Proceedings of the Korean Nuclear Spring Meeting
Gyeong ju, Korea, May 2003

A Method for Risk-Informed Safety Significance Categorization Using the Analytic Hierarchy Process (AHP) and Bayesian Belief Networks (BBN)

Jun Su Ha and Poong Hyun Seong

Korea Advanced Institute of Science and Technology
373-1, Guseong-Dong, Yuseong-Gu, Daejeon, South-Korea, 305-701

Abstract

A risk-informed safety significance categorization (RISSC) is to categorize structures, systems, or components (SSCs) of a nuclear power plant (NPP) into two or more groups, according to their safety significance using both probabilistic and deterministic insights. In the conventional methods for the RISSC, SSCs are quantitatively categorized according to their importance measures for the initial categorization. The final decisions (categorizations) of SSCs, however, are qualitatively made by an expert panel through discussions and adjustments of opinions by using the probabilistic insights compiled in the initial categorization process and combining the probabilistic insights with the deterministic insights. Therefore, owing to the qualitative and linear decision-making process, the conventional methods have the demerits that they are very costly in terms of time and labor; that it is not easy to reach the final decision, when the opinions of the experts are in conflict; and that they have an overlapping process due to the linear paradigm: the categorization is performed twice — first, by the engineers who propose the method, and second, by the expert panel. In this work, a method for RISSC using the AHP and BBN is proposed to overcome the demerits of the conventional methods and to effectively arrive at a final decision (or categorization). By using the AHP and BBN, the expert panel takes part in the early stage of the categorization (that is, the quantification process) and the safety significance based on both probabilistic and deterministic insights is quantified. According to that safety significance, SSCs are quantitatively categorized into three categories such as high safety significant category (Hi), potentially safety significant category (Po), or low safety significant category (Lo). The proposed method was applied to the components such as CC-V073, CV-V530, and SI-V644 in Ulchin Unit 3. By using this method, we could categorize the components quantitatively on the basis of experts' knowledge and experience in an early stage.

1. Introduction

The regulations for design and operation of NPP has traditionally been based upon deterministic approaches that define a set of accidents that the plants must tolerate without incurring significant public health impacts. There is no consideration of the probability of occurrence of the accidents in the deterministic approaches — it is “determined” the accidents will occur, and the plant is designed and operated to prevent and mitigate such accidents [1-2]. As reactor years of operation are accumulated, the data relevant to actual transients, accidents, and plant equipment performance are obtained. As a result, the probabilistic approaches using these data were introduced to estimate the overall risk from plant operation by modeling a large number of potential accident sequences including sequences not considered in the deterministic regulatory basis [1].

At present the NRC has a major effort underway to “risk inform” the regulations using the insights from probabilistic safety assessments (PSA). As a result, with the support of EPRI (Electrical Power Research Institute) and the NEI (Nuclear Energy Institute) and the cooperation of the NRC, the utilities have performed pilot studies in graded quality assurance (GQA), inservice testing (IST), and technical specification (TS). These studies used the risk information available in their plant-specific PSA or IPE (Individual Plant Examinations) to support a more focused use of resources [3].

A risk-informed safety significance categorization (RISSC) is used in risk-informed regulation and application (RIRA) to categorize the SSCs into two or more groups, according to their safety significance using both deterministic and probabilistic insights [4-5].

In addition, recent paradigms for risk-informed decision-making call for a participatory procedure, in which the different stakeholders are involved early in the risk analysis process to “characterize” risks, even before they are given a formal assessment (see Fig. 1.1). This does not diminish the role of modeling and quantification, but is aimed at eliciting the “values” and the perspectives of the community involved so that the multiple dimensions of risk can be taken into account early on in the assessment [6].

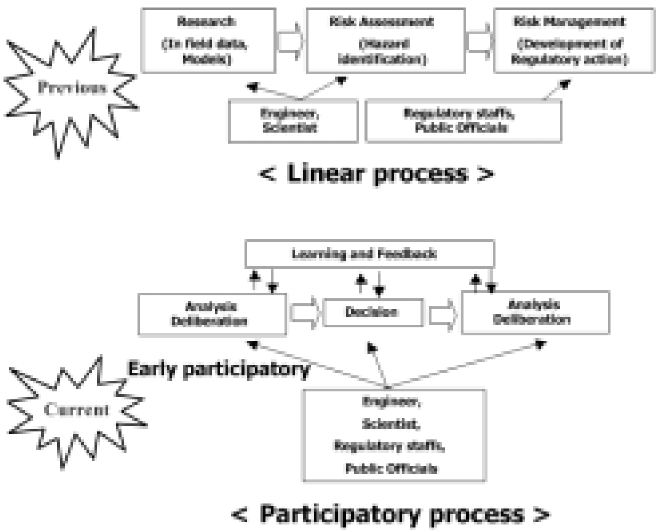

Fig. 1.1 The US NRC, 1982 linear paradigm vs. 1996 participatory paradigm [6]

