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Correlation in the time-based human reliability analysis model and its quantification

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1. Introduction

The reliabilities of human actions are becoming more important for the probabilistic safety assessment due to the introduction of portable equipment such as flexible coping strategies (FLEX) or multi-barrier accident coping strategies (MACST). One of the widely used approaches is time-based human reliability model, which defines the human error as a delayed human action based on the time available and the time required for human action. In the real world, the two types of times have uncertainties, and the times are represented as random variables. If there are multiple required human actions to mitigate accident, the total time required can be derived as the sum of individual random variables for required human actions. On the other hand, the times required are affected by several factors such as operator's experience or training level, stress level, man-machine interface, and so on. These factors are referred to as performance shaping factors and affect the parameters of the time uncertainty distributions. Even though the individual times required are treated as independent variables, the times required share some performance shaping factors and it makes correlation between the times required.

In this paper, a mathematical model for the correlation between the times required is proposed and quantification method for the total time required with the correlation is also presented. Furthermore, a benchmark problem is applied to demonstrate the effect of the correlation.

2. Methods

2.1 Human error probability in time-based model

In the time-based model, there are two types of times, time required and time available. The time required is the time taken for human action and the time available is the time until the system becomes irreversible state. If the system becomes irreversible state, the operators cannot correct their actions and the human actions are treated as failure. Therefore, the human error probability is defined as a probability that the time required exceeds the time available. In general, the time available is analyzed by thermal-hydraulic analysis and represented as conditional system failure probability given times for human actions. Therefore, the human error probability can be defined as

$$P_{Fr} = \int f_{T_{req}}(t) P_{sys}(t) dt \qquad (1)$$

where $f_{T_{req}}$ is probability density function for the total time required and P_{sys} is conditional system failure probability derived from thermal-hydraulic analysis. Therefore, the human error probability is a weighted sum of conditional system failure probabilities, and the weight is the probability density of the total time required.

In the human reliability analysis, the time required is typically modeled as lognormal random variable and the performance shaping factors affect the parameters of the lognormal random variable. Hannaman et al. proposed the relationship between the performance shaping factors and the uncertainty distribution for the time required [1]. In the proposed method, the median value of the time required is a function of the performance shaping factors and baseline median value.

$$T_{req} | k_1, k_2, k_3 \sim LN(\ln(\mu^0 k_1 k_2 k_3), \sigma^2) \qquad (2)$$

where μ^0 is baseline median value and k_i s are performance shaping factors.

If the performance shaping factors are correlated lognormal random variables, the product of the performance shaping factors also follows lognormal distribution.

$$k_1, k_2, k_3 \sim \boldsymbol{LN}(\boldsymbol{\mu_k}, \boldsymbol{\Sigma}) \qquad (3)$$

$$k = k_1 \cdot k_2 \cdot k_3 \sim LN(\sum \boldsymbol{\mu}_{\boldsymbol{k}}^{i}, \sum \boldsymbol{\Sigma}_{i,j}) \qquad (4)$$

where $\boldsymbol{\mu}_{\boldsymbol{k}}^{i}$s are mean of logarithm of *i*-th performance shaping factor and $\boldsymbol{\Sigma}$ is covariance matrix of logarithm of performance shaping factors.

Then, the unconditional time required can be derived by marginalizing the conditional time required over performance shaping factors.

$$T_{req} \sim LN(ln\, \mu^0 + \sum \boldsymbol{\mu}_{\boldsymbol{k}}^{i}, \sigma^2 + \sum \boldsymbol{\Sigma}_{i,j}) \qquad (5)$$

2.2 Correlation between the times required

In some cases, individual human actions share same performance shaping factor. For example, all the human actions are performed by same operator crew. When the individual human actions share performance shaping factors, the times required have same performance shaping factor values. If we know the performance shaping factors, the times required for individual human actions are independent each other. However, it is hard to know the actual performance shaping factor values in an accident condition. Therefore, the unconditional times required are dependent due to the same, but unknown performance shaping factors. The joint probability density function for unconditional times required can be derived by marginalizing a joint probability density function for the times required over the performance shaping factors. Then, the covariance between the unconditional times required for individual human actions is

$$Cov(T_{req1}, T_{req2}) = Var(k)\mu_1^0\mu_2^0 e^{\frac{1}{2}\sigma_1^2+\frac{1}{2}\sigma_2^2} \quad (6)$$

Therefore, the total time required is the sum of correlated lognormal random variables. However, there is no closed-form expression for the sum of lognormal random variables. In this paper, the Monte Carlo integration with change of variables proposed by Song and Kim is applied to quantify the probability density function for the sum of correlated lognormal random variables [2].

