Study on Human Reliability Considering Dependence among Tasks in Operation under Accumulative Stress Condition

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ABSTRACT

For analysis of human error rate in nuclear power plant safety, THERP (Technique for Human Error Rate Prediction) is mainly used. In the THERP, an engineering judgment is required to determine a level of dependence and stress. A mechanical and theoretical approach is more useful to determine the dependence. Furthermore, a stress level will change through tasks in one operation. This paper aims to evaluate the dependence quantitatively and to modify the stress level during the operation so as to analyze human error rate more particularly. Firstly, we propose a method for determining level of dependence mechanistically. Here the dependence is defined as a factor that comes from similarity among tasks and affects human error rate of current task depending on the result of previous task. In this paper, we assume that dependence is determined by three factors; personnel, time and place, and that level of dependence is determined by a weighted average of a level of similarity of these three factors. In order to determine weight of these factors, we apply AHP (Analytic Hierarchy Process) method. In the AHP, we set a purpose, an evaluation criteria and an alternative as each hierarchy and determine weight by comparing with importance of two elements in the hierarchy from the view point of contents of upper hierarchy. Then we modify the stress model so as to take into account the change of the level through tasks. Here the stress is a factor that is caused by environmental changes due to accidents and raises human error rate. In this paper, we assume that a level of stress is determined by not only scale of the accident but also a change for the worse during operation for the accident. Then we assume that a level of stress rises when personnel fails in a task. Furthermore, we set difference stress model in accordance with the skill of the personnel (beginner and veteran). In the paper, an optimization of personnel distribution with beginner and veteran in one operation is also discussed based on the present method.

KEYWORDS

Level-1 PRA, THERP, Dependence model, Stress model.

1. INTRODUCTION

In a probabilistic risk assessment (PRA), one must take two categories of failure probability into account for assessment of nuclear plant safety. One is a failure probability due to mechanical and electrical characteristics and the other is that due to human error. Since a high uncertainty that is affected strongly by an environmental and emotional condition appears at the human error, it is apparent that an analysis of Human Error Probability (HEP) is of importance in the PRA.

For analysis of HEP especially in level one PRA of nuclear power plant, THERP (Technique

for Human Error Rate Prediction) [1] is mainly used. In the THERP, one operation consists of a series of "tasks" (a unit of work done by personnel) and "recoveries" (redoing of failed task) as shown in Fig. 1 and the HEPs of each task and recovery are estimated considering a dependence of each task and a stress level of the personnel. The dependence is determined using parameters such as personnel, time and place and the same stress level through the operation is assumed in the THERP. Furthermore, those are evaluated simply based on an engineering judgment.
In this paper, a quantitative investigation of the dependence using a hierarchical analysis and a modification of stress level, where it varies during the operation considering such as a prior tasks states and characteristics of personnel (beginner or veteran), have been carried out so as to enhance a quality of the HEP estimation. Moreover, an optimization of personnel distribution with beginners and veterans in operation is also discussed by applying the present method.

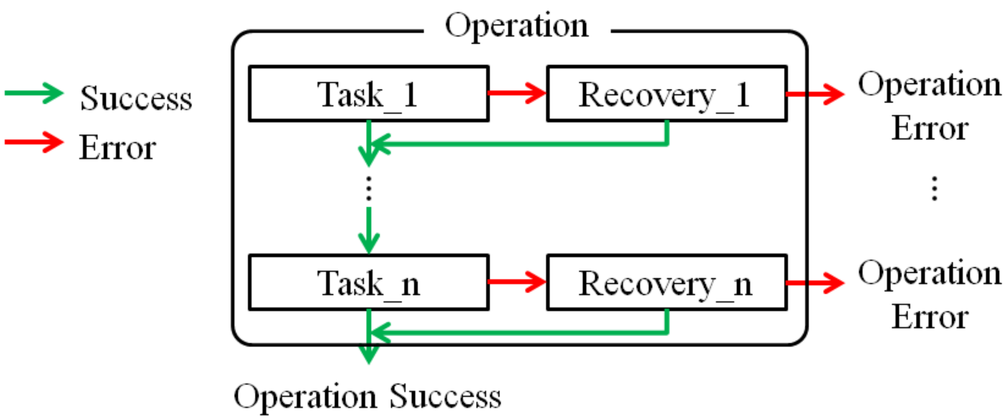


Fig. 1 Example of operation in THERP.

