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# Determination of the Optimized Automation Rate considering Effects of Automation on Human Operators in Nuclear Power Plants

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## 1. Introduction

Automation refers to the use of a device or a system to perform a function previously performed by a human operator. It is introduced to reduce the human errors and to enhance the performance in various industrial fields, including the nuclear industry. However, these positive effects are not always achieved in complex systems such as nuclear power plants (NPPs). An excessive introduction of automation can generate new roles for human operators and change activities in unexpected ways. As more automation systems are accepted, the ability of human operators to detect automation failures and resume manual control is diminished. This disadvantage of automation is called the Out-of-the-Loop (OOTL) problem [1,2,3]. We should consider the positive and negative effects of automation at the same time to determine the appropriate level of the introduction of automation. Thus, in this paper, we suggest an estimation method to consider the positive and negative effects of automation at the same time to determine the appropriate introduction of automation.

## 2. Analysis of the Positive Effect of Automation

The concept of the automation rate has been recognized since automation was introduced in various industrial fields. In manufacturing industries, terms such as the process automation rate or the facility automation rate have been broadly mentioned. The portions of tasks substituted by automation and let us know how much the automation can relive human operators` tasks. However, it cannot define how much a human is supported by automation. To create an automation rate with a measure that accounts for the effectiveness of human operators, changed or newly generated human operators` tasks due to the acceptance of automation system should be considered.

A system automation rate that considers the monitoring tasks newly generated due to acceptance of system automation is required and it is defined as follows:

$$\frac{S}{T+M}\times 100\,[\%]$$

where,
T: total number of original tasks
S: the number of automation system`s tasks
M: the number of newly generated monitoring tasks

When system automation conducts the number of tasks S, the remaining tasks, including the newly generated tasks, i.e., T-S+M, should be achieved by human operators. Most of the tasks in NPPs are described in procedures. Thus, the number of tasks that human operators should cover can be found by analyzing the procedures. As the main control room (MCR) is digitalized and because computer systems are widely applicable to NPPs, numerous computer-based human operator support systems have been developed. Among them, it is necessary to concentrate on the CPS, which will replace the existing paper-based procedures. The CPS has the original functions of the procedures, that is, to command what human operators should do. It can also contain additional functions that summarize and reduce the information to a succinct form or that monitor and diagnose the status, for instance. CPSs including these functions can allow human operators to conduct tasks which require human cognitive functions [2].

If cognitive automation such as CPSs is accepted, the number of human operators` tasks does not change but the human cognitive task loads to when carrying out the tasks is reduced. Therefore, a cognitive automation rate considering how much the automation can reduce the required human cognitive task loads can be defined.

$$\left[1-\frac{\sum_{i=1}^{H} f_{n(x_i)}(x_i)}{\sum_{i=1}^{H} f_1(x_i)}\right]\times 100\,[\%]$$

where,
H: total number of human operator`s tasks (H=T-S+M)
$x_i$ :$i_{th}$ task
$n_{(xi)}$: automation level of $i^{th}$ task
$f_{n(xi)}(xi)$ required cognitive load for doing xi task which is n-level automated

To quantify the human cognitive task load, Conant`s model, which is an information-theory-based information-flow quantification method, was used [1,3].

## 3. Analysis of the Negative Effect of Automation

If automation consistently replaces the human operators' work for a long time, the operators' participation frequency for manual control decreases, and many issues associated with human interaction with automated systems have been attributed to poor situation awareness [4]. To assess the human operators' SA, the process of how human operators conduct their SA should be expressed. The production rule suitable for describing human operators' SA process contains an if-clause. Thus, a mathematical expression for conditional clauses is necessary. The Bayesian inference based on a conditional probability-based mathematical method has been effectively demonstrated as being suitable for describing the human operators' SA process quantitatively [5].

Let us assume that X means a set of statuses of the NPPs, while Yi means a set of the i$^{th}$ indicators.

$$X = \{x_1, x_2, \cdots, x_l\}$$

$$Y_i = \{y_{i1}, y_{i2}, \cdots, y_{in_i}\}$$

where,

$i = 1, 2, \cdots, m$

$l$: the number of the plant statuses

$n_i$: the number of states of the i$^{th}$ indicators

The production rule of IF-THEN can be mathematically described by conditional probabilities:

$$P(y_{ij}|x_k) = \begin{cases} 1 - e & if\ y_{ij} \text{ is expected upon } x_k \\ \dfrac{e}{n_i - 1} & if\ y_{ij} \text{ is not expected upon } x_k \end{cases}$$

where, $e$: the error probability of a sensor or an interface

If a human operator observes $y_{ij}$ on the indicator Yi, the probability of the plant status $x_k$ is revised:

$$P(x_k|y_{ij}) = \frac{P(y_{ij}|x_k)P(x_k)}{P(y_{ij}|x_k)P(x_k) + P(y_{ij}|\overline{x_k})P(\overline{x_k})}$$

Through the above equation, the human operator's SA for the status $x_k$ after observing $y_{ij}$ is expressed. The changes of the SA in terms of multiple observations related to the status $x_k$ can be derived by repeating calculations.

