The Effects of Providing Functionally Abstracted Information in Process Control Tasks

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Abstract

This paper reports an experimental study that investigated the effectiveness of providing functionally abstracted information to the operator in process control. Regarding this question, EID (Ecological Interface Design) framework emphasizes providing functionally abstracted information in terms of goal-means relations, based on the AH (abstraction hierarchy) of the work domain. In this study, three experiments were conducted in two typical process control task situations (fault diagnosis and operation) using a computer-based simulation of the secondary cooling system of a nuclear power plant. The results showed that the performance of process control tasks was improved by providing functionally abstracted information, and that the information was more effectively used by explicitly presenting the goal-means relations between higher-level and lower-level abstract information. The results suggest three principles for designing information display. First, information at all the abstraction levels of the work domain should be provided. Second, the goal-means relations among the abstraction levels should be explicitly presented. Third, information should be grouped to support information integration along decomposition structure within an abstraction level. Finally, this study proposes a procedure of goal-means work domain analysis using the AH concept.

1. Introduction

Information display is a medium through which the operator in a process control system receives the system state information and performs various types of control operation to change the state [1]. Currently, as advanced information technologies are used for designing information display, the designer's degree of freedom increases and accordingly the risk of poor design becomes higher. Several researchers described that information contents design becomes the most critical factor to the effectiveness of information display [1-2, 6-7]. Thus many researchers have studied systematic methods and principles for properly designing information display contents.

Functional structure of a work domain is the concept emphasized by the ecological approach [6]. In order to support the operator's adaptive knowledge-based problem solving, information display should provide inherent functional structure of a work domain in a systematic way. Rasmussen's AH (Abstraction Hierarchy) can be used for this design problem. This is well reflected by EID (Ecological Interface Design), a new design framework developed by Vicente and Rasmussen [10]. AH is a multilevel knowledge representation framework for describing the functional structure of a work domain. AH is defined by goal-means relations between levels, with higher levels containing functionally abstracted information and lower levels containing physical information [3]. There have been several studies evaluating the effectiveness of AH-based information display in several work domains [4-5, 9, 11-12, 14-15]. However, to better apply the advantage of AH-based information representation in practice, it is necessary to investigate the effects of information contents based on the AH concept, separated from the effects of sophisticated graphic formats that have been found in the EID-type displays. Especially, the effectiveness of functionally abstracted information in the AH should be empirically evaluated in an analytical manner. This paper describes three experimental studies conducted for this purpose.

2. The work domain and the display

The work domain of this study is the secondary cooling system of nuclear power plants (NPP) (Figure 1). Though simplified, this work domain features several representative characteristics of complex systems such as highly coupled subsystems, dynamic behavior of the system, a high degree of potential hazard in operating the system, the need for unanticipated events, etc. [13].

