Preliminary Investigation of Time Remaining Display on the Computer-based Emergency Operating Procedure

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Abstract. One of the important things in the mitigation of accidents in nuclear power plant accidents is time management. The accidents should be resolved as soon as possible in order to prevent the core melting and the release of radioactive material to the environment. In this case, operators should follow the emergency operating procedure related with the accident, in step by step order and in allowable time. Nowadays, the advanced main control rooms are equipped with computer-based procedures (CBPs) which make it easier for operators to do their tasks of monitoring and controlling the reactor. However, most of the CBPs do not include the time remaining display feature which informs operators of time available for them to execute procedure steps and warns them if the they reach the time limit. Furthermore, the feature will increase the awareness of operators about their current situation in the procedure. This paper investigates this issue. The simplified of emergency operating procedure (EOP) of steam generator tube rupture (SGTR) accident of PWR plant is applied. In addition, the sequence of actions on each step of the procedure is modelled using multilevel flow modelling (MFM) and influenced propagation rule. The prediction of action time on each step is acquired based on similar case accidents and the Support Vector Regression. The derived time will be processed and then displayed on a CBP user interface.

Keywords: computer-based procedure, time remaining, multilevel flow modelling, support vector regression, PWR type reactor, steam generator tube rupture

1. Introduction
In an emergency situation, operators receive a lot of information related with the plant condition, such as alarm and warning messages. In this condition, they have to investigate the initiating event based on the alarm signals and then mitigate the accident in order to prevent the core melting and the release of radioactive material to the environment. However, they only have short time to do the actions. In some cases, the overload information and cognitive workload will make them confused and may cause wrong decision and actions. Therefore, the proper investigation of initiating event is important in order to reduce the worst case.

The response of operators in mitigating the accidents can be divided into three phases: initiating event; diagnose the event; and perform safety-related operator action. Figure 1 shows the phases [1]. In the initiating event, which is indicated by T_0, operators investigate the initiating event based on the alarms and other information. Then, in the period time between T_s (even alarm) and T_d (end of event...
diagnose), operators start to diagnose the event and find the adequate operating procedure to mitigate the accident. Finally, safety related actions are conducted in time interval $T_i$ (operator first significant response triggered by the procedure step), $T_c$ (first significant action initiation) an $T_e$ (action completion) following the operating procedure and accident management.

![Figure 1. Response time of accident management[1]](image)

This paper discusses the third phase of figure 1, which is the time available for operators to take the action on each step of emergency operating procedure. Information about the time available for operators to take actions on each step is very important. However, the information should be properly presented on the computer-based procedure (CBP) and does not cause more cognitive workload to the operators. In this paper, the sequence and impact of operators’ action on each procedure step are modeled using Multilevel Flow Modeling (MFM). MFM [2] [3] is a methodology to model the industrial plants in term of objectives, function and structures which represent the physical structure, and also relation among them. MFM implements influence propagation rule and cause-effect relations, which are useful for determining the flow of the counter actions. In addition, the operators’ actions are represented by a control function in MFM model.

The data for estimating the time available for operators to take the action on each procedure step is taken from historical data of time needed to execute counter actions from similar accidents. A support vector regression method is used to predict the time. Then the time is presented on a CBP user interface as remaining time information. Operators should do an action before the time is exceeded, otherwise they will get the warning message. In addition, the presentation of the information will consider the emergency situation and human factor engineering. This paper presents the result of a preliminary investigation to implement a necessary feature proposed in [4].

2. Safety of Nuclear Power Plant
Safety is the most important thing in a nuclear power plant. A nuclear power plant, including main control rooms have been developed to increase the safety and minimize the consequences of accidents. The main objective of safety measure of a nuclear power plant is to prevent the spreading the accident by automatic shutdown and preventing the release of radioactive to the environment by cooling the reactor and the containment. In addition, based on the literature [5] there are four main objectives of accident management: 1) Prevention of the accident from leading to core damage; 2) Core damage termination; 3) Maintaining the containment integrity; and 4) minimizing the release of radioactive on-site and off-site. In order to achieve the objectives, the mechanism of reactor accidents, including controlling safety and non-safety related system should be understood by operators.

When an anomaly happens in the reactor, which is indicated by changing parameter levels shown on the visual display unit, the reactor safety system will trip the reactor automatically to prevent the spreading the accidents. During this time, operators should diagnose the cause of accidents and try to find the suitable counter actions and emergency operating procedure to mitigate the accident.

