Effect of Safety Culture to Event Occurrences using Bayes' Theorem and Bayesian Network Analysis

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1. Introduction

Following the previous studies on the effects of safety culture vulnerability to safety culture-induced events on component failures or events at nuclear power plants [see Ref. [1-4], this study was conducted an assessment using Bayes' theorem and Bayesian network analysis (BNA) method with an aim to evaluate potential frequency of occurrence of the safety culture related events during a 46-year period (1978–2023) at nuclear power plants.

A safety culture related contributor is commonly defined as an initiating event precursor that could lead to incident or event conditions. In other words, that safety culture related contributor is an event precursor (see Ref. [5]). Therefore, identification of major safety culture related events would be used as preventive actions and/or corrective actions to avoid recurrence of the event or to prevent a new event consequently.

The frequency of safety culture induced occurrence was derived based on the failure causes type such as mechanical failure, electrical failure, human error, etc. using Bayes' theorem. Then for assessing the effect of the safety culture-related contributors on the component failures to the events, Bayesian network analysis was applied to derive the vulnerabilities of the safety culture-related event occurrences for nuclear power plants.

In order to assess the safety culture-related vulnerability, occurrence frequency of incidents at nuclear power plants was evaluated by Bayes' theorem. The frequency of safety culture induced occurrences was derived based on safety culture related events and failure type such as mechanical failure, electrical failure, human error, etc. Following the Bayesian network analysis method was applied to explore an effect of safety culture to event occurrences.

As a result of this study, it is concluded that a new approach can be usefully used in deriving the frequency of occurrence of the safety culture related events for nuclear power plants to avoid recurrence of the event or to prevent a new event consequently.

2. Methods and Results

2.1 Identification of safety culture-related contributor

In order to identify safety culture related events, safety culture related events were identified a total of 52 cases due to a lack of safety culture for 632 events (component failures) from the operating experiences during 46 years (1978-2023) at 27 NPPs as listed in Table 1.

2.2 Data evaluation by Bayes' theorem

The frequency of safety culture induced event occurrences was derived based on safety culture-related contributors and failure type such as mechanical failure, electrical failure, human error, etc.

The basic approach for updating the generic distributions is to apply Bayes' theorem. If the failure rate of a component, λ, which is defined as the number of failures per unit time, is the parameter of interest, we can update the datum using Bayes' theorem, which states that:

$$\mathrm{f}(\lambda/E) = \frac{\mathrm{f}(\lambda)\mathrm{L}(E/\lambda)}{\int_0^n \mathrm{f}(\lambda)\mathrm{L}(E/\lambda)\mathrm{d}\lambda}$$

where, f(λ/E) is predicted distribution of the failure probability which is conditional on the evidence E, f(λ) is the prior distribution without having the evidence E, and L(E/λ) is posterior likelihood function of the failure probability of the evidence E for a given value of λ.

The discrete form of Bayes' theorem is given by

$$f(\lambda_i/E) = \frac{f(\lambda_i)L(E/\lambda_i)}{\sum_{j=1}^{n} f(\lambda_j)L(E/\lambda_j)}$$

where, $f(\lambda_i/E)$, $f(\lambda_i)$ and $L(E/\lambda_i)$ are discretized predicted distribution, discretized prior distribution and discretized posterior likelihood function respectively

In this study, an uniform distribution is used as a prior distribution due to limited information on the failure rates of safety culture related events. However, log-normal distribution is applied for likelihood function and predicted distribution for failure rates, λ. The general formula for the probability density function of the lognormal distribution is:

$$f(\lambda) = \frac{e^{-\left(\left(\ln\left((\lambda-\theta)/m\right)\right)^2/(2\sigma^2)\right)}}{(\lambda-\theta)\sigma\sqrt{2\pi}} \quad \lambda > \theta; m, \sigma > 0$$

where σ is the shape parameter (and is the standard deviation of the log of the distribution), θ is the location parameter and m is the scale parameter (and is also the median of the distribution).

Note that the lognormal distribution is commonly parameterized with

$$\mu = log\ (m)$$

The μ parameter is the mean of the log of the distribution. If the μ parameterization is used, the lognormal probability density function is

$$f(\lambda) = \frac{e^{-\left((\ln((\lambda-\theta)-\mu)^2/(2\sigma^2)\right)}}{(\lambda-\theta)\sigma\sqrt{2\pi}} \quad \lambda > \theta;\ \sigma > 0$$

The geometric mean of the percentiles and error factor are defined as $M = (\lambda_\gamma \lambda_{1-\gamma})^{1/2}$ and $EF = ln(\lambda_\gamma \lambda_{1-\gamma})^{1/2}$, respectively.