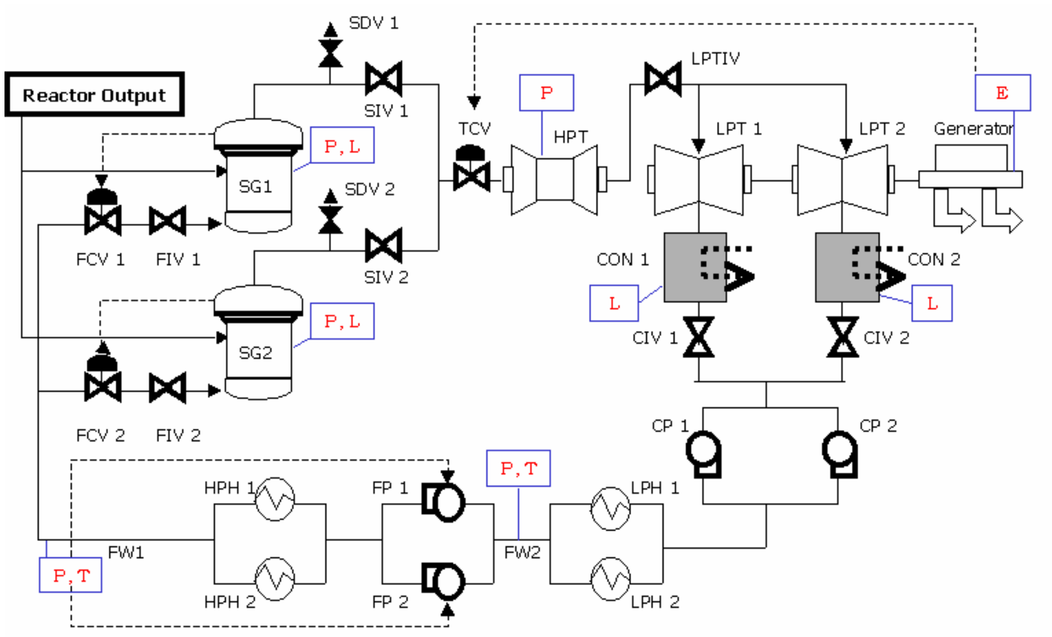


Figure 1. The work domain: secondary cooling system of nuclear power plant

2.1. Knowledge analysis of the work domain

In order to develop the content and structure of information display, the work domain is analyzed according to abstraction hierarchy (AH). The result is represented in terms of goal-means hierarchical relations. Here the knowledge of the work domain is analyzed for the five levels of AH, as suggested by Rasmussen [12]. The following is the description of five abstraction levels of the work domain.

Functional purpose (FP): The purposes of the work domain are (1) to produce electricity as demanded, and (2) to maintain safety. In order to accomplish the two purposes, all of the monitoring variables should be kept within range from maximum level to minimum level.

Abstract function (AF): The causal relations in the work domain are described according to the first principles in this level. In this domain, the relations are represented in terms of the conservation of mass and energy for the steam generator and condenser. FP justifies the reason for why the conservation laws of mass and energy should be kept. The functions at AF level work as the basis for accomplishing FP, and they are in turn realized by GF represented on the levels below.

Generalized function (GF): This level represents the work domain in terms of standard engineering functions. The GFs of the work domain include heat transfer (heating and cooling), mass flow, feedback control, and power supply. These functions can be frequently found in other engineering systems regardless of the physical objects fulfilling them.

Physical function (PF): The GFs are represented by physical mechanisms at this level. In our case, PFs are the variables that the operator has control over. The PFs include: steam generation, condensation, feedwater heating, feedwater/steam stream, flow control, and turbine operation.

Physical form (F): This function level describes the appearance, condition, and location of each component, and the spatial proximity among the components.

Figure 2 illustrates how the properties within levels of the AH are related each other. After identifying the properties within levels of the AH representation, it is necessary to understand the relations among the levels. Figure 3 illustrates how the properties of different levels are mapped in terms of goal-means relations. Such a work domain analysis using the AH describes the various layers of functional structure that are inherent in the work domain. EID concept claims that the display lacking some levels of the AH may be ineffective in coping with task situations challenging the system safety, so that display designer should make efforts to represent all the levels of the AH on the information display.

In order to analyze the activities that the human operator should conduct to control the work domain, prototypical control task situations were identified [13]. Prototypical task situations of the work domain are two folds: normal and abnormal situations. In normal situation, monitoring the state of the system and detecting the occurrence of abnormal situations are major activities. In