In the main control rooms of nuclear power plant, the action managements of operators, especially in mitigating accidents are related with the control and time. Control means that they have to take action by controlling or changing the parameter levels of components following the operating procedure and accident management. On the other hand, the term “time” means that their actions are limited by time. They have to take the action during the time provided, otherwise the worst condition
will happen. Therefore, the dependency between operators performance and time to execute the control actions should be considered in order to get an adequate performance of control system [6].

3. Computer Based Procedure

Most of advanced and modern of nuclear power plants are equipped with computerized procedures (CPs). According to EPRI 1015313 [7] there are three types of computerized procedures: 1) Electronic procedures (EP), which is the duplicate of PBPs which are displayed on the VDU in text or graphical format; 2) Computer-based procedures (CBPs) 3) CBPs with procedure-based automation (PBA), which have the capability to perform multiple procedure steps and take the control actions as mentioned in the procedure steps.

This paper only discusses the CBP. A CBP is not just the electronic version of paper based procedure (PBP) but provides some features which can overcome the drawbacks of PBPs, for example, the ease of finding, retrieving and displaying information related with a procedure step; linking with other procedures easily; and keeping track of operator’s position on the procedure. In addition, a CBP is also intended to increase the usability of emergency operating procedure (EOP); to minimize operators workload in while finding the correct procedure and controlling the reactor in emergency condition; and to reduce the time needed for making decision and taking the actions to mitigate the accident.

CBPs are already used in several nuclear power plants around the world such as COMPRO in Switzerland, N4 Computerized Procedure System in France, Plant safety monitoring and assessment system (PLASMA) in Hungary, Computerized Procedure System in Korea and On-Line Procedure System (OLPS) in Taiwan [7]. Because the purposes of the development and implementation of CBPs are to reduce operators workload and increase safety, the design should be based on human factor engineering.

4. Desirable Features

As mentioned in section 3 that CBPs offer some benefits compare with PBPs. However, some problems will be faced by operators when using the CBPs. A literature [4] proposed the desirable features that will be added on the CBP to overcome the problems. This section discusses the CBP problems and the proposed features.

Firstly, reading the information on the visual display unit (VDU) is not as easy as on papers because of the limited information displayed on the VDU [8] that can cause operators lose a sense of their current position in completing the procedure steps. In addition, reading on VDU is slower and more fatiguing which can reduce human reliability and impair operator response [9]. The functional information feature is proposed to overcome these problems. The feature provides information about components influenced and future plant behaviour caused by the actions of operators on each procedure step. This information will help operators to understand the procedure step and make it easier for them to make decision and take action. The investigation of this feature has been conducted by first author.

Secondly, operators tend to spend much time on a specific step of the procedure before making decision and taking action related with the plant condition. This behaviour will inhibit the mitigation process of the plant to the safe operation condition. It can be solved by adding the remaining time display feature on the CBP which gives information and warning to operators to take a specific before reaching the provided time. This paper will discuss the preliminary investigation of techniques to generate and display the time remaining display.

Finally, some operators do not aware of the importance of all steps in the procedure or because of they do not understand the purpose of the procedure steps, then they try to skip the steps. This action is kind of commission error which may cause other impacts on the plant condition. The dynamic operation permission feature which based on work developed by [10] [11] is included on the CBP and
used to reduce commission error by operators. Warning messages will be displayed if operators skip or do not follow one or more steps.

5. MFM as a Base Technique to Model a Plant for Generating Information

5.1. Overview of MFM

Multilevel flow modelling (MFM) was developed by Lind [2] to represent the complex system in graphical format and in terms of functions, structures and objectives and also interconnected relation among them. MFM is one of the functional modelling methods, which represents the plant in several levels of abstraction. The MFM models a system in means (tools) to achieve the ends (objectives) and part-whole expression (description of aggregation in different levels). MFM has been widely used to model the large and complex systems such as nuclear power plant, chemical plant and other industrial processes. In addition, MFM is also applied for operator support system [12] [13] and dynamic operation permission [10]; alarm and root cause analysis [14]; and supervisory control [15].

As mentioned before that MFM is a representation of system in graphical format, some graphical symbols are needed. Figure 2 shows the MFM symbols including functions and relations. The function primitives (source, transport, storage, etc) are connected each other (interconnected) using influence relations to build mass flow or energy flow structure. The function primitives are used to represent physical systems. For example, a tank can be represented as a storage function and a pump as a transport function in an MFM model.