The conventional methods for RISSC generally have three phases. The first and the second phases are performed by a working group that has developed the RISSC method and then the third phase is performed by an expert panel (or integrated decision-making panel (IDP)). The phases performed by the working group are referred to initial categorization process and the phase by the expert panel integrated decision-making process.

In the first phase, by using the probabilistic insights, the components are allocated into two or more categories, according to their relative importance with respect to core damage frequency (CDF). Usually, Fussell-Vesely (FV) importance and Risk Achievement Worth (RAW) measures are utilized as quantitative safety significance measures [2, 7]. In the second phase, the results of the first phase are supplemented by qualitative assessments based on deterministic insights. In the third and final phase, the expert panel makes qualitatively a final decision (categorization) of SSCs through discussion and adjustments of opinions by using insights compiled in the initial categorization process and combining that with other deterministic insights. As the decisions of the expert panel are arrived at by discussion and adjustments of opinions, the conventional methods have merits that they can consider a variety of opinions of experts and may have a synergy effect through the discussion and adjustments of opinions. On the other hand, they have also demerits as follows: (1) They are very costly in terms of time and labor. Since there were a multitude of SSCs in a NPP, there are limitations to the application of the conventional method. (2) When the opinions of the experts are in conflict, it is not easy to reach the final decision. (3) They may have an overlapping process due to the linear paradigm shown in Fig. 1.1: the categorization is performed twice — first, by the working group that propose the method, and second, by the expert panel.

In this work, we propose a RISSC method that can overcome the above demerits of the conventional method and allow us to effectively arrive at a final decision (or categorization). We use both the importance analyses of PSA and the qualitative assessments based on the deterministic insights as decision factors for the decision problem RISSC and both the probabilistic and the deterministic insights are based on level 1 and 2 internal event PSA and normal operating conditions. To improve the overall decision-making process and perform integrated evaluation quantitatively, we introduce the early participatory of the expert panel using the AHP and BBN to the RISSC, as shown in Fig. 1.2.

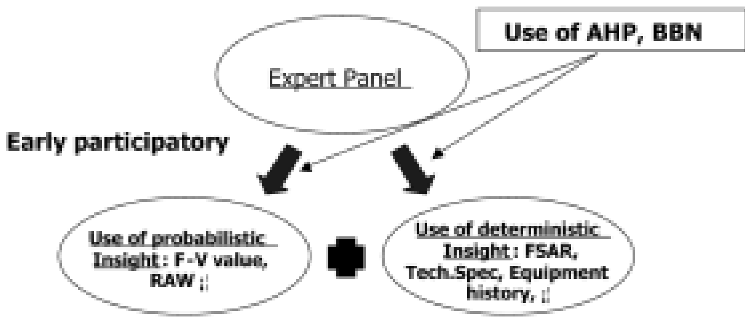

Fig. 1.2 Early participatory of expert panel using AHP and BBN

We explain a method for RISSC using AHP and BBN in section 2. Applications and results of the proposed method to the components such as CC-V073, CV-V530, and SI-

V644 in Ulchin Unit 3 are given in section 3. Discussions are given in section 4. Finally, conclusions are presented in section 5.

2. A Method for RISSC Using the AHP and BBN

2.1. Probabilistic and Deterministic Insights

A RISSC is performed using probabilistic and deterministic insights. Hence we, first, have to identify the probabilistic and deterministic insights that are available. In this work, both the probabilistic and the deterministic insights are based on level 1 and 2 internal event PSA and normal operating conditions.