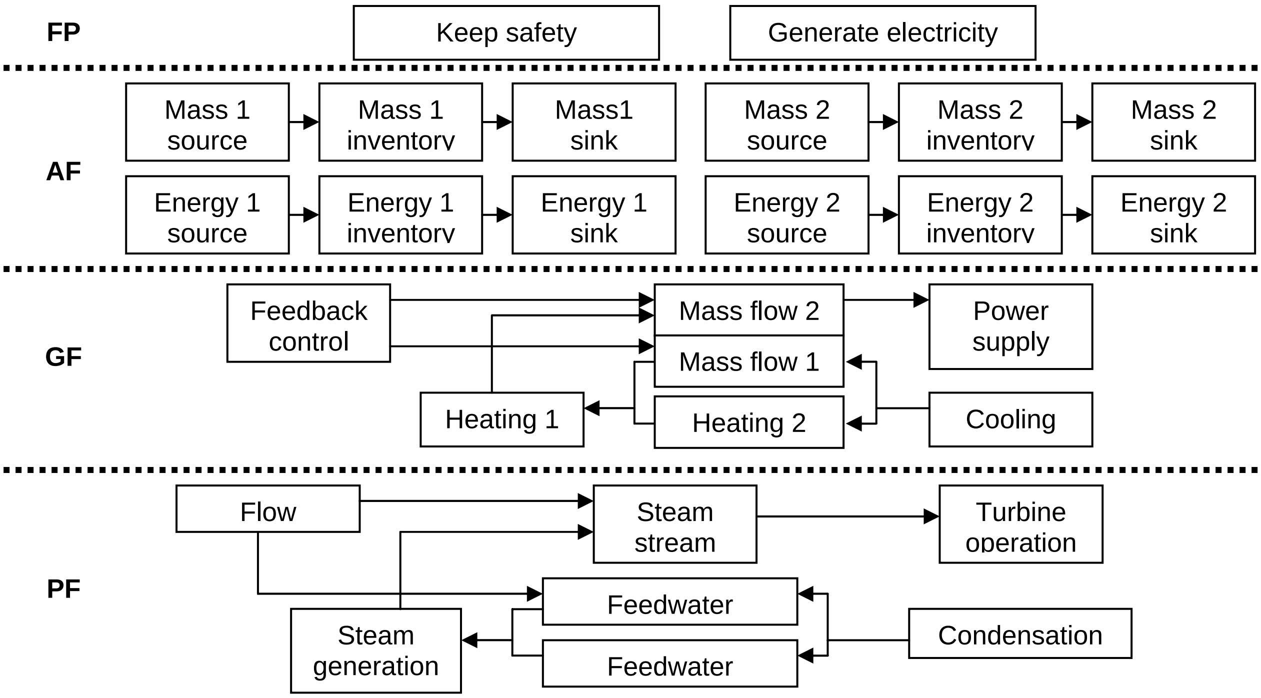


Figure 2. Relationships within an abstraction level of the work domain

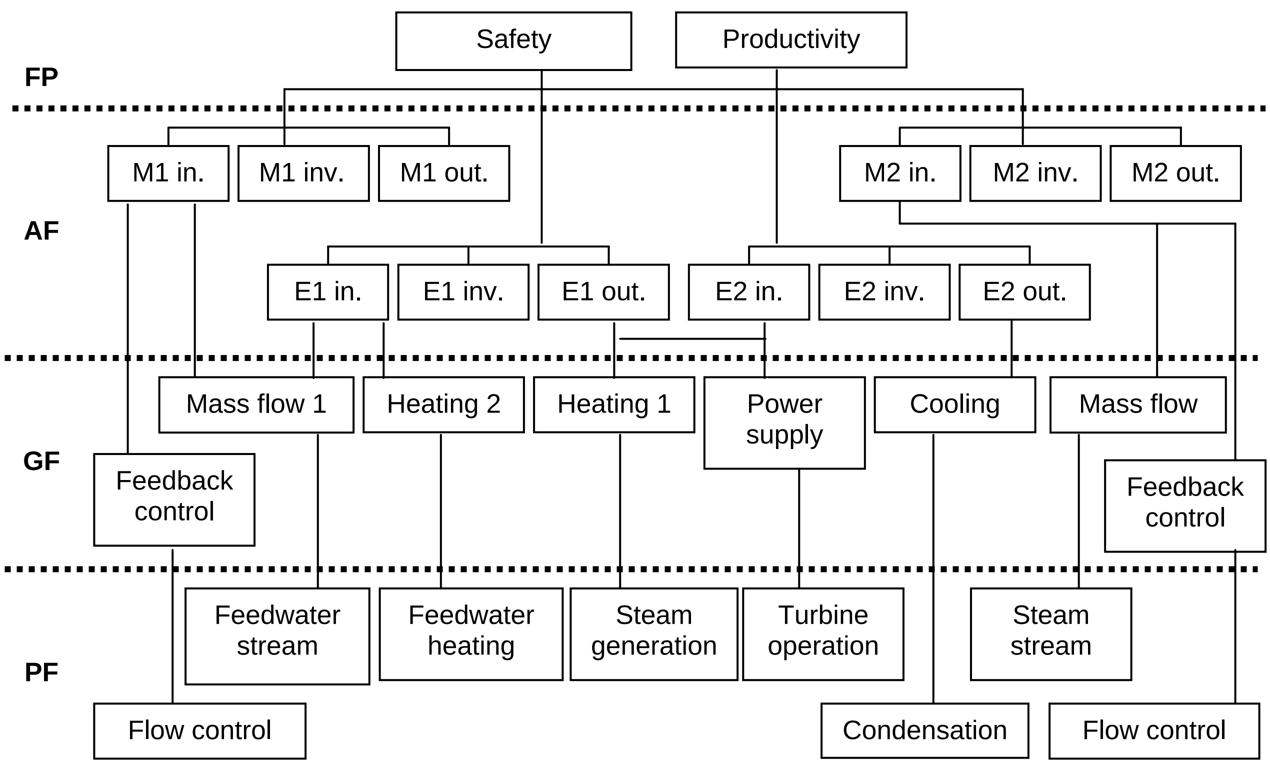


Figure 3. Goal-means relations between the abstraction levels of the work domain

Table 1. Five display types used in three experiments

	Abstraction levels				Information grouping in terms of goal-means relations
	FP	AF	GF	PF	
P	●			●	
PG	●		●	●	
PA	●	●		●	
PGA	●	●	●	●	
PGA2	●	●	●	●	●

case of the abnormal situations, the human operator should diagnose the fault causing the problems while maintaining the systems stable. In this study, the following faults can occur at the components of the work domain.

Isolation/ Dump valve: fail closed/ open
Control valve: too high/ low
Condensation pump: fail on/ off
Feedwater pump: too high/ low
Reactor output: increase/ decrease
Steam generator: tube rupture
Heater: too high/ low

These faults cause the following 14 abnormal situations of monitoring variables the human operator should observe continuously to identify the system state.

SG1 (Steam Generator 1) level increase/ decrease
SG2 level increase/ decrease
SG1 pressure increase/ decrease
SG2 pressure increasee/ decrease
HPT (High Pressure Turbine) increase/ decrease
CON1 (Condenser 1) increase/ decrease
CON2 increase/ decrease

