Combination Importance Measure Considering Seismic Correlation

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Abstract: In recent years, enhancing the continuous safety of nuclear power plants has become increasingly important. Establishing a rational risk management system is essential to achieve the enhancement. Fussell-Vesely (FV) and Risk Achievement Worth (RAW) have been widely employed to identify critical components of the system. However, these conventional measures primarily focus on individual components, the measures are insufficient for addressing the common cause failures and multi-hazards, such as earthquakes and tsunamis. The conventional measures could also not capture the interaction effects that are critical for complex systems such as nuclear power plants. This paper introduces combination measures define for overcoming these limitations. We demonstrate the effectiveness of the measures a system model triggered by a Loss of Coolant Accident (LOCA). The results illustrate that proposed combination measures provide a more accurate identification of critical components.

Keywords: FV, RAW, Common Cause Failure, Interaction Effect

1. INTRODUCTION

Nuclear power is expected to be a source of clean energy. Ensuring safety is the most important issue. After the Fukushima Daiichi nuclear disaster, interest in safety evaluations of nuclear power plants has increased worldwide. This background demands enhanced risk assessment and accident prevention measures in nuclear power plants. Fussell-Vesely (FV) and Risk Achievement Worth (RAW) measures have been widely used to quantify the impact of specific component failures on overall system safety. FV shows how much a specific component's failure contributes to the top event of the system. RAW evaluates how much the system's risk increases if a specific component fails. However, these measures focus on a single component. It is difficult to evaluate risks when multiple components interact. Natural disasters like earthquakes and tsunamis can cause multiple components to fail simultaneously. We need to consider these common cause failures. Traditional single-component evaluation methods cannot adequately reflect these complex interactions. Therefore, we need new importance measures that consider the interactions of multiple components.

In this study, we propose Combination FV and Combination RAW as new measures to evaluate the impact of multiple component combinations on overall system safety. These measures consider the interactions between any two components. They reflect the overall system's damage correlations and assess their effectiveness against common cause failures and multi-hazards. Specifically, we use a system model with a LOCA (Loss of Coolant Accident) initiating event to evaluate the effectiveness of the proposed measures.

2. Conventional Importance Measure

In this study, we focused on the conventional measures FV (Fussell-Vesely) and RAW (Risk Achievement Worth).

2.1. Fussell-Vesely (FV) importance measure

FV is a measure to determine the ease of CDF reduction if the target component never fails. Components with high FV values are more effective for improvement measures.
FV is expressed by the following equation:(1).

$$FV_i = \frac{F(CDF|x) - F(CDF|x_i = 0)}{F(CDF|x)} \tag{1}$$

where
x_i: Failure probability of equipment i.

2.2. Risk Achievement Worth (RAW) importance measure

RAW is a measure to determine the ease of CDF increase if the target component always fails. Components with high RAW values are important for safety and reliability.
RAW is expressed by the following Eq. (2).

$$RAW_i = \frac{F(CDF|x_i = 1)}{F(CDF|x)} \tag{2}$$

where, x_i is state of equipment *i*.

3. Definition of Combination Importance Measure

This chapter describes the proposed method of focusing on combinations. Conventional FV and RAW focus on individual components. However, they face challenges in evaluating the interaction effects of multiple components, common cause failures, and multi-hazards like earthquakes and tsunamis. To address these issues, our measure reflects the interaction effects between any two components (i, j) and considers the correlation of system-wide damage through Monte Carlo simulations. The combination FV is given by Eq. (3) below.

$$FV_{i,j} = \frac{F\big(fail|\rho(x_1, \ \dots \ , x_n)\big) - F\big(fail|\rho(x_1, \ \dots \ , x_n); x_i = 0, x_j = 0\big)}{F\big(fail|\rho(x_1, \ \dots \ , x_n)\big)} \tag{3}$$

Also, combination RAW is given by Eq. (4)

$$RAW_{i,j} = \frac{F\big(fail|\rho(x_1, \ \dots \ , x_n); x_i = 1, x_j = 1\big)}{F\big(fail|\rho(x_1, \ \dots \ , x_n)\big)} \tag{4}$$

where
x_i: Failure probability of equipment *i*
x_j: Failure probability of equipment j

In the equations, 1 means damage and 0 means no damage. Also, $\rho(x_1, \dots, x_n)$ represents that components 1 through *n* have failure correlation.