In the case of probabilistic insights, the risk importance measures of PSA are commonly used for RISSC. The most often used measures are the FV importance and the RAW [2, 7]. The FV importance and RAW are evaluated through the importance analysis of the PSA. There are various importance analyses in PSA, such as basic analyses and sensitivity analyses. The FV importance and RAW in the basic analyses are calculated with mean failure rates by failure modes of a component including common cause failure (CCF). On the other hand the FV importance and RAW in the sensitivity analyses are recalculated after increasing and/or decreasing the failure rates of the component(s) that include single event failure (SEF) and CCF rates or modifying the PSA models (i.e. minimizing or removing test and maintenance unavailabilities, removing the human actions to recover from specific component failures, changing a truncation limit, and so on in the PSA models) [4]. The importance measures of the PSA, however, have limitations associated with the structure of the PSA model, their assumptions, and the input data. Although the sensitivity analyses are performed in the abovementioned manner to complement the limitations, they cannot ensure the result of the safety significance categorization. Therefore, the qualitative assessments based on deterministic insights such as the functional attributes of SSCs are used for validating and complementing the result of the importance analyses [2, 8]. The significant attributes in the qualitative assessments are the impact of the SSCs on initiating events and the SSCs functions that are important to the prevention or mitigation of the core damage and the consequences of accidents that can result in potential offsite exposure [9]. Hence, the qualitative assessments are determined on the basis of the following: (1) the key plant safety functions that ensure the integrity of the reactor coolant pressure boundary, that ensure the capability to shutdown and maintain the reactor in a safe shutdown condition, and that ensure the capability to prevent or mitigate the consequences of accidents that can result in potential offsite exposure; (2) the specific normal operating functions that can result in the initiating events or shutdown scrams and that prevent or mitigate abnormal conditions. In this work, the deterministic insights include the following qualitative assessments [5, 9, 10]:

- Accident response functions
  - Is the SSC required to shut down the reactor and maintain if in safe shutdown condition?
  - Is the SSC required to maintain the reactor coolant pressure and fuel cladding boundaries?

  - Is the SSC required to remove atmospheric heat and radioactivity from containment and maintain containment integrity?
  - Is the SSC required to remove heat from the reactor?
- Normal operations
  - Is the SSC required to provide primary side heat removal?
  - Is the SSC required for power conversion?
  - Is the SSC required for primary, secondary, or containment pressure control?
  - Is the SSC required to provide cooling water, component, or room cooling?

Consequently, the importance analyses and the qualitative assessments are utilized as decision factors for RISSC in this work.

2.2 Early Participatory of the expert panel

In order to make a decision in the RISSC, the decision problem shall be analyzed. The decision problem consists of the decision factors such as the importance analyses and the qualitative assessments. Consequently, the safety significances in the respective decision factors shall be evaluated and the results of the evaluations reflected in the final decision. Also, the reflection of the results shall be conducted according to the relative importance of the decision factors.

In this work, we introduce the early participatory of the expert panel using the AHP and BBN to improve the overall decision-making process and perform an integrated evaluation quantitatively. The early participatory of the expert panel is applied to perform the RISSC in an early stage on the basis of the expert's knowledge and experience; the AHP to structure the decision problem RISSC with the decision factors and to obtain the relative importance of the decision factors, that is, the weighting values of the decision factors; and the BBN to evaluate the probabilities that a component falls in *Hi (high safety significant category)* in the respective decision factors as safety significances in the respective decision factors.

2.3 Setting up the Decision Hierarchy using the AHP

The AHP has the merits of being useful to structure a decision problem hierarchically and to obtain the weighting values quantitatively. The AHP serves as a framework to structure complex decision problems and provide judgments based on the expert's knowledge and experience to derive a set of weighting values by using the pair-wise comparison [11].

As shown in Fig. 2.1, the decision problem is the RISSC and the decision hierarchy is set up by breaking down the decision problem into a hierarchy of interrelated decision elements. The decision is made using both the probabilistic and deterministic insights. The probabilistic insights include the level 1 and 2 PSA. The level 1 PSA is based on CDF and the level 2 PSA large early release frequency (LERF), respectively. The level 1 and 2 PSA for the RISSC include the importance analyses. Also, the deterministic insights consist of the qualitative assessments. The decision factors are located in the respective bottom level.

