Proceedings of the Korean Nuclear Society Spring Meeting

Pohang, Korea, May 1999

A Methodology for Quantitative Evaluation of Dynamic Aspects of NPP Fault Diagnostic Systems

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Abstract

Evaluation is an important issue for expert systems, such as fault diagnostic systems. The purposes of this study are 1) to define the evaluation criteria of dynamic aspects in fault diagnostic systems of nuclear power plants (NPPs) and 2) to propose the quantification methodology of the criteria. The hierarchy of the evaluation criteria is described in detail. Quantification methods are effectively proposed with simple numerical expressions. Our classification and quantification will make it possible to evaluate dynamic aspects of fault diagnostic systems systematically and objectively.

1. Introduction

Expert systems have been successfully introduced to industrial, medical, scientific, and other fields over last 20 years. In nuclear industry, a variety of expert systems, including fault diagnostic systems (FDS), have already been implemented and more systems are expected to be developed. A variety of fault diagnostic expert systems have also been developed for NPP: loose parts detection, turbine-generator diagnostics, noise analysis, signal validation, and alarm diagnosis and filtering.

Evaluation of one's research includes making observations of all aspects of it, perhaps making some judgments of merit based on those observations, and reporting both to the research community. In FDS, evaluation should not be limited to observing and judging only how our systems perform. It is a vital part of all the stages of research that lead up to performance evaluation and follow it [1]. Dynamic aspect is concerned with the way FDS responds to the input during normal operation. What a FDS does and how it does are involved in the dynamic aspects. Static aspects contain the knowledge base of FDS, hardware, software, and so on.

There are two objectives for FDS evaluation. The first is to integrate evaluation into development process. Evaluation is needed as feedback at each step. In fact, due to the iterative and incremental nature, it is of primary importance that evaluation is performed after each step so that the work done is assessed and wrong construction steps are corrected [2]. Moreover, evaluation is an implicit activity in each development step of the blueprint; it is required to deal with the various types of judgements and decisions, by users and developers alike, that are inherent in the development process. The second is to compare the alternatives which are prepared for being applied. When different FDS's are proposed to be implemented for the same problem, it is necessary to have appropriate criteria to compare and rank them.

In this study, we define the evaluation criteria of NPP FDS's dynamic aspect hierarchically and propose their quantification using simple numerical expressions.

II. Backgrounds

II.1. Fault Diagnostic Systems in NPP

FDS is a kind of operator support system which is implemented to reduce the human error which may cause NPP accidents and to increase NPP efficiency. FDS is a new type of instrument through which an operator directly obtains not only the values of plant parameters but also the meaning of those parameters and, when appropriate, suggestions on corrective action. Areas of application range from turbine-generator diagnostics to alarm diagnosis. Several applications in NPP are as follows [3]:

· *Turbine-generator diagnostics* Turbine-generator diagnostics constitute an excellent opportunity for the application of expert systems. The rationale for this particular application is as follows: First, excepting instances of outright error such as failure to supply lubricating oil, turbine-generators rarely fail in a precipitous manner. Second, when they do occur, the failures tend to be catastrophic. The resulting economic damage entails not only the loss of the turbine-generators but also the cost of replacement electricity. Third, generator failures occur so infrequently that plant personnel may lack the expertise to recognize the early warning signals. The expert systems that are now available for turbine-generator diagnostics include both interactive and real time approaches.

· *Noise analysis* The basic premise of noise analysis is that each possible malfunction in a given piece of equipment will manifest itself through a unique perturbation of the signal pattern obtained from the equipment's associated sensors. Noise analysis is a form of pattern recognition and it is normally associated with sophisticated numerical methods such as the fast Fourier transform.

- *Signal validation* Signal validation is the process by which estimates of the true value of a given parameter are obtained by comparing readings from several disparate sensors and, possibly, from analytic calculations with one another. Like noise analysis, signal validation is commonly associated with analytic programming.
- *Alarm diagnosis and filtering* Alarm diagnosis and filtering is area that is of particular concern to the nuclear industry. Reactor control rooms may contain as many as a thousand individual alarm modules. Often these are assembled as large arrays of annunciators mounted above the various control room consoles. When a malfunction occurs, the operator must determine its cause by observing the identity and sequence of the alarms received. Each alarm is indicative of a particular event. The operator's function is to recognize the pattern of these events and thereby identify the root cause of the problem at hand. This task is never easy and, in the event of a major malfunction, the possibility of information overload is very real. Hence, methods for suppressing irrelevant alarms and those for the automatic identification of root cause are actively being researched. In addition, such systems must be accurate because they are in direct competition with reactor operators who will trust their judgment rather than that of an automated processor. These include status and sequence monitoring and information prioritization.

