMI evaluation method which bridge poor performance and design improvement. Lessons learned from the existing studies lead to a question about how to optimize the whole HMI design. Human factors principles provide the foundation for guidelines of various codes and standards in designing HMIs. Also in NPPs, a lot of guidelines directly from various codes and standard and derived from various research and development projects are available for designing MCR HMIs. However it is not easy to optimize and balance a great deal of information sources provided in NPP MCRs in a systematic manner.

In this study, a balancing principle for HMI design optimization is proposed to be used in the HMI design of complex supervisory tasks in NPPs. Two measures, Design preference to Importance Ratio (DIR) and Balancing Index (BI), based on the balancing principle are developed. The proposed principle and measures are applied to an HMI design of a simplified NPP simulator. By using the proposed measures, unbalanced design features could be found out and reasonable recommendation could be made based on the evaluation results. As a further study, more extensive attention should be paid to considerations on how to find out and apply various design and importance attributes in various HMI designs.

2. A Balancing principle for HMI design

The balancing principle is that a HMI element (e.g., an indicator or a push button) should be designed according to its importance.

2.1. Design preference to Importance Ratio (DIR)

To balance the HMI elements with their importance, a ratio measure, named as Design preference to Importance Ratio (DIR), is defined as follows;

$$DIR_{ijk} = \frac{\frac{DP_{ij}}{\sum_{i=1}^{n} DP_{ij}}}{\frac{I_{ik}}{\sum_{i=1}^{n} I_{ik}}} \qquad (1)$$

DIR_{ijk} = DIR of HMI element-i in design attribute-j and importance attribute-k
DP_{ij} = Design Preference of HMI element-i in design attribute-j
I_{ik} = Importance of HMI element-i in importance attribute-k
l = the total number of design attributes
m = the total number of importance attributes
n = the total number of HMI elements

The numerator and the denominator of equation (1) represent normalized values of design preferences evaluated over all design attributes and of importance evaluated over all importance attributes for HMI element-i, respectively. Both the numerator and the denominator range from 0 to 1. DIR_{ijk} is a relative measure representing the relative extent of design preferences compared to the relative extent of importance of HMI element-i. The numerator should be equal to the denominator in order to optimally balance the design of HMI element-i with its importance. Hence all DIR_{ijk} values should approach unity for optimal balance.

2.2. Balancing Index (BI)

Now another measure, named as Balancing Index (BI), is defined to consider all HMI elements as a whole;

$$BI_{jk} = \frac{\left|\sum_{i=1}^{n} \log_{10} DIR_{ijk}\right|}{n} \quad (2)$$

BI_{jk} = BI in design attribute-j and importance attribute-k

The BI should approach zero to optimize the balance of HMI design for all HMI elements. The BI can be interpreted as an overall measure incorporating all DIR_{ijk}. Design preference (the numerator) and importance (the denominator) of HMI elements need to be evaluated in a quantitative manner to be used with Equation (1) and (2).

3. An HMI evaluation based on the balancing principle

It is explained in this section how to apply the balancing principle and Equation (1) and (2) with an example tasks (monitoring and detection tasks). The proposed principle is applied to a case study in which an HMI design of a simplified simulator is evaluated with the proposed measures, DIR and BI. Generally HMIs are evaluated in terms of specific design principle or features and each evaluation results are integrated for a certain decision-making. Situation awareness (SA) among various design review principles provided in NUREG-0700 (rev02) Appendix A [5] is selected and focused on for the case study. Two design attributes and one importance attribute are defined for the HMI evaluation in terms of SA. The first design attribute considered is “detection usability for SA”, which represents how well each HMI element is designed to facilitate effective detection for developing SA. The mimic and graphical formats are usually favored design techniques for effective detection in process control systems. The second design attribute is “maintainability for SA”. To maintain SA, operators in process control systems have to accumulate knowledge of changing trend in each of HMI elements. For the importance attribute, only one attribute of “informational importance” is considered in this study. There are usually considerable correlations between process variables in NPPs. Such correlations could permit an observer to monitor a subset of the displays and to provide estimates of other variables. Such correlations lead to expectancy for required information sources and prioritization (assessment of value) of information sources and form obvious rules of the behavior of a plant system which are transferred into the knowledge to be taught to NPP operators. The knowledge of such correlations is established as a form of the operator’s mental model, which determines the importance of information sources. This kind of importance was defined as an informational importance in the authors’ previous studies [4, 6]. The informational importance can be considered as a function of its ability to discriminate among competing hypotheses (abnormal states) of the cause of a plant symptom. The AHP (Analytic Hierarchy Process) was used as a tool to quantify the informational importance in the authors’ previous study.