![Figure 2. MFM symbols](image)

Figure 3 shows the example of MFM model of a PWR plant. It can be seen that there are some mass flow (mfs) and energy flow structures (efs). The primary system is represented by mfs1 which contains sto3 (reactor vessel), sto10 (pressurizer), bal7 (steam generator) and tra5 (reactor coolant pump). On the other hand, the secondary system (mfs2) includes sto4 (steam generator), tra16 (main steam isolation valve), sto6 (turbine) and sto7 (condenser). The MFM model also include a model of safety systems such as efs9 (ECCS), mfs4 (PORV). In this model, the control rod is represented by mfs3 to control the fission reaction to produce heat in reactor vessel. The heat generated in reactor vessel (efs1) is then delivered from primary to secondary system in efs7 through steam generator. In efs6 (turbine) the heat energy is converted to mechanical energy. Subsequently, the mechanical energy is converted by generator in efs8 to produce the electricity which is delivered to the grid. In this case, the objective obj1 to produce the electricity is achieved.
5.2. MFM for generating functional information

The mitigation process of accident depends on controls and time. The controls are conducted by operators following the EOP. The controls and their impacts to the plant can be modelled and investigated using MFM. In this case, operators’ actions are represented by the control structure in MFM model as shown in figure 4. The control structure consists of control function primitive (pc01) and parameter to be observed (obj1). As can be seen in figure 4, the control function pc01 is actuated to control the transport function tra1 in mfs1 if the level of storage function sto1 is met the requirement in the operating procedure or accident management. For example, the low level in sto1 will actuate the control function pc01 to start the transport function tra1 to flow, which is the objective of the control action (obj2).
In addition, MFM is based on cause-effect relation. It means that the action which change the state of a function primitive will impact the connected function primitive. The impact then will propagate to other function primitives, function structure, objective and whole system. This is the concept of influence propagation rule. Table 1 shows the definition of states in MFM. The definition will be used to investigate the cause-effect and influence propagation in MFM model.

Table 1. Definition states of MFM symbols

| Symbols | States |
|---------|--------|
| source  | normal, high output flow potential, low output flow potential, no output flow potential |
| sink    | normal, high input flow, low input flow, no input flow |
| transport | normal, high flow, low flow, no flow |
| storage | normal, high volume, low volume, no volume |
| barrier | normal, leak |
| balance | normal, unbalance (fill or leak) |
| threat  | exist (high), exist (low), non-exist |
| objective | true (high), true (low), false |

The control structure, the definition of state and the influence propagation rule together can be used to investigate the components influenced and future plant behaviour because of the operator actions on procedure steps. These information is useful for operators and can be used as consideration before taking the action on each procedure step. The study of investigating the techniques to derive additional information (components influenced and future plant behaviour) has been conducted by first author.

6. Time remaining display

Information of time available for operators to take the action is displayed on the CBP user interface. The time is started when operators select the procedure steps. The time is counting down. When the counting reach the limit, warning message is given to the operators which order operators to take the actions. The information is presented by considering the emergency condition and human factor engineering in order to prevent the worst condition and reduce cognitive work load. In addition, the information is presented clearly and easy to watch. The time information is intended to increase the awareness of operators about the safety and conduct the proper action to mitigate the accident.

The process of deriving the remaining time is provided in figure 5. From the figure, it can be seen that when operators open the CBP user interface, it will initialize the MFM model subsystem and operating procedure subsystem. Furthermore, if the procedure step is selected, it will initiate the MFM model of the procedure step. From this point, the information about the components influenced and future plant behaviour is displayed on the functional information field of the CBP. The next step is, on selected procedure step, the system tries to find the time to take the action in the time list. Once it is found, the system starts to count the time and displayed on the CBP user interface as the time remaining display.

Figure 6 shows the proposed of CBP user interface with the time remaining display feature. If operators click on the procedure step, the time is started to count and displayed in the warning field on the CBP user interface. Operators should take actions during the available time, otherwise the warning message will be given to operators and order them to take the actions as soon as possible.
Figure 5. Process of time remaining display

![Diagram](image)

Figure 6. Proposed CBP user interface with time remaining display feature

**7. SVR as a Promising Technique for Time Remaining Display**

**7.1. Overview of SVR**

This section discusses the overview of support vector machine (SVM) and support vector regression (SVR) which will be used to predict the time provided for operators to take the actions on each procedure step. Support vector machine (SVM) was developed by Vapnik [16]. Initially was used for...
classification and then expanded to solve regression problems. Compared with other methods, SVM is relatively new and has better performance. SVM and SVR have been widely implemented for several purposes such as for forecasting [17], travel time prediction [18] and nuclear engineering [19][20]. SVM can be applied for linearly separable data and non-linearly separable data.