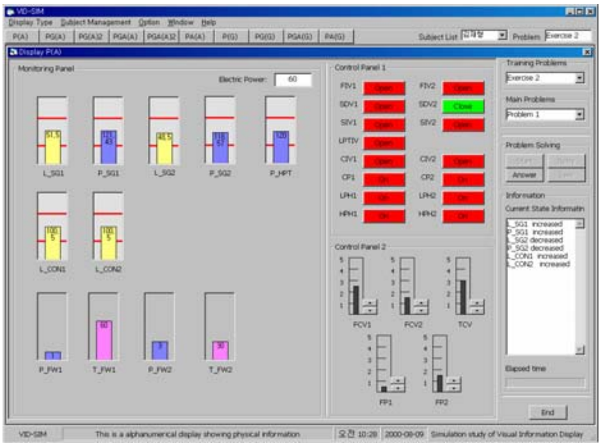
2.2. Display types

Three experiments evaluated five display types that are different in two aspects: the information contents in terms of AH, and information grouping in terms of goal-means relation. Table 1 shows the differences among the five displays P display represents the functional purposes and physical properties of the work domain in an alphanumerical format. Compared to P display, PG display additionally represents GF-level information in an alphanumerical format. Compared to P display, PA display represents AF-level information additionally in an alphanumerical format. The common property of PG and PA displays is that they include functionally abstracted information that was rarely presented in traditional displays of the 'single-sensor-single-indicator' type. PGA and PGA2 displays represent information at all the levels of AH. The difference between them is that information is grouped in terms of goal-means relations in PGA2 display. The grouping is accompanied by grouping in terms of the decomposition levels of the system, so that PGA2 display partially shows the physical structure of the work domain. It is important to note that we used only an alphanumerical format, so that the five displays differ only in their information content, not in sophisticated graphical effects. Figure 4 shows each display type..

3. The experiments

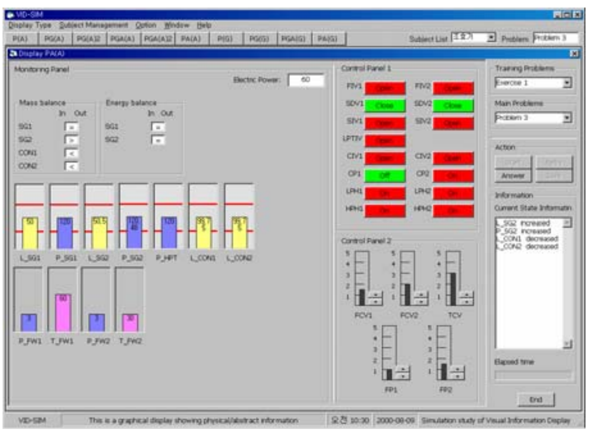
In order to investigate the effectiveness of providing high-level functional information in process control tasks, three experiments were conducted. Additionally, the effect of information grouping in terms of goal-means relations was also evaluated in the experiments. Table 2 provides a summary of three experiments.

The first experiment compared the three display types in the task of fault diagnosis: P, PG, and PA. The results showed that the PG display exhibited the best performance, the PA display next. This implies that GF-level and AF-level information are effective to enhance the operator’s diagnosis performance. In particular, it is suggested that information aiding for fault diagnosis should absolutely include information at the GF-level of a work domain. However, a question arose out of the fact that the PG display was superior to the PA display. The most plausible explanation was as follows. To diagnose faults in this experiment, the operator should integrate PF-level data to test the normality of components. GF-level provided information integrated from PF-level data because they are directly related in terms of goal-means relations. Being further abstracted than GF-level information, AF-level information did not have direct goal-means relations with PF-level data. Therefore, in the PA display, AF-level information could not be appropriately used because it was represented without GF-level information directly connected to it in terms of goal-means relations. The other was that the value of AF-level information could be more



(a) P display (experiment 1)

(b) PG display (experiment 1, 2, and 3)



(c) PA display (experiment 1)

(d) PGA display (experiment 2,3)

(e) PGA2 display (experiment 2)

(f) PGA2' display (experiment 3)

Figure 4. Display types used in the experiments

Table 2. Summary of three experiments

	Purposes	Tasks and Display types	Results
Experiment 1	- Effects of providing GF-level information added to physical information - Effects of providing AF-level information added to physical information	Fault diagnosis	PG >> P PA > P PG > PA
		P, PG, PA	
Experiment 2	- Effects of providing AF-level information, together with GF-level information added to physical information - Effects of information grouping in terms of goal-means relations	Fault diagnosis	PGA >= PG PGA2 >= PG PGA2 = PGA
		PG, PGA, PGA2	
Experiment 3	- Effects of providing AF-level information, together with GF-level information added to physical information - Effects of information grouping in terms of goal-means relations	Operation including fault compensation and diagnosis	PGA >> PG PGA2' >> PG PGA2' >> PGA
		PG, PGA, PGA2'	

appreciated in other task contexts than in fault diagnosis situations.