2. QUANTITATIVE ASSESSMENT OF DEPENDENCE

2.1. Current Dependence Model in THERP and SPAR-H

Dependence means that HEP of current task is affected by the result of last task. If the result of last task is "Success", the HEP of current task will decrease. If the result of last task is "Error", the HEP of current task will increase. The dependence comes from a similarity between the two tasks, such as buttons on a same panel and same personnel through the tasks. The more similarities there are between two successive tasks, the higher level of dependence is.
In THERP and SPAR-H [2], level of similarity is determined on the basis of level of similarity in some factors; personnel, time, place, and so on. For example, level of dependence is determined in SPAR-H based on level of similarity with four factors; personnel, time, place, and additional cues as shown in Table 1 [2]. In this method, level of dependence among successive tasks where buttons adjacent to each other are pushed by same personnel at almost the same time is "Complete". Then the HEP is changed based on the level.

Table 1. Method to determine level of dependence in SPAR-H.

Personnel	Time	Place	Additional cues	Level of dependence
Same	Close	Same	Not exist	Complete
			Exist	Complete
		Different	Not exist	High
			Exist	High
	Not Close	Same	Not exist	High
			Exist	Moderate
		Different	Not exist	Moderate
			Exist	Low
Different	Close	Same	Not exist	Moderate
			Exist	Moderate
		Different	Not exist	Moderate
			Exist	Moderate
	Not Close	Same	Not exist	Low
			Exist	Low
		Different	Not exist	Low
			Exist	Low

2.2. Quantitative Analysis of Dependence

2.2.1. AHP (Analytic Hierarchy Process)

In order to determine a level of dependence based on a level of similarity in multiple factors, it is important to determine weight of each factor quantitatively. Therefore we apply AHP (Analytic Hierarchy Process) method. In AHP, three layers; goal, criteria and alternative are set typically [3]. In this study, we set these three layers; Similarity (first layer), Evaluator of weight of each factor in third layer (second layer) and Factors (third layer). Level of dependence is determined based on weight of each evaluator in second layer and weight of each factor in third layer. Hierarchy diagram for determining weights of factors is shown in Fig. 2.

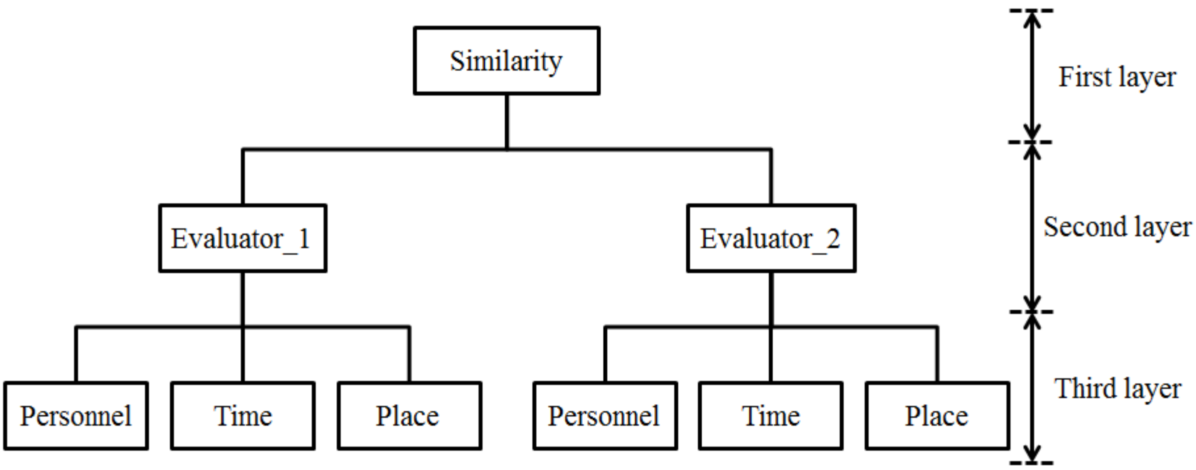


Fig. 2 Hierarchy diagram for determining weights of factors

In the third layer, a weight among the factors is evaluated using a pairwise comparison method. In the pairwise comparison, we determine a relative importance between two factors (A and B) and evaluate the pairwise comparison scale. Table 2. shows the typical scale.