While judging the status $x_k$, the amount of information that a human operator receives by observing $y_{ij}$ is derived based on the forward conditional mutual information. Bayesian inference calculation to express the diagnosis of the status $x_k$ in NPPs by observing $y_{ij}$ can be used to calculate the forward conditional mutual information with a hypothesis. It is assumed that the judgment of one status does not affect to the judgment of another status. Thus, $P(x_k) = P(\overline{x_k}) = 0.5$ for a status that human operators diagnose inceptively. Then, an equation to calculate forward conditional mutual information can be modified as follows:

$$H(x_k) - H(x_k|y_{ij})$$

where,

$$H(x_k) = P(x_k)log_2\frac{1}{P(x_k)} + P(\overline{x_k})log_2\frac{1}{P(\overline{x_k})}$$

Through the above equation, the reduced amount of the uncertainty to diagnose the status $x_k$ after observing $y_{ij}$ can be calculated; in other words, how much information that the human operator receives for judging $x_k$ can be calculated. The total amount of information that a human operator receives while diagnosing all statuses can be calculated as a sum of the amount of information that human operator receives for diagnosing each status. By comparing the amount of the received information using an automated procedure with using the manual procedure, the ostracism rate, how much the amount of information that a human operator receives decreases due to the use of the automation is defined as follows [6]:

$$1 - \frac{\sum_{k=1}^{l}[1 - H_a(x_k|y_{ij})]}{\sum_{k=1}^{l}[1 - H_m(x_k|y_{ij})]}$$

where,

1-H($x_k|y_{ij}$): the amount of information for diagnosing the status $x_k$

$H_a(x_k|y_{ij})$: the uncertainty of the automated procedure-based SA for the status $x_k$ after observing $y_{ij}$

$H_m(x_k|y_{ij})$: the uncertainty of the manual procedure-based SA for the status $x_k$ after observing $y_{ij}$

$l$: the number of the plant status

## 4. Integration of Estimation method of Positive and Negative Effects of Automation

We suggested the automation rate to estimate the positive effects of automation and the ostracism rate to estimate the negative effects of automation. Based on considering the both suggested estimation method at the same time, the optimized automation rate assuring the best human performance can be derived. Through the experiment conducted by Seung et al. [1], it was proven that the automation rate and the decreasing rate of the working time of human operators have linear relation passing through the two points of automation rate 0% with decreasing rate of the working time 0% and automation rate 100% with decreasing rate of the working time 100%. Thus, it is expected that the automation rate is proportional to the decreasing rate or the working time. In case of the ostracism rate, it is proven that the ostracism rate has a linear relationship with an accuracy of SA by Seung et al. [6]. Thus, if the relationship between the ostracism rate and the decreasing rate of the working time would be analyzed, then the automation rate and the ostracism rate could be considered at the same time in terms of the decreasing rate of the working time. The process of the quantitative optimization of the automation rate was shown in Fig. 1 [7].

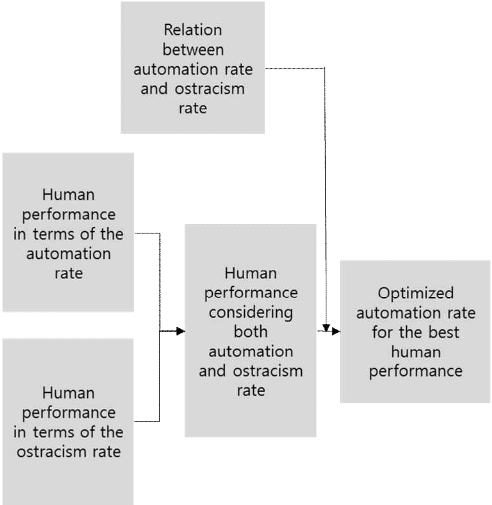

Fig. 1. Process to quantitatively estimate the optimized cognitive automation rate

## 5. Conclusions

The concept of automation rates has been adopted since automation was introduced. This concept is limited in that it does not consider the effects of automation on human operators. Thus, a new estimation method for automation rate was suggested to overcome this problem. The approach of this proposed estimation method concentrates on the effects of introducing automation. If positive and negative effects of automation are considered at the same time, a more appropriate automation rate can be derived. From this point of view, the estimation method of the automation rate can be seen as the first step in the derivation of an optimization method of automation rates in NPPs.

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