With these notations,

$$\theta = ln\, M \text{ and } \sigma^2 = ln(\frac{EF}{x_{1-\gamma}}).$$

Where, $x_{1-\gamma}$ is the100(1-γ)th percentile of a standard normal distribution. Therefore, parameters of the log-normal distribution can be obtained following relations:

Mean= $exp^{(\theta+\sigma^2/2)}$

Median = $exp^{(\theta)}$

Variance = $exp^{((2\theta+\sigma^2))}\left[exp^{(\sigma^2)} - 1\right]$

It is further observed that M is the median of a log-normal distribution and that the two percentiles are $\lambda_{1-\gamma} = EF \cdot M$ and $\lambda_\gamma = M/EF$

The frequency of safety culture-related event occurrence is given as a log-normal distribution with median and standard deviation (square root of the variance) for safety culture related events classified into the failure causes type such as mechanical failure, electrical failure, human error and by reactor type.

The frequency of safety culture induced event was occurrence was calculated by the following ways: first suppose prior distribution. Then collect event related cases, and these are used as new events for calculating posterior likelihood function and the predicted distribution.

The evaluation of occurrence frequency for safety culture related events are conducted using Bayes' theorem based on two periods phases; (i) safety culture related events (SC_1) identified 52 cases among 632 events (component failures) from the operating experiences during 38 years (1978-2015) at 24 NPPs as prior events, and (ii) safety culture related events (SC_2) identified 32 cases among 44 events (component failures) from the operating experiences during 8 years (2016-2023) at 27 NPPs as posterior events. The events were classified into the failure causes type as shown in Table 1. The evaluation results for conditional probabilities of safety culture induced event occurrences for components failure types during the period between 2016 and 2023 based on prior probabilities of safety culture induced event occurrences during 1978–2015 are shown in Figure 1 respectively.

According to the results, it is observed that the predicted conditional probabilities are decreased for all component failures due to decrease of components failure rates during the during the period between 2016-2023. Figure 1 shows that the predicted conditional probabilities for all types failures (red colored dot lines) are decreased rather than prior probabilities of safety culture induced failures (green colored dot lines) because posterior probabilities of safety culture induced failures were decreased.

2.3 Bayesian Network Analysis (BNA)

BNA can and have been used to represent joint probability distributions compactly. Indeed, this is the most common usage of them today. This ability comes from local pdfs that are attached to each variable in the network, whose purpose is to quantify the strength of the causal relationships depicted in the BN through its structure: these local pdfs mathematically describe the behavior of that variable under every possible value assignment of its parents. Given the structure and the local probability distributions of a BN, the joint probability distribution of the domain of n variables $\Pr(X_1, X_2, \cdots, X_n)$ can be calculated as

$$\Pr(X_1, X_2, \cdots, X_n) = \prod_{i=1}^{\bar{n}} \Pr\,(X_i|Pa_i)$$

where Pa_i are the parents of variable X_i in the Bayesian network.

A Bayesian network is a graphical representation of a probability distribution over a set of variables $\mathcal{U}(X_1, X_2, \cdots, X_n)$ t consists of two parts: (a) the directed network structure in the form of a directed acyclic graph (DAG), and (b) a set of the local probability distributions (local pdfs), one for each node/variable, conditional on each value combination of the parents as shown following example:

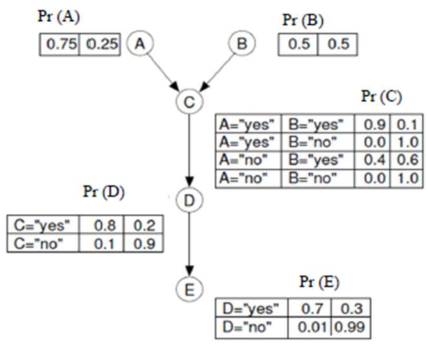

Figure 2. Example of conditional probability in a Bayesian network structure

The conditional probabilities, $\Pr\,(X_i|Pa_i)$ defining the pdf of variable X_i given a value assignment of its parents Pa_i in the network graph in this equation is exactly those local pdfs specified for each variable in the domain. Using the above formula, every combination of assignments to the variables $X_1, X_2, \cdots, X_n$ *can* be calculated.