Table 2. Pairwise comparison scale of A depending on relative importance of A against B.

Importance of A	Pairwise comparison scale of A	Importance of A	Pairwise comparison scale of A
as much as B	1		
a little more than B	3	a little less than B	1/3
more than B	5	less than B	1/5
much more than B	7	much less than B	1/7
absolutely more than B	9	absolutely less than B	1/9

Then we regard factors as row number and column number, and create pairwise comparison scale matrix where the entry is pairwise comparison scale of factor in the row against factor in the column. Weight of each factor is set to a normalization of the geometric mean of pairwise comparison scale of the element. Example of pairwise comparison matrix of the third layer evaluated by "Evaluator_1" is shown in the Table 3.

Table 3. Example of Pairwise comparison matrix of the third layer evaluated by "Evaluator_1".

	Personnel	Time	Place	Geometric mean	Weight
Personnel	1	3	5	2.47	0.64
Time	1/3	1	3	1.00	0.26
Place	1/5	1/3	1	0.41	0.10

Weights of "Personnel" ($w_{Personnel}$), "Time" (w_{Time}) and "Place" (w_{Place}) can be described by following matrix, Table 4.

Table 4. Weights of factors evaluated by " Evaluator _1" and " Evaluator _2".

	Evaluator_1	Evaluator_2
Personnel	$w_{Personnel,1}$	$w_{Personnel,2}$
Time	$w_{Time,1}$	$w_{Time,2}$
Place	$w_{Place,1}$	$w_{Place,2}$

Similarly, we determine weights of evaluators in second layer using a pairwise comparison method. Weights of "Evaluator_1" ($w_{Evaluator\_1}$), and "Evaluator_2" ($w_{Evaluator\_2}$) can be described by following matrix, Table 5.

Table 5. Weights of evaluators.

Evaluator_1	$w_{Evaluator\_1}$
Evaluator_2	$w_{Evaluator\_2}$

Then, we determine weights of factors by following matrix multiplication of two matrices shown in Table 4. and Table 5.

$$\begin{bmatrix} w_{Personnel,1} & w_{Personnel,2} \\ w_{Time,1} & w_{Time,2} \\ w_{Place,1} & w_{Place,2} \end{bmatrix} \begin{bmatrix} w_{Evaluator\_1} \\ w_{Evaluator\_2} \end{bmatrix} = \begin{bmatrix} w_{Personnel} \\ w_{Time} \\ w_{Place} \end{bmatrix} \quad (1)$$

2.2.2. Evaluation of Dependence and HEP

In order to determine level of dependence based on level of similarity in multiple factors, it is important to define criteria of level of similarity in the factor. We create following criteria shown in Table 6. by using NUREG CR-1278 (1983) [1] as a reference.

Table 6. Criteria of level of similarity in the factor.

Factor	Criteria	Level of similarity
Personnel	Same veteran	High
	Same beginner	Moderate
	Different	Low
Time	Interval between tasks is 0-1.0[sec]	High
	Interval between tasks is 1.0-60[sec]	Moderate
	Interval between tasks is more than 60[sec]	Low
Place	Same panel (adjacent)	High
	Same panel (not adjacent)	Moderate
	Defferent panel	Low

In criteria of personnel, a level of similarity is "High" or "Moderate" when same personnel perform two successive tasks. We assume that a level of similarity in situation where same veteran personnel perform is higher than that in situation where same beginner personnel perform. It is because that beginner is not confident in themselves skill and tends to perform tasks more carefully than veteran does.

In criteria of time, we assume that the shortness of interval between two successive tasks is important. The shorter the interval is, the more performer of the task tends to regard two successive tasks as one big task.

In criteria of place, a level of similarity is "High" or "Moderate" when two successive tasks are performed in same panel. In Table 6. "adjacent" means that the place where present task is performed is adjacent to place where previous task is performed.