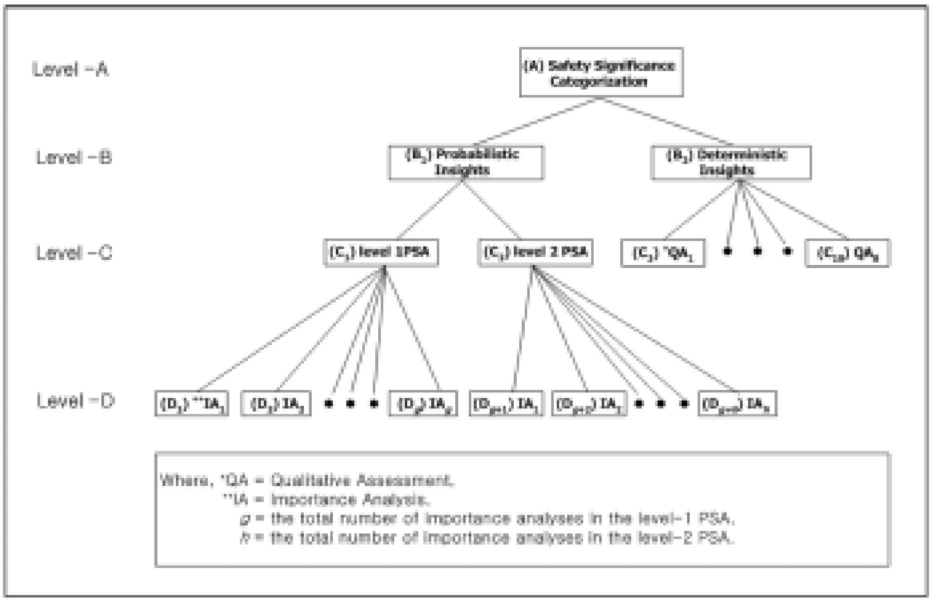

Fig. 2.1 Setting up the decision hierarchy

2.4 Calculating the Probabilities that Target Component Falls in Hi in the Respective Decision Factors using BBN

In this work, the safety significances in the respective decision factors are represented as the probabilities that a component falls in *Hi* in the respective decision factors. By using the BBN, those probabilities are evaluated on the basis of the experts' knowledge and experience. The probability that a component falls in *Hi* in decision factor-*i* (i=1, 2,…, l, where l is the total number of the decision factors) is denoted by $P(S_i=Hi)$. The most useful merit of the application of the BBN to the evaluations is that the probabilities, $P(S_i=Hi)$ can be updated, as the evaluations performed by experts are compiled.

When an expert performs the evaluation in a certain decision factor, the expert probably thinks that if the component falls in a certain criterion, the component falls in a certain safety significance category with certainty x or if a component falls in a certain safety significance category, the component falls in a certain criterion with certainty y. The basic concept in the Bayesian treatment of certainties in causal networks is *conditional probability* (e.g. the certainty x *or* y) [12]. In this work, the conditional probability is the certainty based on the expert's knowledge and experience.

The BBN model for calculating $P(S_i=Hi)$ consists of one parent variable S_i and the same number of child variables C_{ij} as the total number of the relevant experts (or evaluators) and a set of directed edges between variables, as shown in Fig. 2.2. The variable S_i represents that the component falls in *Hi (High safety significant category)* or *Lo (Low safety significant category)* in decision factor-*i* and the variable C_{ij} represents that a component falls in a certain decision criterion, such as c_1, c_2,…, or c_m in decision factor-*i*, on the basis of the judgment of expert-*j* (j=1, 2,…, n, where n is the total number of the experts), where m is the total number of the criteria in decision factor-*i*. Each variable has a finite set of mutually exclusive states. To variable C_{ij} for each j with parent S_i there is attached a conditional probability table $P(C_{ij}|S_i)$; If S_i has no parents then the table reduces to unconditional probabilities $P(S_i)$

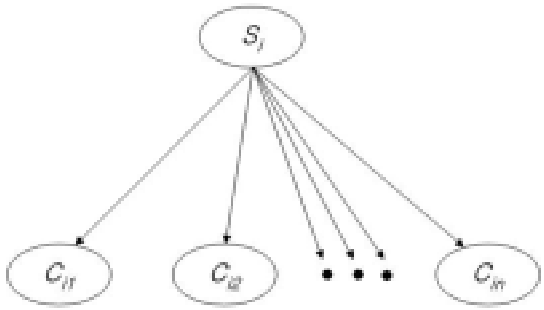

Fig. 2.2 A BBN model in decision factor-*i*

The decision criteria in the importance analyses of the PSA and the qualitative assessments based on the deterministic insights are shown in Fig. 2.3 and Table 2.1, respectively.