(1) Network modelling

A simple model of a Bayesian network in a discrete domain is shown in Figure 3. It depicts a fictitious situation, a domain abstracted to five variables, all of them Boolean. Such structures represent alternative paths of possible influence between certain variables in the cycle.

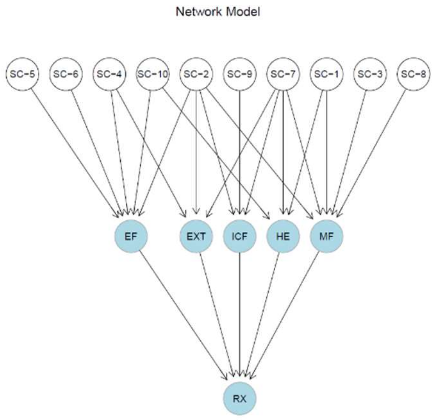

Figure 3. An example Bayesian network modeling

Vertices (nodes) in the network is modelling as SC (representing the safety culture-related contributors leading to the events), EF/EXT/ICF/HE/MF (representing the event that it is electrical failure, external failure, instrument/control failure, human error or mechanical failure, respectively), and RX (representing the event that it is reactor shutdown). In the domain of Figure 3 where all variables are binary, each row of each conditional probability table records the probabilities of that variable taking the value "success" or "fail" for a particular combination of values ("success" or "fail") of its parents. The intuitive meaning of the structure BN in Figure 3 is that all vertices (nodes) in the network are independent. BN consists of a set of statistical conditional independence statements that are implied by its structure.

To derive the conditional probabilities for component failure (CO) due to safety culture precursors (SC_1, SC_2) and for reactor shutdown (RX) due to CO, it is conducted to analyze the BN-structure consisted of two safety culture precursors, component failures and events for failure type-based. An input network model related to event sequences with safety culture related events was shown in Figure 4. The figures shows that two stage 1 nodes (contributors as event sequence precursors at the prior phase and the posterior phase) propagate to the stage 2 node (component failures) and 3rd stage node (event) subsequently.

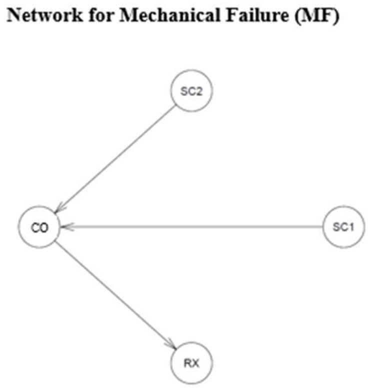

Figure 4. An example network for component failures due to mechanical failure

(2) Bayesian Network Analysis

Bayesian network is a graphical model of the relationships among a set of random variables. It consists of two components; a) a network structure in the form of a directed acyclic graph (DAG). In this graph, nodes represent the random variables and directed edges represent stochastic dependencies among variables; and b) A set of conditional probability distributions, one for each variable, characterizing the stochastic dependencies represented by the edges. These conditional distributions are specified by the network parameters.

If there is a directed edge in a DAG from node SC to node CO, CO is said to be a parent of RX; likewise, RX is called a child of CO. An important feature of a BN is that each variable represented by a node is understood to be conditionally independent of the set of all its predecessors in the graph, given the values of its parents. In other words, the absence of a directly connecting arrow between any two nodes implies that these two variables are independent given the values of any intermediate nodes. The joint probability distribution for the entire set of variables represented by a BN can be decomposed into a product of conditional probabilities using the graphical structure and the chain rule of probability calculus:

$$\mathrm{P}(x|\theta) = \prod_{i=1}^{n} \mathrm{P}\ (X_i|Pa_i(x_i), \theta_i)$$

where x $= (x_1, x_2, \cdots, x_n)$ are the variables (nodes in the BN) and $\theta = (\theta_1, \theta_2, \cdots, \theta_n)$ are the BN's parameters, where each θ_i is the set of parameters necessary to specify the distribution of the variable xi given its parents $Pa(x_i)$. This implies that knowing the states of CO (component failure) renders RX (reactor shutdown) independent of SC_1 and SC_2 as shown in Figure 5. The joint distribution of all five variables can thus be factored according to above equation as: render

$$\mathrm{P}(SC_1, SC_2, CO, RX) = P(RX|CO) \cdot P(CO|SC_1 SC_2)| \cdot P(SC_1) \cdot P(SC_2)$$

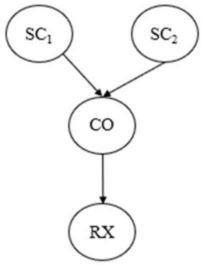

Figure 5. A simple BN representing the relationship between (CO), (RX) and two precursors (SC_1, SC_2).