The HMI elements selected to be evaluated are shown in Fig. 1. They are as follows:

- PZR=Pressurizer
  - P=Pressure
  - L=Level
  - T=Temperature
- S/G=Steam Generator (A=Loop A, B=Loop B)
  - L=Level
  - FF=Feed Flow
  - SF=Steam Flow

An evaluation table was used to evaluate each of design preference (DP_{ij}) of HMI element-*i* in design attribute-*j*, as shown in Table 1. A 5-scale evaluation scheme is utilized in this evaluation table.

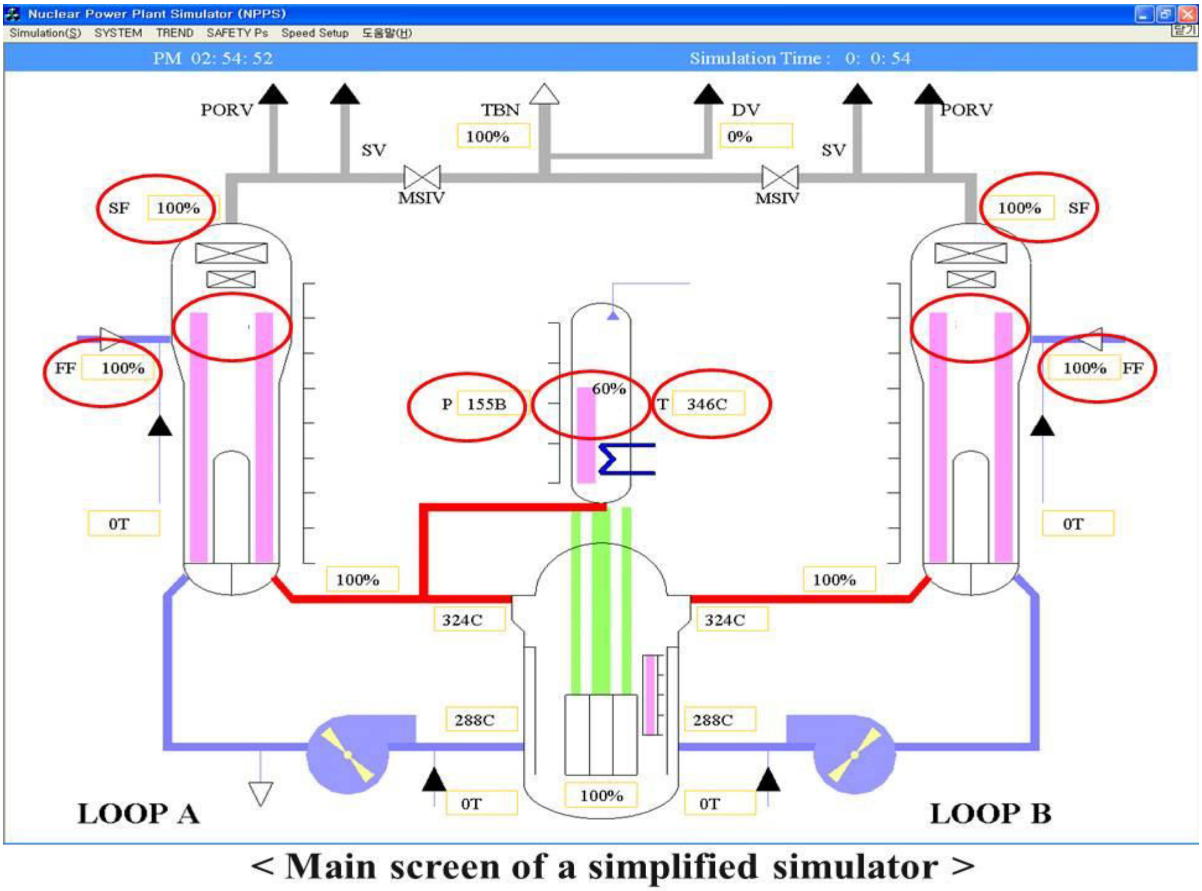

Fig. 1. Selection of HMI elements to be evaluated.

Table 1. Evaluation Table for Design Preference.

Design Preference	Value
Very Good	5
Good	4
Moderate	3
Weak	2
Very weak	1

The evaluation results using the evaluation table are summarized in Table 2. All the HMI elements considered have been designed based on the mimic display. They were evaluated as “moderately preferable” for the “detection usability”. In addition, level indicators have been designed with a graphical format which was given 2 more remarks. For the “maintainability for SA”, S/G level indicators were rated as the lowest rank with the mark of 1 point, because only bar type graphs were provided without digit number indicator which made operators hard to remember the trend change. The bar type graphs are thought to be effective in terms of detection for SA. However digit number indicators should be added for the maintenance of SA.

Several sets of the informational importance were evaluated by using the Analytic Hierarchy Process (AHP) and the results are summarized in Table 3. It is assumed that only the following seven accidents may occur in this study:

- LOCA : Loss of Coolant Accident
- SGTR (A) : Steam Generator Tube Rupture (A)