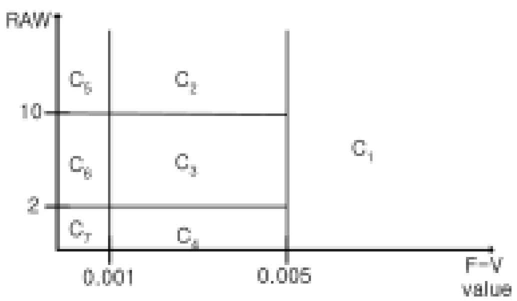

Fig. 2.3 Decision criteria in the importance analyses

Criteria	Descriptions
C_1	**A component is required directly and there are no other systems or components that perform an identical or similar function**
C_2	**A component is required directly and there is one more system or component that performs an identical or similar function**
C_3	**A component is required directly and there are two or more systems or components that perform an identical or similar function**
C_4	**A component is required indirectly (e.g. the component that can affect the human action(s) or component(s) required directly in the above attribute and so on.)**
C_5	**A component is not required at all**

Table 2.1 Decision criteria in the qualitative assessments

In order to complete the BBN models , conditional probabilities $P(C_{ij}|S_i)$ are needed. The conditional probabilities $P(S_i|C_{ij})$ are easier to come by than the conditional probabilities $P(C_{ij}|S_i)$. We, first, obtain $P(S_i|C_{ij})$ from the experts comprising the expert panel.

When the experts evaluate $P(S_i|C_{ij})$, it is not easy for the experts to evaluate $P(S_i|C_{ij})$ as point values. $P(S_i|C_{ij})$, hence, is evaluated band values, as shown in Table 2.2 and the medians of the band values are used as the representative values to compute $P(S_i|C_{ij})$. If the median of the band value is not appropriate on the basis of an expert's opinion, an expert can substitute appropriate one for the median.

Degree of Safety Significance	*P (S=Hi)*	*P (S=Lo)*
(1) Very significant	**1.0 ~ 0.8 (0.9)**	**0.2 ~ 0.0 (0.1)**
(2) Significant	**0.8 ~ 0.6 (0.7)**	**0.4 ~ 0.2 (0.3)**
(3) Potentially significant	**0.6 ~ 0.4 (0.5)**	**0.6 ~ 0.4 (0.5)**
(4) Low significant	**0.4 ~ 0.2 (0.3)**	**0.8 ~ 0.6 (0.7)**
(5) Very low significant	**0.2 ~ 0.0 (0.1)**	**1.0 ~ 0.8 (0.9)**

Table 2.2 Band values for the experts' evaluations

If $P(S_i|C_{ij})$ for each i and j is obtained, $P(C_{ij}|S_i)$ for each i and j can be calculated using Bayes' theorem, as follows:

$$\begin{aligned} P(C_{ij} \mid S_i) &= \frac{P(S_i \mid C_{ij}) \times P(C_{ij})}{P(S_i)} \\ &= \frac{P(S_i \mid C_{ij}) \times P(C_{ij})}{P(S_i \mid C_{ij} = c_1) \times P(C_{ij} = c_1) + \ldots + P(S_i \mid C_{ij} = c_m) \times P(C_{ij} = c_m)} \\ &= \frac{P(S_i \mid C_{ij}) \times P(C_{ij})}{\sum_{k=1}^{m} P(S_i \mid C_{ij} = c_k) \times P(C_{ij} = c_k)} \end{aligned} \tag{1}$$

If no information is provided, let us assume that $P(C_{ij}=c_1)=,\ldots,= P(C_{ij}=c_m)=1/m$. $P(C_{ij}|S_i)$ for each i and j can be calculated using Eq. (1) with $P(S_i|C_{ij})$. If the conditional probability table $P(C_{ij}|S_i)$ are obtained, the construction of the BBN model for each i is completed.

Now, if a target component is selected, we update $P(S_i)$ for each i using the evidences judged by experts. First, if expert-1 judges that the target component falls in c_1 in decision factor- i, that is, $P^*(C_{i1})$ = (1, 0, 0, …), where evidence on C_{ij} is denoted by $P^*(C_{ij})$ or E_{ij} ($P^*(C_{ij}) = E_{ij}$), the probabilities $P^*(C_{i1})$ = (1, 0, 0, …) are utilized as evidence to update $P(S_i=Hi)$, as follows:

$$\begin{aligned} P^*(S_i = Hi) &= P(S_i = Hi \mid C_{i1} = c_1) \times P^*(C_{i1} = c_1) + \ldots + P(S_i = Hi \mid C_{i1} = c_m) \times P^*(C_{i1} = c_m) \\ &= P(S_i = Hi \mid C_{i1} = c_1) \times P^*(C_{i1} = c_1) \end{aligned} \tag{2}$$