4. Application of Combination Importance Measures

We applied the proposed combination measures to the system model proposed by Vishanav et al. (2020) (LOCA-initiated FT/ET model; 25 components). [6] The failure correlations within events (FT) and between events were set as shown in Table 1, and 100,000 simulations were conducted to calculate the combination measures.

Table 1. Failure correlations for example calculations

	Components within the same system	Components from different systems
Case 1	0	0
Case 2	0.5	0.25

Additionally, the combination importance measures for each sequence were calculated, in addition to the CDF importance measures.

5. Results of Combination Importance Measures

In this study, we evaluated a system model with a LOCA (Loss of Coolant Accident) initiating event using the proposed importance measures.

5.1. Results of Combination FV and Combination RAW for CDF

As shown in Table 1 for Case 2, the combination FV and combination RAW were calculated based on the failure rates of each component. The results are shown in the following figures. The results indicated that in the combination FV, the combination of Component 1 (Reactor Trip Scram) and Component 17 (Auxiliary Feedwater System (AFWS)) had high importance. Similarly, the RAW values indicated high importance for the combination of Component 1 and 17, the combination of Component 4 and 5 (Emergency Core Cooling System (ECCS)) and Component 14 and 15 (AFWS), as well as the combination of Components 6 and 7 (High Pressure Coolant Injection (HPI)). These results show that when these combinations of components fail simultaneously, they have a significant impact on CDF. Considering the system-wide damage correlation, the importance of specific component combinations became clear. The proposed combination importance measures were particularly effective in situations involving common cause failures and multiple hazards.

Table 2 shows a comparison of the summed FV values and the combination FV values for Component 1 and Component 17. From the results in Table 2, the summed FV values were 0.509, while the combination FV values were 0.631. This shows that the combination FV values are higher than the summed FV values. We confirmed the effectiveness of the combination importance measure.

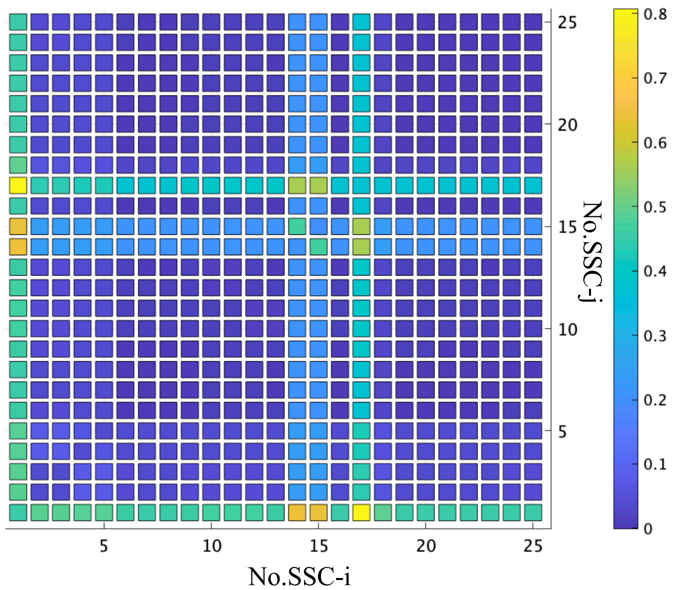

Figure 1. Combination FV Importance (Case 1)