Next, we calculate a level of dependence by a weighted average of a level of similarity of these three factors. Then we define numeric value of level of similarity "High", "Moderate", and "Low" as 1.0, 0.5, and 0.0, respectively. By putting level of similarity of three factors; $s_{Personnel}$, s_{Time}, and s_{Place}, we describe level of dependence (D) as follows.

$$D = \sum w_j \times s_j \quad (2)$$

In this study, HEP of current task (HEP_{Ti}) is affected by the result of last task under the situation where dependence exists. By putting HEP after modification by stress (a method for modification is explained in chapter 3.) HEP_{Ti}^{s}, HEP_{Ti} is described as follows when the result of last task is "Success".

$$HEP_{Ti} = (1 - D) \times HEP_{Ti}^{s} \quad (3)$$

On the other hand, HEP_{Ti} is described as follows when the result of last task is "Error".

$$HEP_{Ti} = 1 \times D + (1 - D) \times HEP_{Ti}^{s} \quad (4)$$

Here, subscript T is type of work (T means Task), subscript i is current task number. Equations. (3) and (4) are also used in THERP.

3. MODELING OF ACCUMULATIVE STRESS

3.1. Stress in HEPs

In THERP, stress is defined as "a continuum, ranging from a minimal state of arousal to a feeling of threat to one's well-being, requiring action" [1]. Degree of stress is classified into four levels; very low, optimum, moderately high, and extremely high, based on task load (for the first three levels) and feeling of threat (for the fourth level). HEPs considering stress are calculated by multiplying Nominal HEPs by modifiers as shown in Table 7.

Table 7. Classification of modifiers for Nominal HEPs [1].

Level of stress	Types of tasks	Modifiers for Nominal HEPs (Veteran)	Modifiers for Nominal HEPs (Beginner)
Very low (Very low task load)		x2	x4
Optimum (Optimum task load)	Step-by-step	x1	x1
	Dynamic	x1	x2
Moderately high (Heavy task load)	Step-by-step	x2	x4
	Dynamic	x5	x10
Extremely high (Threat stress)	Step-by-step	x5	x10
	Dynamic	HEP=0.25 (This is not modifier.)	HEP=0.50 (This is not modifier.)

It is noted that the HEP will increase higher in "Very low" condition than that in "Optimum" condition as in Table 7. It is because that personnel's attention tends to be insufficient in case of very low task.

3.2. Accumulative Stress Model

In the stress model of THERP, level of stress is constant during the operation. However, in a crisis, e.g. after serious accident, level of stress will change through tasks because of a change of the worse, e.g. reduction of margin. Then we create the following accumulative stress model so as to take into account the change of a level of stress through tasks.

In the accumulative stress model, it is assumed that all personnel engaging in an operation share stress. On the other hand, a level of stress varies between a beginner and a veteran. An initial accumulated stress (S) is set to zero at the beginning of the operation. When personnel fails in a task, the accumulated stress increases as follows.

$$S_i = S_{i-1} + \alpha N_i \omega_i \tag{5}$$

$$\alpha = \begin{cases} 2 & (Beginner) \\ 1 & (Veteran) \end{cases} \tag{6}$$

α is the sensitivity against stress. In general, beginners are pathetically weak against failures rather than veterans. Hence α of the beginner is set to twice as much as that of veteran in this study.

N_i is the number of times of failure in task from the beginning of the operation to the present.

ω_i is weight of task$_i$ in the operation. ω_i is determined by engineering judgment.

As concerns beginners, we assume that HEP of current task ($HEP_{Ti,B}$) is much affected by the accumulated stress and original value of $HEP_{Ti,B}$ ($HEP^o_{Ti,B}$) is modified in the following. Here, subscript B means Beginner.

$$HEP^s_{Ti,B} = \begin{cases} \left(1 - HEP^o_{Ti,B}\right) \times S_{i,B} + HEP^o_{Ti,B} & \left(0 \le S_{i,B} < 1\right) \\ 1 & \left(S_{i,B} \ge 1\right) \end{cases} \tag{7}$$

On the other hand, veterans have a lot of experience and training for each task. Accordingly, we assume that HEP of current task ($HEP_{Ti,V}$) does not vary until a certain level of stress ($0 \le S_{i,V} < 1$). When the $S_{i,V}$ reaches a threshold ($S_{i,V} = 1$), veterans cannot stand up to stress and $HEP_{Ti,V}$ increases suddenly as shown in the following equation. Here, subscript V means Veteran.