II.2. A Review of Approaches to Expert System Evaluation

The evaluation methods of expert system that have been studied for last decade can be divided into three categories: knowledge-base oriented approach, empirical approach, and subjective approach [2],[4]. Knowledge-base oriented approach, often called knowledge base verification, has generally been directed at consistency and completeness issues [5]. This approach can be constructed to be the demonstration of logical correctness of the rule set, wherein checks are performed for superfluous, incorrect, or missing rules, which would eventually impair system performance. Empirical approach is for testing the predictive accuracy of the knowledge base against the judgement accuracy of experts and for checking the improvement of operator's performance when using the expert system. Subjective approach is such as using questionnaires to assess users' opinions of the system's strength and weakness.

Except knowledge-base oriented approach, if without any direction, evaluation would be easily performed incompletely. Therefore, defining the evaluation criteria is needed for the objective and complete evaluation. For this reason, we propose, in this work, the detailed evaluation criteria of dynamic aspects of NPP FDS and the simple numerical expressions that can quantify those criteria.

III. Evaluation Criteria and Quantification of Dynamic Aspects of NPP FDS

III.1. Evaluation Criteria of Dynamic Aspect of NPP FDS

Dynamic aspects are concerned with the way FDS responds to the input during normal operation. Dynamic aspect includes two subjects, namely: *content* of diagnostic information and FDS's *behavior*. Figure 1 shows the hierarchy of the evaluation criteria of NPP FDS's dynamic aspect.

1. Content of Diagnostic Information

Content is related with what FDS provides. "For a given problem, if FDS provides correct answers", or "For a given fault, if FDS can generate the diagnostic results" corresponds to *content*. *Content* can be evaluated in view of coverage and accuracy.

A. *Coverage*

Coverage represents the set of domain concepts and the types of problems a FDS can deal with [2]. It can be further decomposed into three components.

· *Extent* - *Extent* represents the set of entities, properties, and relations a FDS deal with. *Extent* is related with the type of fault and the target system that a FDS deals with. *Extent* is formerly defined before evaluating content.

· *Detail* - *Detail* represents the level of detail of the representation of extent. For example, the fact that pump operation is described through qualitative or quantitative equation using a certain extent of physical dimension, that is, temperature, pressure, and flow rate, concerns *detail*.

· *Depth* - *Depth* represents the level of information a FDS offers. For example, the fact that a FDS notifies operators to be an abnormal situation, diagnoses the fault after analyzing the obtained values of plant parameters, suggests the corrective action, and informs operators how the situation progresses, concerns *depth*.

B. *Accuracy*

Accuracy means the ability of a FDS to generate correct solutions for a given problem within its actual coverage. For example, the fact that for the symptom of steam line break, a FDS provides LOCA as the result of diagnosis, concerns *accuracy*.

2. Behavior

Behavior represents how a FDS provides operators with information and behaves during operation, i.e., the way and form its problem solving activity is actually carried out and display to operators. *Behavior* is categorized into six aspects as follows.

A. *Robustness*

Robustness represents the ability of a FDS to behave in an acceptable and consistent way outside or near of its coverage. For example, for a FDS diagnosing turbine generator faults, when secondary loop pressure drops for the fault of other facilities, the fact that the FDS provides the result of "Turbine generator is normally operating. Pressure drop may be caused by the fault of another facility." concerns *robustness*.

B. *Understandability*

Understandability means the ability of a FDS to behave in a way operators understand its operation easily. How much coincident the operator's internal model of NPP is with the FDS's representation is related with *understandability*.

C. *Transparency*

Transparency represents the ability of a FDS to provide the information operators want to know so as to have a deeper understanding of situation, for example, its inference or internal process and values of plant parameters. Providing help menu is also involved in *transparency*.

D. *Effectiveness*

Effectiveness represents the ability of a FDS to provide effective results. The number of wrong hypotheses resulting from diagnosing the symptoms of plant before arriving right solutions concerns *effectiveness*.

E. *Communicativeness*

Communicativeness represents the ability of a FDS to provide the effective and easy-to-use man-machine communication. The use of the language which is easy to understand, and the I/O and environmental equipment which is familiar to operators and easy to use, concern *communicativeness*.

F. *Timeliness*

Timeliness represents the ability of a FDS to provide appropriately the diagnosis results at the time needed. For example, the fact that the diagnosis results which are provided after the due time when operators must take response actions to faults is meaningless concerns *timeliness*.

III.2 Quantification of Evaluation Criteria

In this study, the quantified values of evaluation criteria are presented as simple numerical expressions as shown in Table 1. The quantification of the lowest criteria of hierarchy is proposed, for the quantification of higher criteria can be generally provided as a priority that is a degree of importance of each branch in hierarchy. The method that is widely employed to obtain the priority is analytic hierarchy process (AHP)[6]. We normalize the quantified values from 0 to 1 so as to make further applications convenient.