With this view in mind, the second experiment was conducted. This experiment compared three display types in the task of fault diagnosis: PG, PGA, and PGA2. The results found that any display group was not better than the others in almost measures. While the effects of AF-level information were not sufficiently strong, the participants using the information tended to show more stable operational performance. And the observation during the experiment suggested that the AF-level information in process control would be more useful in more cognitively complex task situations including monitoring and controlling of the system. Regarding the effect of information grouping, it might be thought that the effect was not significant because the PGA2 display did not show goal-means relations explicitly. These two points were considered in the third experiment.

The third experiment compared three display types under the complex tasks involving operation, fault diagnosis and compensation, which are the same as in the second experiment. But the PGA2 display of this experiment was somewhat revised to show more explicitly goal-means relations. However, this would make the integrated interpretation of the results of experiment 2 and 3 a little too hard. The experimental results showed that the AF-level information was additionally effective on a display that already has physical information and GF-level information. The effect was the most pronounced when the task situation was cognitively demanding such as the cases of complex diagnosis and compensating operation. Presentation of goal-means relationships by information grouping greatly increased the effectiveness AF-level information.

To summarize the three experimental results, providing functionally abstracted information improved the human operator’s performance in process control tasks. And the abstracted information could be used more effectively by explicitly presenting goal-means relations between higher-level and lower-level abstract information. The value of the abstracted information was dependent on task types and problem complexity.

Regarding the experimental results, one might argue that the advantage of a display over the others was simply due to the additional information. However, more information would simply not result in better performance unless it is additionally helpful. For instance, Yoon and Hammer [16] showed that additive information provision might actually degrade the diagnostic performance despite the ostensible utility. Therefore, it is reasonable to conclude that the display effectiveness in this experiment was dependent on the semantic property of the display. In this regard, as Vicente et al. [11] indicated, what is important is that the system's purpose-relevant functional information should be identified and represented on the displays in a systematic way.

Functionally abstracted information has rarely been included in a systematic way in the traditional design of information display. The goal-means work domain