$$HEP^s_{Ti,V} = \begin{cases} HEP^o_{Ti,V} & \left(0 \le S_{i,V} < 1\right) \\ 1 & \left(S_{i,V} \ge 1\right) \end{cases} \tag{8}$$

4. OPTIMIZATION OF PERSONNEL DISTRIBUTION IN OPERATION

4.1. Modeling of Operation

In this study, we deal with work after serious accident, e.g. manual boot of a safety system, as an operation. Personnel team consists of beginners, veterans (they are performers of tasks), and one leader of the team (he is performer of recoveries), and they work in main control room. With regard to the character of beginners and veterans, we assume that beginners are more liable to fail task due to shortage of skill than veterans. With regard to the character of leader, we assume that he is liable to omit a check on the result of task performed by veteran due to confidence in him.

A part of operation model in this study is shown in Fig. 3. In this study, the operation consists of a series of tasks and recoveries, and tasks and recoveries are performed step by step. We take account of dependence among two successive tasks instead of that between task and recovery because task and recovery are different in character. Leader checks whether the result of task is "Success" or "Error" immediately after the task is performed. If the result of task is "Error", accumulated stress of beginners and that of veterans increase, and leader redoes the task. We call a series of works, "Check a result" and "Redoing a task", recovery. If either "Check a result" or "Redoing a task" is failed, the result of recovery is "Error". If the result of recovery is "Error", the operation ends in "Error", too. On the other hand, if personnel team completes all tasks without an "Error" of recovery, the operation ends in

"Success".
In human reliability analysis, there are two categories of human error. One is "Omission error" that means personnel do not perform task and the other is "Commission error" that means that personnel perform task wrong. However, in this study, we take only "Omission error" into account because "Commission error" affects the system and personnel team has to perform tasks dynamically.
In this study, we assume that leader distributes separate personnel into each task at the beginning of the operation. In that case, if many tasks are required after serious accident, it is possible that the number of veterans is insufficient. Therefore, in order to avoid operation error, it is important to consider optimization of personnel distribution in operation, that is a problem which task is suitable for distribution of veteran.