In order to quantify *extent*, the target system and faults a FDS is expected to diagnose are determined at first. The FDS is examined next. *Extent* is evaluated by the ratio of 'the extent of the systems or faults a FDS can diagnose' to 'the extent of the systems or faults a FDS is expected to diagnose'.

Detail is quantified by using Utility Function I shown in Figure 2. After the scale or dimension minimally required is put to 0 and the scale or dimension that can be maximally achieved is put to 1, the level of detail a FDS represents is valued according to Utility Function I.

For *depth*, if a certain FDS that provides the occurrence of fault, diagnosis results, operator's corrective action, and the expected direction of event progress is designated to 1, an evaluated FDS is relatively compared by using Utility Function I.

Accuracy can be divided into two aspects: the accuracy of knowledge base and the accuracy of inference engine. Accuracy is quantified by following expression.

$$Accuracy = P(A\_K) \times P(A\_I | A\_K) = P(A\_I \cap A\_K)$$

A_K and A_I mean the cases that the knowledge base and the inference engine are accurate, respectively. The probability that the knowledge base is accurate is expressed as follow:

$$P(A\_K) = \frac{the\ number\ of\ sound\ rules}{the\ number\ of\ total\ rules}$$

The sound rules are checked by the knowledge base verification that is a process to find the logical anomalies of knowledge base [5]. The probability that the inference engine is accurate can be expressed in a similar way.

Robustness is quantified as 'the number of a FDS to provide some appropriate warnings, or explanations' to 'the number of cases out of extent', as defined in previous part.

Understandability is evaluated through subjective method using questionnaires to assess operator's opinion about matching between FDS's internal representations and the internal models of the operator. Then, it is normalized with the values from 0 to 1.

For *transparency*, supposing that a certain FDS that can provide the inference or internal process, alarm data, the states of instruments, the values of plant parameters, and help menu is 1, the extent which the target FDS can provide additional information to is relatively evaluated.

Generally, the diagnostic results have their own probabilities or levels of confidence according to inference process. Therefore, *effectiveness* is evaluated as follows:

$$Effectiveness = \frac{\begin{array}{c} \textit{sum of the probabilities or levels of confidence of right hypotheses} \\ \textit{provided by a FDS} \end{array}}{\begin{array}{c} \textit{sum of the probabilities or levels of confidence of all hypotheses} \\ \textit{provided by a FDS} \end{array}}$$

A FDS whose human-machine communication interfaces are familiar with operators and of ease to use is considered as 1. Afterwards, by using Utility Function I, *communicativeness* is quantified.

Supposing that the time interval from fault occurrence to due time until which operator's action is essentially required is t_o, and the time interval from fault occurrence to time when the right diagnostic results are provided is t_d, as shown in Figure 4, *timeliness* is evaluated as follows:

$$Timeliness = \frac{t_d}{t_o}$$

Timeliness follows Utility Function II shown in Figure 3 since larger value is more acceptable.

IV. Conclusion

The main contributions of this study are the analytic classification of evaluation criteria of NPP FDS's dynamic aspects and their quantification. The evaluation criteria are defined hierarchically in this work. Then, the quantification, through simple numerical expression using Utility Functions and probability, has been performed for the lowest criteria. Our study is expected to make the FDS evaluation more systematic and objective. Furthermore, the experience gained from FDS evaluation will help us formulate guidelines for evaluation of other operator support systems or main control room.

V. References

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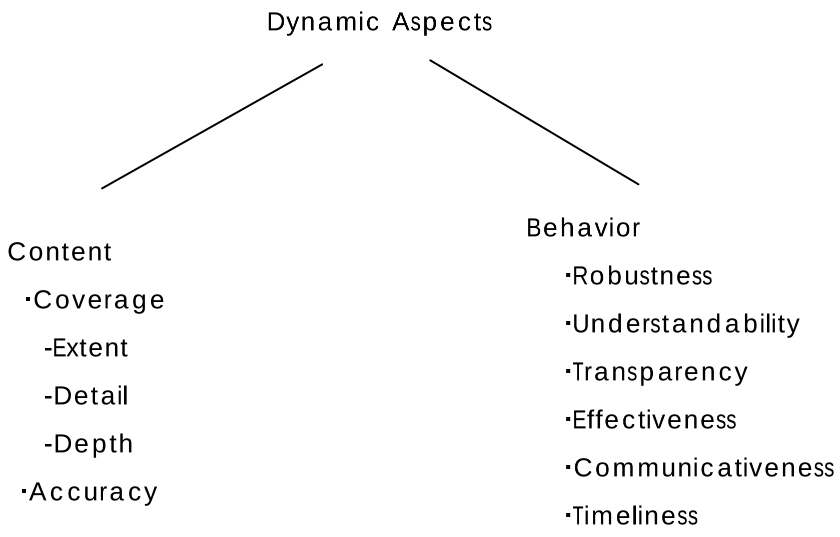