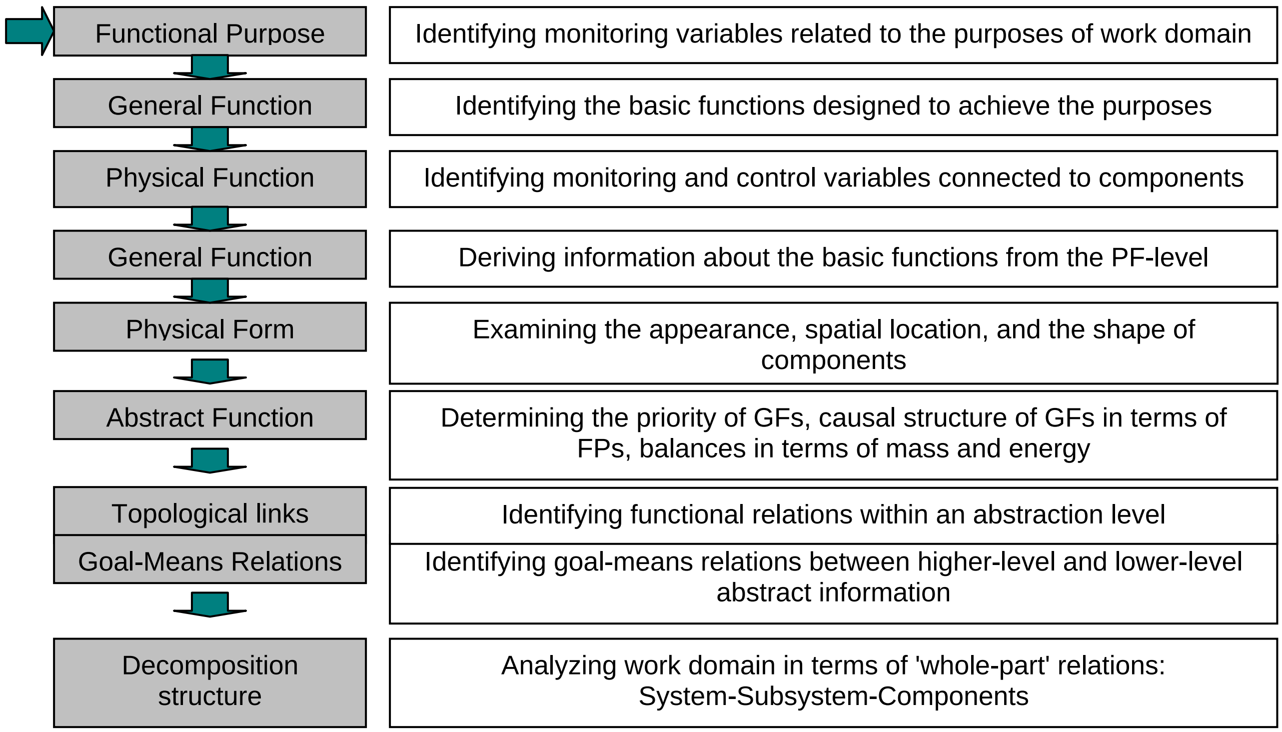


Figure 5. A procedure of goal-means work domain analysis using the AH concept

analysis along AH levels is a useful method to identify and organize multi-level functional information that can help the human operator to produce better and safer performance. The experimental results supported the EID concept that the AH with purpose-relevant functional information of work domain can be an important basis for designing information content and structure.

4. Goal-means work domain analysis using the AH

As proved in this study, goal-means work domain analysis based on the AH is useful to develop information contents for process control. However, it may be difficult for the designers to understand the AH concept and apply it practically. Thus, it is necessary to provide a way to use it systematically. Figure 5 shows a procedure of goal-means hierarchy analysis using five abstraction levels. This procedure is based on the authors' experience of applying the AH to various process control systems.

First, the purposes of work domain (FP) should be defined. It is important to note that the purposes do not include the aims the human operator attempts to achieve in performing their activities [13]. Namely, a focus should be given on identifying the inherent and unchangeable objectives for which the work domain is designed. In process control, monitoring variables connected to the purposes should be identified. Second, the designers should understand the purposes-relevant functions (GF) that are designed to achieve the functional purposes. These functions are directly connected to the functional purposes. Thus, it is rather easy to identify these functions. It should be noted that they do not have any connection with physical objects and processes [8]. Third, physical object-based functions (PF) for achieving GFs should be defined. The difference between GF and PF is that PF has a connection with physical components. At this step, monitoring and control variables connected to components should be identified. Fourth, information related to GFs should be derived from the variables at PF-level. Fifth, real object (P) selected for accomplishing physical functions should be examined. Information about appearances, color, shape of an object and spatial location between objects is concerned with this level. Sixth, basic principles and priorities governing purpose-relevant functions (AF) should be identified taking consideration of FPs. In process control, mass and energy balances in terms of causal relations are typical properties at this level. Seventh, topological links within an abstraction level and goal-means relations between higher and lower abstraction levels should be determined. Finally, physical structure of work domain in terms of 'whole-part' relations should be analyzed.

However, the designers do not have to make a work domain analysis necessarily with five abstraction levels. What is important is that the designers have a mind to identify all kinds of information on work domain functions affecting the possibilities of the operator's activity in terms of goal-means relations, with the purposes at the top level and the physical objects at the bottom level. And the designers should always keep in mind that 'why-what-how' and 'many-to-many' relations characterizing goal-means hierarchy. [8, 13]

5. Concluding remarks

In this paper, three experimental studies were reported that investigated the effects of providing functionally abstracted information in process control tasks in an analytical way. The experimental results found that presenting functionally abstracted information enhanced the operator's performance in process control tasks such as fault diagnosis and compensation. Additionally, when the information was grouped in terms of goal-means relations, the operator could use the information more effectively. The results supported the claim of the EID (Ecological Interface Design) concept that a multilevel hierarchy with goal-relevant functional information of the work domain should be a basis for designing information content and structure. The design process of displays in this study and the experimental results also confirmed that using the AH (Abstraction Hierarchy) as the basis for knowledge representation is a viable way to provide the operator with the system's purpose-relevant information in a structured way.