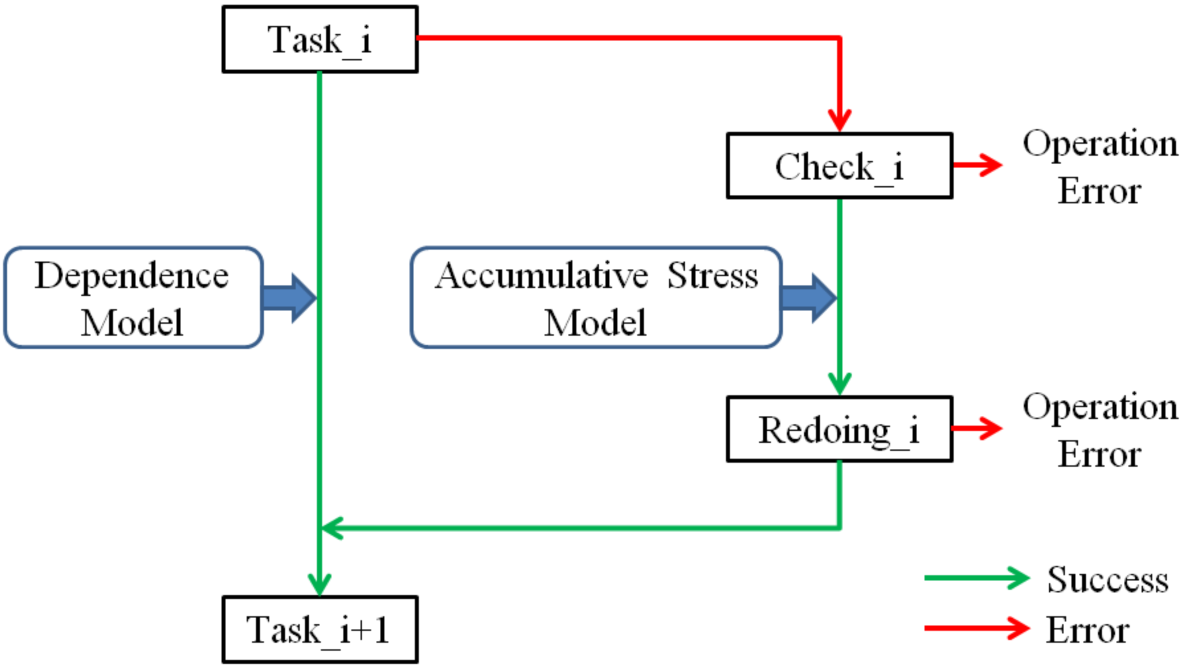


Fig. 3 A part of operation model in this study.

4.2. Analysis Conditions

In this study, the operation consists of 10 tasks and 10 recoveries. After we determine the number of veterans in team, we calculate operation error probability (OEP) in all distributions with Monte Carlo simulation, and search the optimum distribution (distribution where OEP is the lowest).
Analysis conditions are shown as follows. In this study, for simplicity, we apply the same condition to all tasks, and all weights of task are equal.
Considering that personnel team performs operation after serious accident and level of stress at the beginning of operation is high, we assume that HEP^o_{Ti} and HEP of check (HEP_{Ci}) are high and define $HEP^o_{Ti,B} = 0.50$, $HEP^o_{Ti,V} = 0.25$, $HEP_{Ci,B} = 0.20$ and $HEP_{Ci,V} = 0.20$. On the other hand, we assume that leader does not fail in redoing a task and define $HEP_{Ri} = 0$ (HEP_{Ri} means HEP of redoing a task). $HEP^o_{Ti,B}$ and $HEP^o_{Ti,V}$ are modified by accumulated stress model and dependence model in this order. As for HEP_{Ci} and HEP_{Ri}, we assume that they are constant regardless of accumulated stress.
In the SPAR-H, level of dependence is "Low" ($D = 1/20$) or "Moderate" ($D = 1/7$) when

separate personnel perform two successive tasks. Therefore, we determine that level of dependence is intermediate between "Low" and "Moderate" ($D = 0.10$).
The number of trials in Monte Carlo simulation is set to 1 million. We apply Mersenne Twister method as a pseudo-random number generator.
Flowchart of Monte Carlo simulation is shown in Fig. 4.