BN-structure is an induced subgraph (a subset of nodes and all the edges between nodes. In the previous cases, SC_1 and SC_2 were dependent only when CO was unobserved; two possibly independent variables become dependent. The conditional probabilities for two precursors (SC_1, SC_2) for component failure (CO) and for reactor shutdown (RX) due to CO. The example results of conditional probabilities for electrical failure (EF) due to two safety culture related precursors (SC_1, SC_2) are shown in Table 2. The derived predicted probabilities are shown in Figure 6 and their results are summarized in Table 3, where the conditional probabilities of all sub-precursors (safety culture induced component failures) were identically recognized.

Table 3 shows that if the corrective actions for the prior safety culture related events were taken (i.e., SC_1 success), the predicted conditional probabilities for all not taken types component failures are decreased. However, if not conducted corrective actions, the predicted conditional probabilities of safety culture induced failures are increased.

3. Conclusions

This study has conducted to analysis an effect of safety culture to the component failures and event occurrences using Bayes' Theorem and Bayesian Network Analysis.

In order to evaluate the effect of safety culture to the component failures and event occurrences, the occurrence frequency for safety culture related events are predicted using Bayes' theorem based on two periods phases; (i) safety culture related events (SC_1) identified 52 cases among 632 events (component failures) from the operating experiences during 38 years (1978-2015) at 24 NPPs as prior events, and (ii) safety culture related events (SC_2) identified 32 cases among 44 events (component failures) from the operating experiences during 8 years (2016-2023) at 27 NPPs as posterior events. According to the results, it is observed that the predicted conditional probabilities are decreased for all component failures due to decrease of components failure rates during the during the period between 2016-2023 because posterior probabilities of safety culture induced failures were decreased.

Following, the Bayesian network analysis (BNA) method was applied to predict the conditional probabilities for component failure (CO) due to safety culture precursors (SC_1, SC_2) and for reactor shutdown (RX) due to CO. According to the results, it is observed that if the corrective actions for the prior safety culture related events were taken (i.e., SC_1 success), the predicted conditional probabilities for all not taken types component failures are decreased. However, if not conducted corrective actions, the predicted conditional probabilities of safety culture induced failures are increased.

In conclusion, it is a new approach to identify the effect of safety culture to event occurrences and of corrective action to the conditional probability of event occurrence using Bayes' Theorem and Bayesian Network Analysis. It is expected that it can be usefully used in deriving the contributors of safety culture that cause failure of components and events of nuclear power plants to avoid recurrence of the event or to prevent a new event consequently.

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Table 1. Safety culture related events during a 46-year period (1978–2023)

Type \ Failures \ Period	1978-2015		2016-2023	
	Component failure	Safety Culture related failure	Component failure	Safety Culture related failure
Mechanical failure	168	10	15	9
Electrical failure	118	6	10	2
I&C failure	197	6	5	0
Human error	104	30	5	21
External failure	45	0	9	0

Table 2. Example of conditional probability for electrical failure (EF) due to two precursors (SC_1, SC_2)

SC \ Pr	Probability	
	Success	Fail
SC_1	0.99835	0.00165
SC_2	0.99350	0.00065

CO \ SC	SC_2 success		SC_2 fail	
	SC_1 success	SC_1 fail	SC_1 success	SC_1 fail
Success	0.99010	0.99835	0.99935	0.99010
Failure	0.00990	0.00165	0.00065	0.00990

RX \ CO	Success	Fail
Success	0.84635	0.99835
Fail	0.00990	0.00165

Table 3. Summary of conditional probability for events due to two precursors (SC_1, SC_2)