- SGTR (B) : Steam Generator Tube Rupture (B)
- SLB (A) : Steam Line Break (A)
- SLB (B) : Steam Line Break (B)
- FLB (A) : Feed Line Break (A)
- FLB (B) : Feed Line Break (B)

The sets of informational importance were evaluated by considering its ability to discriminate among competing hypotheses (abnormal states) of the cause of a plant symptom. Hence, averaged values over all the abnormal states considered are used as the final set of informational importance.

Table 2. Evaluation of HMI elements in design attributes.

HMI Element-*i*	Detection Usability for SA (*j*=1)	Maintainability for SA (*j*=2)	Remarks
PZR-L	5	3	Mimic and graphic format (better detection)
PZR-P	3	3	Only Mimic design
PZR-T	3	3	Only Mimic design
S/G (A)-L	5	1	Mimic and graphic but hard for SA maintenance
S/G (A)-FF	3	3	Only Mimic design
S/G (A)-SF	3	3	Only Mimic design
S/G (B)-L	5	1	Mimic and graphic but hard for SA maintenance
S/G (B)-FF	3	3	Only Mimic design
S/G (B)-SF	3	3	Only Mimic design

Table 3. Evaluation of Informational Importance.

Accident	PZR-L	PZR-P	PZR-T	S/G (A)-L	S/G (A)-FF	S/G (A)-SF	S/G (B)-L	S/G (B)-FF	S/G (B)-SF
LOCA	0.2338	0.1688	0.1331	0.0675	0.0675	0.0675	0.0675	0.0675	0.0675
SGTR(A)	0.1275	0.0920	0.0726	0.0959	0.2157	0.1200	0.1057	0.0604	0.0604
SGTR(B)	0.1275	0.0920	0.0726	0.1057	0.0604	0.0604	0.0959	0.2157	0.1200
SLB(A)	0.0655	0.0655	0.0655	0.1148	0.2181	0.1492	0.1250	0.0848	0.0848
SLB(B)	0.0655	0.0655	0.0655	0.1250	0.0848	0.0848	0.1148	0.2181	0.1492
FLB(A)	0.0707	0.0707	0.0707	0.0909	0.2267	0.1247	0.1027	0.1027	0.1027
FLB(B)	0.0707	0.0707	0.0707	0.1027	0.1027	0.1027	0.0909	0.2267	0.1247
Mean	**0.1087**	**0.0893**	**0.0787**	**0.1004**	**0.1394**	**0.1013**	**0.1004**	**0.1394**	**0.1013**