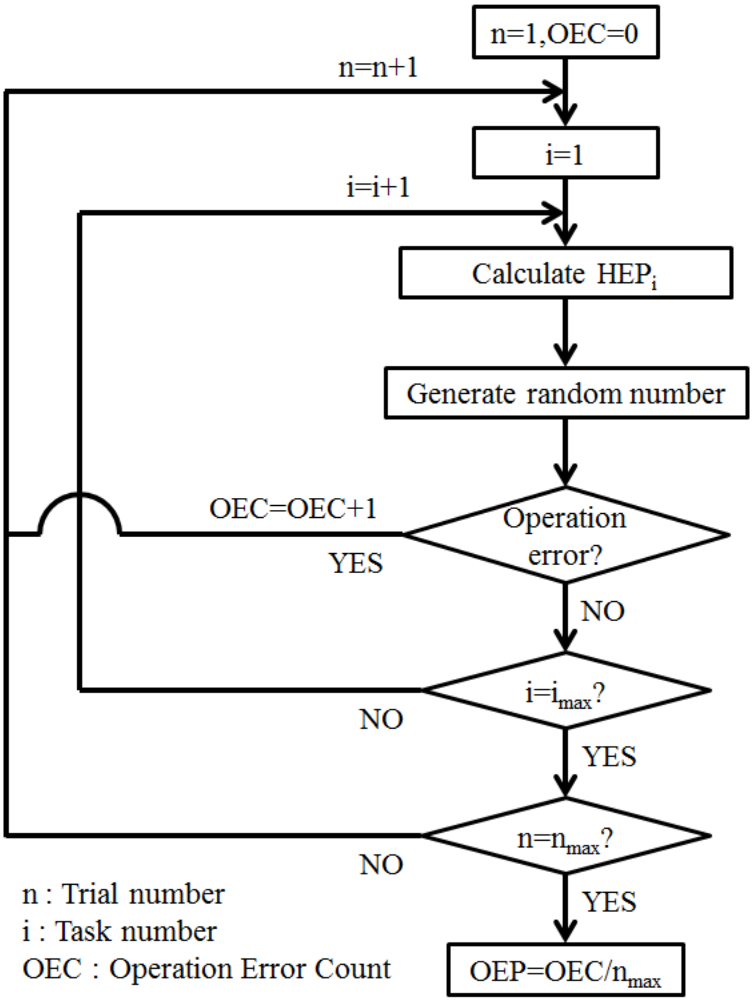


Fig. 4 Flowchart of Monte Carlo simulation.

4.3. Results and Discussion

First, we focus on the optimum distribution and the worst distribution (distribution where OEP is the highest) when the number of veterans in team is 5. Mean of performer's accumulated stress depending on task number in optimum distribution and worth distribution are shown in Fig. 5 and Fig. 6, respectively. In optimum distribution, veterans are distributed into task 3~7. In the worst distribution, veterans are distributed into task 6~10.
The reason why veterans are distributed there in optimum distribution is that performer's accumulated stress tends to be less than 1.0 there. In accumulative stress model, if S_V becomes more than 1.0, HEP_{Ti}^{S} becomes 1.0. Under this situation, it is worse to distribute veteran because $HEP_{Ci,V}$ is more than $HEP_{Ci,B}$. A distribution like this is seen in the worth distribution. In the worth distribution, it is observed that some veterans' mean of accumulated stress is more than 1.0.

However, in the optimum distribution, veterans are distributed into not only initial phase (task 1~3) but also middle phase (task 4~7) in spite of the fact that accumulative stress in middle phase is higher than that in initial phase. It is because that in order to avoid operation error, it is important to lower not only $S_{i,V}$ but also $S_{i,B}$. Therefore, some beginners are distributed into initial phase.

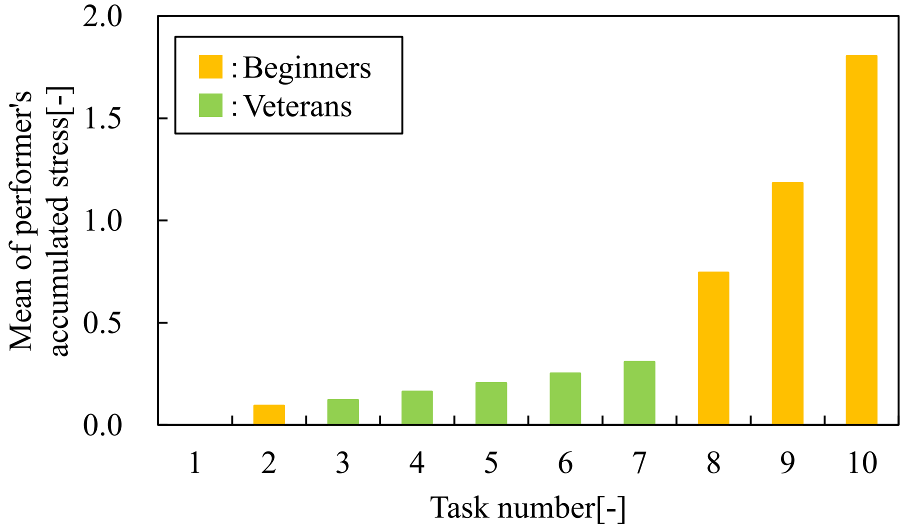


Fig. 5 Mean of performer's accumulated stress depending on task number in optimum distribution (veterans are distributed into task 3~7).