	SC_1 success		SC_1 fail		CO	
	$SC_{2,success}$ → CO_{fail}	$SC_{2,fail}$ → CO_{fail}	$SC_{2,success}$ → CO_{fail}	$SC_{2,fail}$ → CO_{fail}	$CO_{success}$ → RX_{fail}	CO_{fail} → RX_{fail}
MF	9.901E-3	1.445E-4	9.901E-4	9.901E-3	5.859E-3	9.900E-3
EF	9.901E-3	6.502E-4	9.901E-4	9.901E-3	9.901E-3	9.900E-3
ICF	9.901E-3	1.301E-2	9.901E-4	9.901E-3	9.901E-3	9.900E-3
HE	9.901E-3	6.19E-5	9.901E-4	9.901E-3	9.901E-3	9.900E-3
EXT	9.901E-3	1.301E-2	9.901E-4	9.901E-3	5.959E-3	9.900E-3

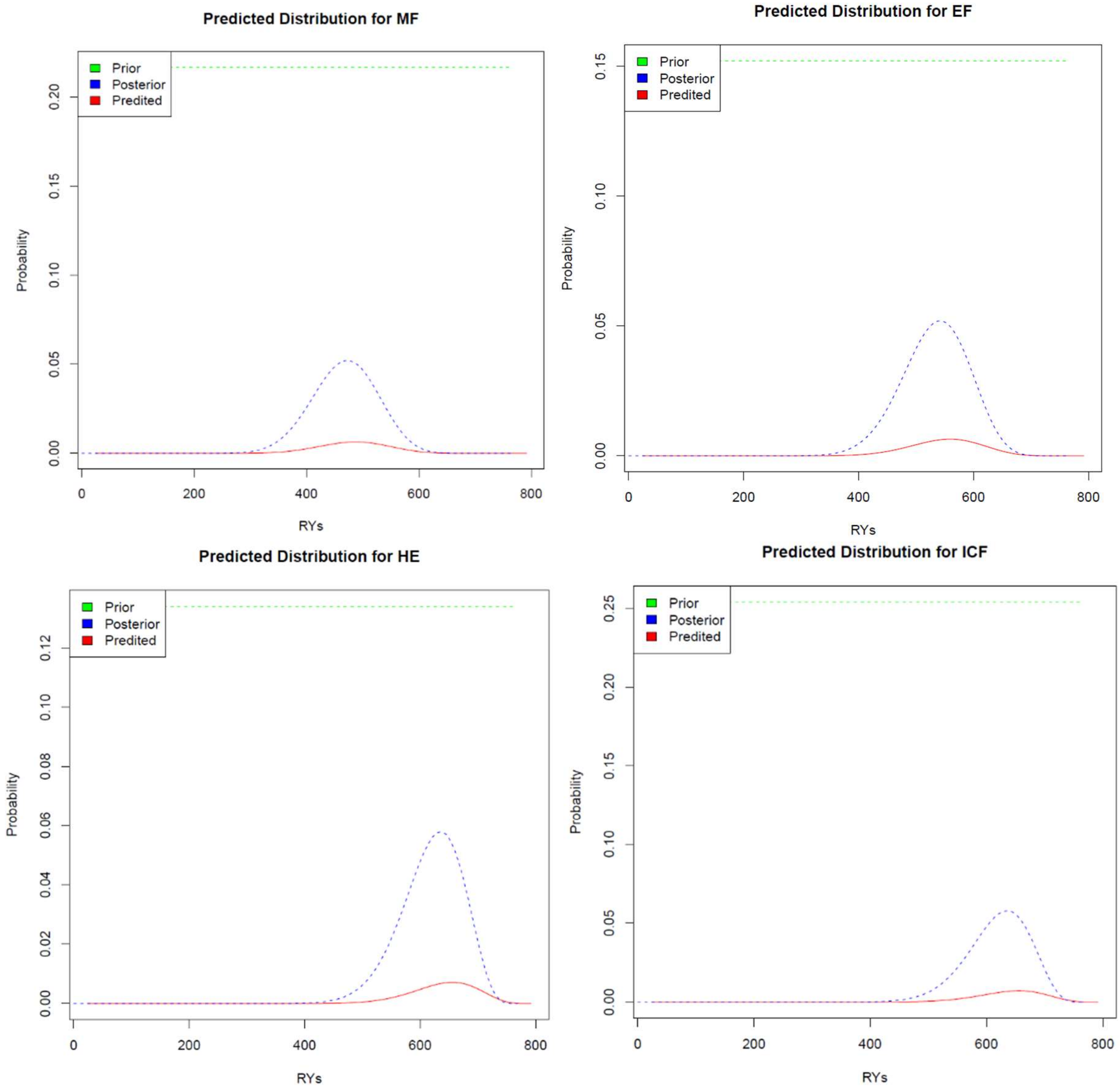

Figure 1. The conditional probabilities of safety culture induced event occurrences during the posterior period between 2016-2023 based on the prior period between 1978–2015