Figure 7. SVM for linearly separable data [21]

Figure 7 shows the example of SVM for linearly separable data. Given the dataset \{x_1,...,x_n\} and \(y_i \in \{1,-1\}\) is the class of data \(x_i\). In this case, data are classified into two classes (class 1 and class 2) that are separated by decision boundary. The boundary can be defined as follows:

\[ w^T x + b = 0 \]  

where \(w\) is the weight vector and \(b\) is the bias.

In figure 7a there are many decision boundaries but the better boundaries are unidentified. Therefore, the optimum decision boundary should be derived which can classify the data and has highest margin. As can be seen in figure 7b, the idea of support vector regression is to find the equation (1) with the highest margin \(m\) by using the following expression:

\[ m = \frac{2}{||w||} \]  

In addition, data that located on the boundary is called the support vector. The detailed explanation of the support vector regression is provided in literature [16]. Therefore, the linear SVR is

\[ y = \sum_{i=1}^{N} (\alpha_i - \alpha_i^*) \langle x_i, x \rangle + b \]  

For non-linear separable data, SVM implements kernel trick. The idea is the input which low dimensional space is taken and converted into a higher dimensional space. The SVR function for non-linear is shown in equation (4)

\[ y = \sum_{i=1}^{N} (\alpha_i - \alpha_i^*) \langle \varphi(x_i), \varphi(x) \rangle + b \]  

\[ y = \sum_{i=1}^{N} (\alpha_i - \alpha_i^*) K(x_i, x) + b \]  

with \(K(x_i, x)\) is the kernel function. For Gaussian Radial Basis Function the kernel function is

\[ K(x_i, x) = \exp(-\gamma ||x_i - x||^2) \]
\[ k(x_i, x_j) = \exp \left( -\frac{||x_i - x_j||^2}{2\sigma^2} \right) \] (6)

Based on the previous explanation, the SVM gives better classification approach for linear and non-linear separable data and optimum generalization bound for regression. Therefore, it can be used to predict the time required by operator to execute the procedure steps.

7.2. A technique of generating time remaining display based on SVR

Time taken by operators to take the action on each procedure step for similar case can be varied for different nuclear power plant. The data can be used in this paper for calculating the remaining time. Based on the data, the time available for operators to take the action on each procedure step is predicted using support vector regression.

This paper and future works will use steam generator tube ruptured (SGTR) accident of PWR accident as a case study. The consideration of choosing SGTR accident due to it is one of common accident in PWR plant. The accident is caused by the degradation of SG due to long time operation or chemical/mechanical thermal stress and pressure shock. The degradation will cause leak of cooling water from primary to secondary side and then to turbine and condenser.

There are many cases of SGTR accident in nuclear power plant in the world, for example in Mihama Unit 2 in Japan, Prairie Island NPP unit 1, and etc. The data of time to take the action on each step of emergency operating procedure of SGTR is collected and then used for predicting the time available for operators to take the action on the proposed CBP.

The prediction is made by using Support Vector Regression. The result of predicted time is saved in the time list which the format as follow:

“Step no “+ “Step description” + “time to take the action”

The flow of deriving the prediction time is shown in figure 8.

![Figure 8. Process of time prediction](image)

8. Conclusion

This paper discussed the preliminary investigation of technique to generate the information of time available for operators to the action on each procedure step. The method includes determining the accident sequence, components influenced and future plant behaviour using MFM. Moreover, the time
is predicted using support vector regression based on the data of time taken by operators to mitigate accidents following operating procedure of similar accident case. The information of the remaining time then properly displayed on the CBP user interface.

Future work is implementing the support vector regression to predict the time for operators to take the action on each procedure step.

Acknowledgements
This study was supported by the scholarship Program for Research and Innovation in Science and Technologies (RISET-Pro) World Bank Loan under Grant number 8245-ID. In addition, a part of the results of this study is obtained by the support of Japan Society for the Promotion of Science (JSPS) [KAKENHI grant number 16H03136].

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