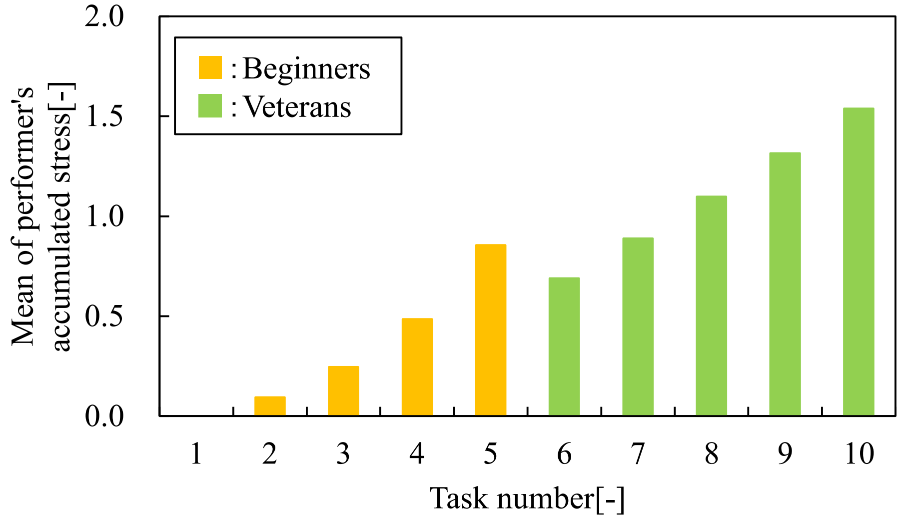


Fig. 6 Mean of performer's accumulated stress depending on task number in the worst distribution (veterans are distributed into task 6~10).

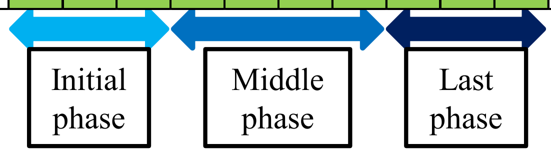
The optimum distribution depending on the number of veterans is shown in Table 8. In optimum distributions, when the number of veterans is small (1~5), veterans are distributed into from initial phase to middle phase.

With accumulative stress model, an indicator of change for worth proposed in this study, we determined the optimum distribution quantitatively by probabilistic approach. In generally, under uncertain situation, it is difficult to distribute suitable personnel into the task. However, with a suitable indicator of change for the worth and understanding of character of personnel, it is possible to distribute suitable personnel based on a relation between indicator and character of personnel.

In this analysis, level of dependence is low because separate personnel perform two successive tasks in operation. Therefore, a relation between optimum distribution and dependence model is not discussed in this study.

Table 8. The optimum distribution depending on the number of veterans (B: Beginners, V: Veterans).

		Task Number										
		1	2	3	4	5	6	7	8	9	10	OEP
The number of veterans	0	B	B	B	B	B	B	B	B	B	B	0.554
	1	B	B	B	V	B	B	B	B	B	B	0.532
	2	B	B	B	V	V	B	B	B	B	B	0.514
	3	B	B	V	V	V	B	B	B	B	B	0.495
	4	B	B	V	V	V	V	B	B	B	B	0.475
	5	B	B	V	V	V	V	V	B	B	B	0.457
	6	B	B	V	V	V	V	V	V	B	B	0.441
	7	B	V	V	V	V	V	V	V	B	B	0.426
	8	B	V	V	V	V	V	V	V	V	B	0.412
	9	V	V	V	V	V	V	V	V	V	B	0.403
	10	V	V	V	V	V	V	V	V	V	V	0.395



5. CONCLUSION

In this study, we proposed the method to determine level of dependence quantitatively and accumulated stress model. Then, we searched the optimum distribution with beginner and veteran in one operation under condition that dependence model and accumulative stress model exist. In the process, the following conclusions were obtained.

- Applying AHP, the method to determine weights of factors quantitatively with the pairwise comparison method, and weighted average method, we obtained the prospect that we can make clearer the process of logic for determining level of dependence quantitatively.
- We proposed accumulative stress model. In this model, change of level of stress in a crisis due to failure of task is demonstrated. Considering difference in accumulative stress model depending on level of skill (beginner or veteran), we assumed that accumulated stress of beginners is more liable to rise due to failure of task by beginners and to influence on error probability of beginners.

- We searched the optimum distribution and discussed a relation between optimum distribution and accumulative stress model. As a result, veterans are distributed into from initial phase to middle phase in optimum distributions when the number of veterans is small (1~5). These results caused by both of modeling of accumulative stress and personnel. In generally, under uncertain situation, it is difficult to distribute suitable personnel into the task. However, with a suitable indicator of change for the worth and understanding of character of personnel, it is possible to distribute suitable personnel based on a relation between indicator and character of personnel.

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