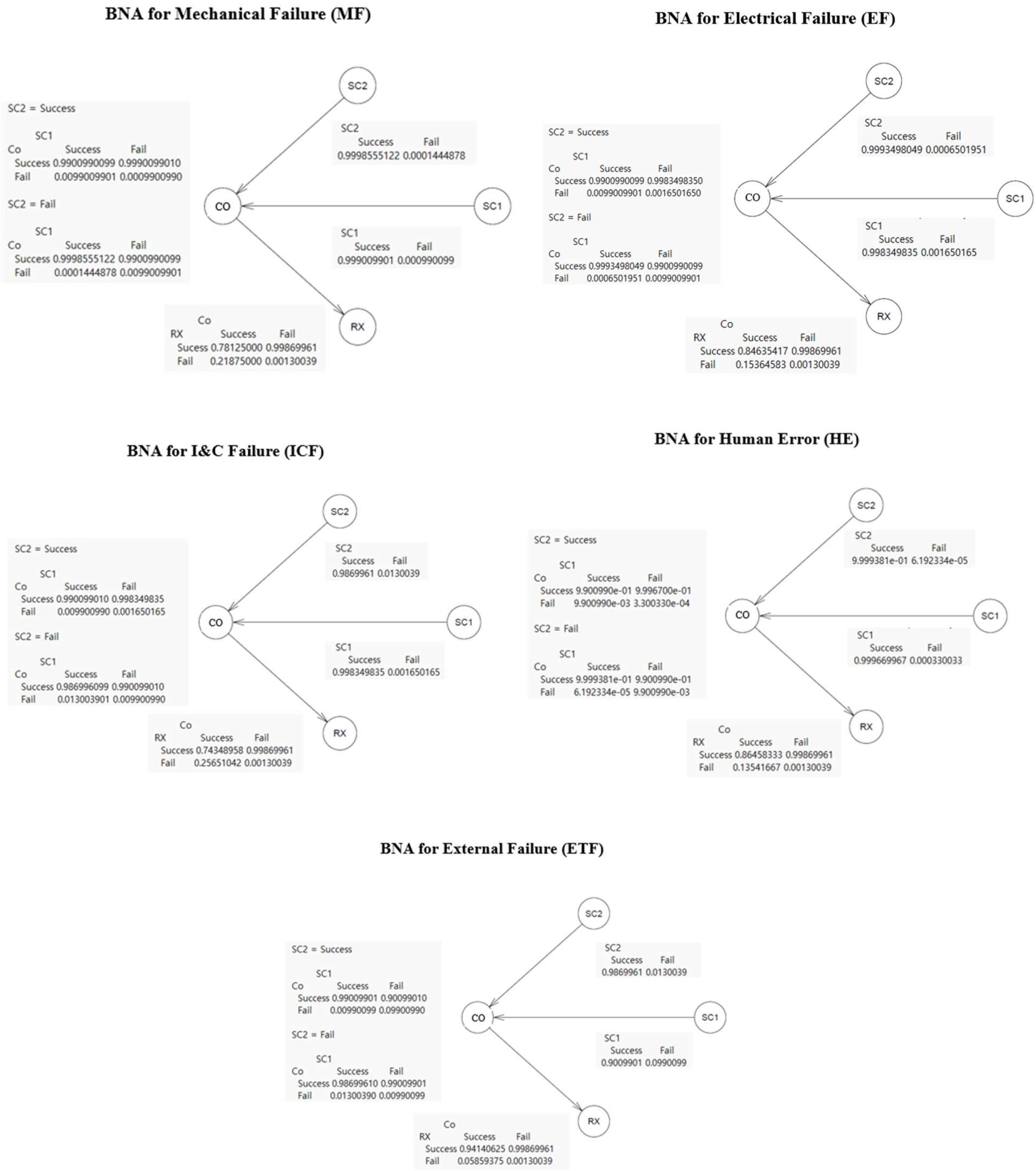

Figure 6. The conditional probability for safety culture induced component failures and event occurrences