The following conclusions can be drawn from the results. The first is that display designers should identify and represent information at all the levels of AH. The second is that goal-means relations between higher-level and lower-level abstract information should be explicitly presented in order to support functional integration. The third is that all the levels of AH should be presented with a format accommodating information integration along structural decomposition within an abstraction level.

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5. References

[1] Bennett, K.B. and Flach, J.M. (1992), "Graphical displays: implications for divided attention, focused attention, and problem solving", *Human Factors*, Vol. 34(5), pp. 513-533.

[2] Bennett, K.B., Nagy, A.L., and Flach, J.M., "Visual displays", in Salvendy, G. (Eds.), *Handbook of Human Factors and Ergonomics* (pp. 659-696), John Wiley, 1997.

[3] Bisantz, A.M. and Vicente, K.J., "Making the abstraction hierarchy concrete", *Int. J. Human-Computer Studies*, vol. 40, pp. 83-117, 1994.

[4] Burns, C.M., "Navigation strategies with ecological displays", *Int. J. Human-Computer Studies*, vol. 52, pp. 111-129, 2000.

[5] Effken, J.A., Kim, N-G., and Shaw, R.E., "Making the constraints visible: testing the ecological approach to interface design", *Ergonomics*, vol. 40, pp. 1-27, 1997.

[6] Flach, J.M., Monta, K., Tanabe, F., Vicente, K.J., and Rasmussen, J., "An ecological approach to interface design", *Proceedings of the Human Factors and Ergonomics Society 42nd Annual Meeting*, pp. 295-298, 1998.

[7] Hansen, J.P. (1995), "Representation of system invariants by optical invariants in configural displays for process control", in Flach, J., Hancock, P., Caird, J., and Vicente, K.J. (Eds.) (1995), *Local Applications of the Ecological Approach to Human-Machine Systems*, (pp. 208-233), Lawrence Erlbaum Associates, New Jersey.

[8] Rasmussen, J., *Information Processing and Human-Machine Interaction: An Approach to Cognitive Engineering*, North Holland, New York, 1986.

[9] Vicente, K.J., "Ecological interface design as an analytical evaluation tool", in *Advances in Human Factors Research on Man/Computer Interactions: Nuclear and Beyond*, June 10-14, Nashville, Tennessee, USA., 1990.

[10] Vicente, K.J. and Rasmussen, J., "Ecological interface design: theoretical foundations", *IEEE Trans. Systems, Man, and Cybernetics*, vol. 22(4), pp. 589-606, 1992.

[11] Vicente, K.J., Christoffersen, K., and Pereklita, A., "Supporting operator problem solving through ecological interface design", *IEEE Trans. Systems, Man, and Cybernetics*, vol. 25(4), pp. 529-545, 1995.

[12] Vicente, K.J., "Operator adaptation in process control: a three-year research program", *Control Engineering Practice*, vol. 5(3), pp. 407-416, 1997.

[13] Vicente, K.J., *Cognitive Work Analysis*, Lawrence Erbaum Associates, New Jersey, 1999.

[14] Watanabe, O., Takura, K., Fujita, Y., and Hayashi, Y., "Evaluation of ecological interface design", *Proceedings of the Sixth International Conference on Human-Computer Interaction*, July 9-14, Tokyo, Japan, 1995.

[15] Xu, W., Dainoff, M.J., and Mark, L.S., "Facilitate complex search tasks in hypertext by externalizing functional properties of a work domain", *Int. J. Human-Computer Interaction*, vol. 11(3), pp. 201-229, 1999.

[16] Yoon, W.C. and Hammer, J.M., "Deep-reasoning fault diagnosis: an aid and a model", *IEEE Trans. Systems, Man, and Cybernetics*, vol. 18(4), pp. 659-676, 1988