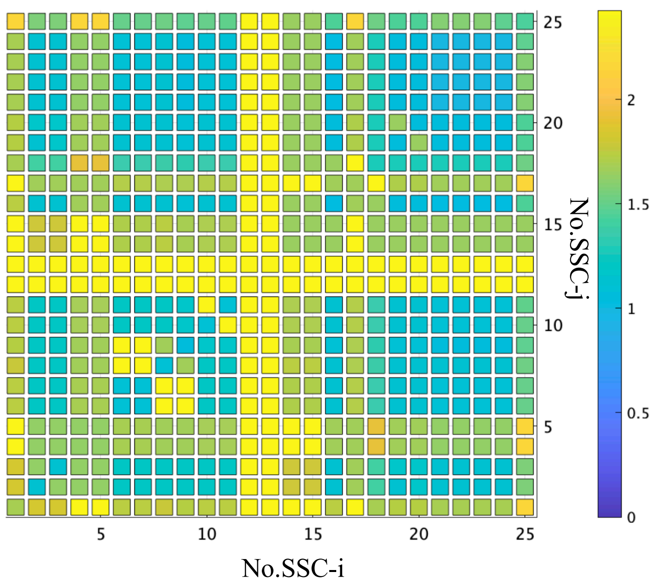

Figure 2. Combination RAW Importance (Case 1)

Table 2. Comparison of Combination FV and Summed FV Importance

	FV values
Addition	0.509
Combination	0.631

5.2. Results of Combination FV and Combination RAW for Sequences

The combination FV and combination RAW for each sequence were calculated. The results are shown below. From the results in Figures 3 and 4, comparing Case 1 and Case 2, the FV values for the High Pressure Coolant Injection (HPI) series (Components 10-12) were 0.1 to 0.2 in Case 1, but 0.4 to 0.6 in Case 2. This shows that introducing correlations between components increased the importance values.

From the results in Figures 5 and 6, comparing Case 1 and Case 2, the RAW values for the ECCS series (Components 4-5) were 2.0 to 2.3 in Case 1, but 2.6 to 2.7 in Case 2. The RAW values for the AFWS series (Components 16-17) were 1.9 to 2.1 in Case 1, but 2.6 to 2.9 in Case 2. This shows that the introduction of correlations between components slightly increased the importance values. From these results, comparing Case 1 and Case 2, we found that by considering correlations in specific sequences, it is possible to evaluate the differences in importance due to the impact of specific component combinations on CDF and damage correlation.

From the results of 5.1 and 5.2, the proposed combination importance measures were shown to be superior to conventional single-component measures for evaluating the overall system risk, which includes complex interactions.

5. CONCLUSION

In this paper, we propose combination importance measures (FV and RAW) to identify critical components for system safety in nuclear power plants. These measures enable the assessment of interaction effects with failure correlations due to earthquakes and multi-hazard failures. We demonstrated the effectiveness of the combination measures using the LOCA (Loss of Coolant Accident) scenario developed by Vaishanav et al. (2020). The system model includes 25 basic events and failure correlations between components. We conducted 100,000 simulations to obtain the combination measures for each case. The results showed differences in importance between combinations of two components. The combination of Reactor Trip Scram (RTS) and AFWS components demonstrated particularly high importance. Additionally, we confirmed the importance for each sequence. These results revealed that considering correlations due to earthquakes can change the importance values. Based on these findings, the combination measures appear to be promising indicators for enhancing the safety of complex systems.