3. A benchmark problem

A benchmark accident mitigation strategy proposed by Suh et al. is used to demonstrate the impact of the correlation between the times required due to the performance shaping factors [3]. The event is total loss of component cooling water with loss of auxiliary feedwater system. The required mitigation actions are injection into steam generator, depressurization of reactor coolant system, and injection into reactor coolant system. Table I shows the parameters of the baseline times required, and performance shaping factors. In the human reliability analysis, it is assumed that there are correlations between the performance shaping factors. Park et al. analyze the interrelationship between the performance shaping factors and Table II shows the analyzed correlation coefficients for the performance shaping factors [4]. Fig. 1 shows the derived probability density functions for the total time required, with and without considering the correlation which comes from the performance shaping factor. It is shown that the probability density function with considering the correlation is shifted to left side and has large variance. This is because the expected values for the two distributions are same, but the variance for the dependent case is larger than that of independent case because of the positive correlation.

Table I: Model parameters of the baseline times required, and the performance shaping factors [3]

Random variables	Parameters	
	μ	σ^2
Injection into SG	4.6024	0.0056
Depressurization of RCS	3.6811	0.0155
Injection into RCS	3.9009	0.0222
k_1 – operator experience	0.0387	0.0634
k_2 – stress level	0.2038	0.0231
k_3 – operator/plant interface quality	0.4484	0.2506

Table II: Correlation coefficients between the performance shaping factors [4]

ρ	k_1	k_2	k_3
k_1	1	0.379	0.418
k_2	0.379	1	0.127
k_3	0.418	0.127	1

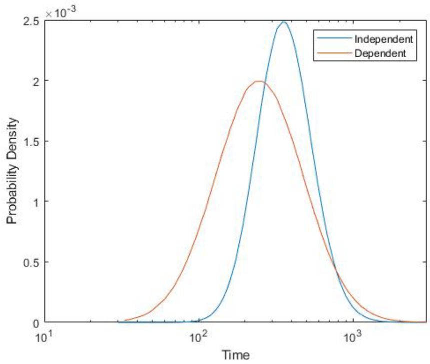

Fig. 1. Probability density functions for the total time required with and without considering the correlation which comes from the performance shaping factors

4. Conclusions

In this paper, the mathematical model for the correlation between the times required is proposed based on performance shaping factors and a benchmark problem is used to demonstrate the effect of the correlation. It is shown that the human error probability without considering correlation has large variance. Above mentioned, the human error probability depends on the conditional system failure probability function. As the probability density function with considering correlation has large probability in large require time, the human error probability without considering the correlation can be underestimated if the conditional system failure probability given large required time is much larger than that of small required time because the large failure probability has larger weight for the correlated case. Therefore, the analyst should consider the correlation between the times required.

REFERENCES

[1] G. W. Hannaman and D. H. Worledge, Some developments in human reliability analysis approaches and tools, Reliability Engineering and System Safety, Vol. 22, p. 235-256, 1988.
[2] G. S. Song and M. C. Kim, Theoretical approach for uncertainty quantification in probabilistic safety assessment using sum of lognormal random variables, Nuclear Engineering and Technology, Vol. 54, p. 2084-2093, 2022.
[3] Y. A. Suh, J. Kim, and S. Y. Park, Time uncertainty analysis method for level 2 human reliability analysis of severe accident management strategies, Nuclear Engineering and Technology, Vol. 53, p. 484-497, 2021.
[4] J. Park, W. Jung, and J. Kim, Inter-relationships between performance shaping factors for human reliability analysis of nuclear power plant, Nuclear Engineering and Technology, Vol. 52, p. 87-100, 2020.