Figure 1 The hierarchy of evaluation criteria

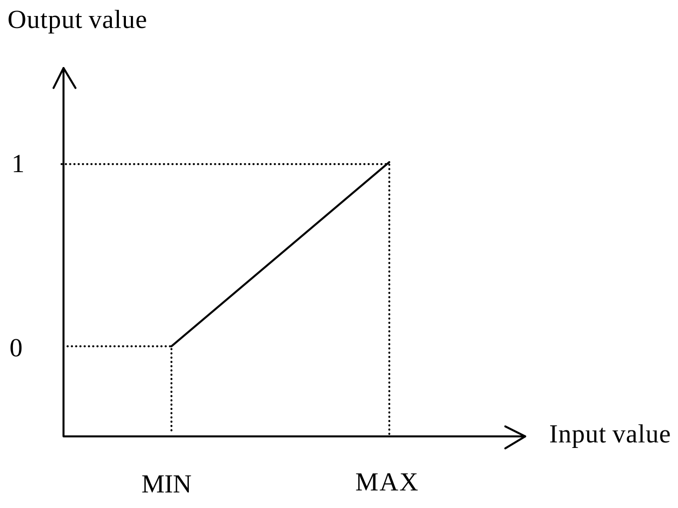

Figure 2 Utility Function I

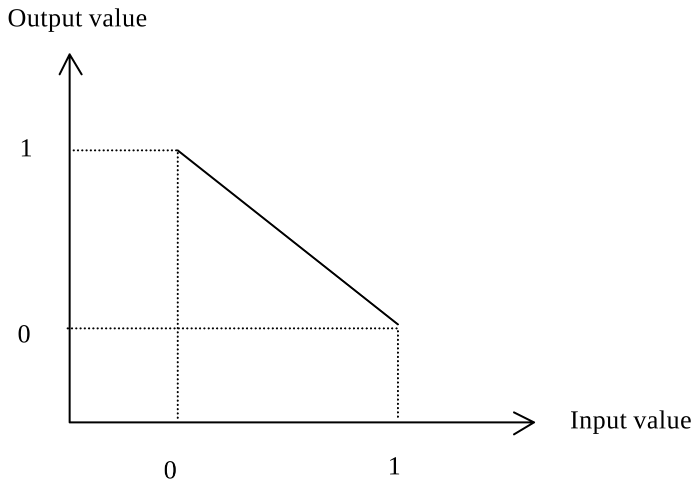

Figure 3 Utility Function II

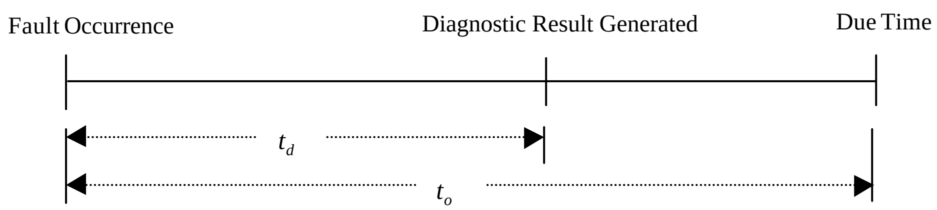

Figure 4 Time interval t_o , t_d

Table 1 The quantification of evaluation criteria

Content	Coverage	Extent	$\dfrac{\textit{the extent of the systems or faults a FDS is able to diagnose}}{\textit{the extent of the systems or faults a FDS is expected to diagnose}}$
		Detail	*the level of detail of the representation of extent*
		Depth	*the level of information a FDS offers*
	Accuracy		$P(A\_K)\times P(A\_I \mid A\_K)=P(A\_I \cap A\_K)$
Behavior	Robustness		$\dfrac{\textit{the number of a FDS to provide some appropriate warnings, or explanations}}{\textit{the number of cases out of extent}}$
	Understanda-bility		*How much coincident the operator' s internal model of NPP is with the FDS' s representation*
	Transparency		*the ability of a FDS to the inference or internal process, alarm data, the states of instruments, the values of plant parameters, and help menu*
	Effectiveness		$\dfrac{\textit{sum of the probabilies or levels of confidence of right hypotheses provided by a FDS}}{\textit{sum of the probabilies or levels of confidence of all hypotheses provided by a FDS}}$
	Communicat-iveness		*the ability of a FDS to provide the effective and easy-to-use man-machine communication*
	Timeliness		$\dfrac{t_d}{t_o}$