4. Evaluation results

DIR evaluation results are summarized in Table 4. The “Detection Usability for SA (*j*=1)” represents how easily change in each information source can be detected. The results show that both S/G (A & B) FF (Feed Flow of Steam Generator Loop A and B) need to be improved in terms of “Detection Usability for SA (*j*=1)”, which means that the current designs of the HMI elements are not sufficient or appropriate compared to their informational importance. The “Maintainability for SA (*j*=2)” represents how effectively the detected knowledge on the current situation can be maintained. The results show that both S/G (A & B) L (Level) need to be improved in terms of “Maintainability for SA (*j*=2)”. It has been validated that the HMI designs of S/G (A&B) L were insufficient for maintaining SA from another experimental study [2]. As a whole, the HMI design is better balanced in terms of Detection Usability for SA (*BI* (*j*=1)=0.006) than in terms of Maintainability for SA (*BI* (*j*=2)=0.03), because BI should approach zero for the best balance.

Table 4. Evaluation Results of DIRs:

(a) In terms of Detection Usability for SA (j=1), BI (j=1)=0.006

HMI elements	*DIR* (*j*=1)	Remarks
PZR-L	1.3361	
PZR-P	0.9761	
PZR-T	1.1081	
S/G (A)-L	1.4478	
S/G (A)-FF	**0.6253**	Need to improve detection usability
S/G (A)-SF	0.8603	
S/G (B)-L	1.4478	
S/G (B)-FF	**0.6253**	Need to improve detection usability
S/G (B)-SF	0.8603	

(b) Maintainability for SA (j=2), BI (j=2)=0.03.

HMI elements	*DIR* (*j*=1)	Remarks
PZR-L	1.1502	
PZR-P	1.4004	
PZR-T	1.5899	
S/G (A)-L	**0.4154**	Need to improve maintainability
S/G (A)-FF	0.8972	
S/G (A)-SF	1.2344	
S/G (B)-L	**0.4154**	Need to improve maintainability
S/G (B)-FF	0.8972	
S/G (B)-SF	1.2344	

5. Conclusion

A lot of guidelines derived from various codes & standard and various R&D activities are available for designing HMIs. Each guideline is usually applied on a case-by-case basis. Hence it is not easy to optimize and balance a great deal of HMIs in a systematic manner. Generally HMIs are evaluated in terms of specific design principle or features and each evaluation results are integrated for a certain decision-making. In this study, two measures, *DIR* and *BI*, are developed on the basis of the balancing principle and applied successfully in a case study. Each HMI can be evaluated in terms of design attribute vs. importance attribute in a systematic way. Finally, all the HMI could be quantitatively balanced with the proposed balancing principle. The case study shows beneficial features of the proposed method. However more extensive attention should be paid to considerations on how to find out and apply various design and importance attributes in the HMI design, because there can be a lot of design and importance attributes to be considered in HMI designing, respectively. The method and principle developed in this study can be applied not only HMI design but also human performance evaluations such as human reliability analysis (HRA) and operator training programs [7, 8]. They can be effectively applied for the evaluation of performance shaping factors (PSFs) used in HRAs. For example, the extent of well-balanced-or-not which can be evaluated with the proposed principle and method can be used for evaluation of the PSFs related to HMI. As for the operator training, important training attributes can be balanced with some of design attributes or importance attributes based on the balancing principle and method developed in this study.

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