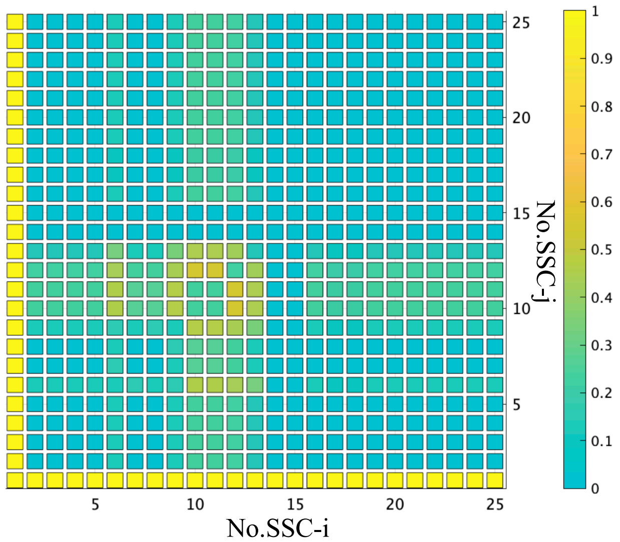

Figure 3. Combination FV Importance (Case 1)

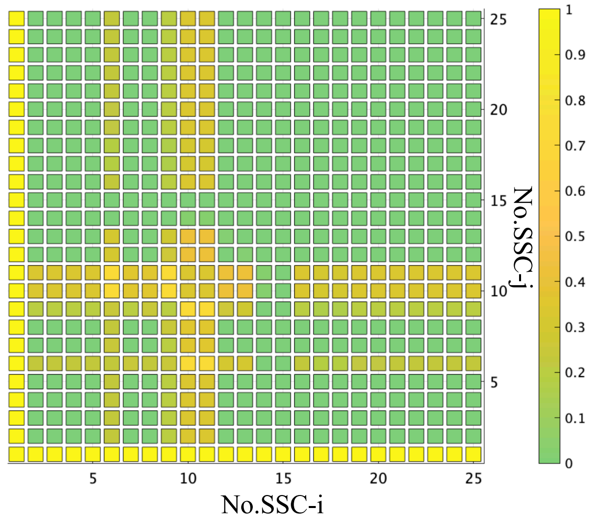

Figure 4. Combination FV Importance (Case 2)

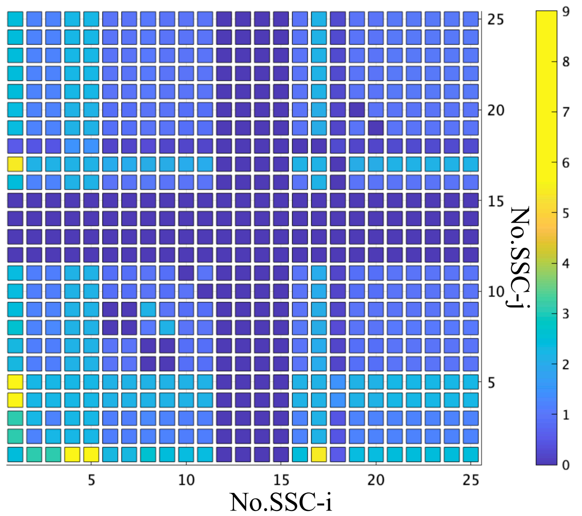

Figure 5. Combination RAW Importance (Case 1)

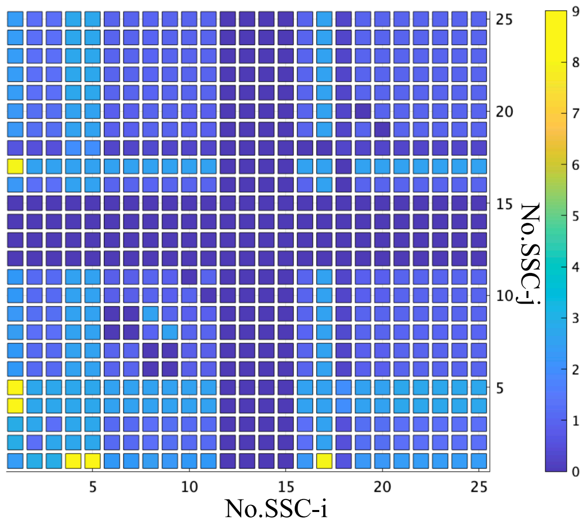

Figure 6. Combination RAW Importance (Case 2)

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