as we already know $P(S_i|C_{i1})$ and $P^*(C_{i1}=c_1)=1$, we can calculate $P^*(S_i=Hi)$ using Eq. (2), where the probability updated by evidence is denoted by *the probability**. In the case of the second update of $P(S_i)$, if expert-2 judges that the target component falls in c_2 in decision factor- i, that is, $P^*(C_{i2})$ = (0, 1, 0, …), the probability is utilized as evidence to update $P^*(S_i=Hi)$ by using Bayes' theorem, as follows:

$$
\begin{aligned}
P^*(S_i = Hi \mid C_{i2} = c_2) &= \frac{P(C_{i2} = c_2 \mid S_i = Hi) \times P^*(S_i = Hi)}{P(C_{i2} = c_2)} \\
&= \frac{P(C_{i2} = c_2 \mid S_i = Hi) \times P^*(S_i = Hi)}{P(C_{i2} = c_2 \mid S_i = Hi) \times P^*(S_i = Hi) + P(C_{i2} = c_2 \mid S_i = Lo) \times P^*(S_i = Lo)}
\end{aligned} \tag{3}
$$

where, $P(C_{i2}=c_2|S_i=Hi)$, $P(C_{i2}=c_2|S_i=Lo)$ and $P^*(S_i=Hi)$ are already known and $P^*(S_i=Lo)$ = 1- $P^*(S_i=Hi)$. Consequently, we can calculate $P^*(S_i=H\ |C_{i2}=c_2)$, which is used for calculating $P^{**}(S_i=Hi)$ that is the second updated $P(S_i=Hi)$.

$$
\begin{aligned}
P^{**}(S_i = Hi) &= P^*(S_i = Hi \mid C_{i2} = c_1) \times P^*(C_{i2} = c_1) + \ldots + P^*(S_i = Hi \mid C_{i2} = c_m) \times P^*(C_{i2} = c_m) \\
&= P^*(S_i = Hi \mid C_{i2} = c_2) \times P^*(C_{i2} = c_2) \\
&(\because P^*(C_{i2}) = (0, 1, 0, \ldots)).
\end{aligned} \tag{4}
$$

In the similar manner, $P(S_i=Hi)$ for each i is updated until the final evidence judge by expert-n is used. Consequently, as the evidences judged by the experts are added into the BBN model, the more reasonable and informed $P(S_i=Hi)$ is obtained.

If the updated $P(S_i=Hi)$ for each i is obtained completely, the weighting values of the respective decision factors are evaluated using the AHP on the basis of the expert's knowledge and experience.

2.5 Evaluating the Weighting Value of the Respective Decision Factors using the AHP

To compute the weighting values of the decision factors using the AHP, we first must obtain the input data for given problems comprising judgment matrices of pair-wise comparisons of the decision elements in one level that contribute to satisfying the objectives of the decision elements in the next higher level. Every element of a judgment matrix can be obtained from such a questioning as: consider, for example, item A and item B; which one contributes more toward objective K and what is the strength of its contribution relative to the other one? Whenever the *pq*–th element of the matrix is filled out, the *qp*–th position is automatically filled out by its reciprocal value.

Second, if all the judgment matrices are provided by the respective experts, combined judgment matrices are obtained by taking geometric mean over all the same elements of the matrices provided by the respective experts as follows [11]:

$$
\bar{a}_{pq} = \prod_{j=1}^{n} (a_{pqj})^{1/n} \tag{5}
$$

where $\bar{a}_{pq}$ is the element (p, q) of the combined judgment matrix, a_{pqj} is the element (p, q)

of the matrix provided by expert-j, and n is the number of the experts. The most important reason to use geometric mean is that it satisfies the reciprocal property of pair-wise comparison: for exaple, if one person assigns the value c and the other the value $1/c$, then the mean should be 1 and not $[c+(1/c)]/2$.

Third, the relative weights of the decision elements are estimated with the combined judgment matrices by using the Saaty's eigenvalue method, as follows [11]: a combined judgment matrix, say, A of size $s{.}s$ has a maximal eigenvalue and the corresponding eigenvector whose components are all positive. This eigenvector, when it is normalized so that its components sum to unity, is a ratio scale which is the estimates of relative weights of s objects in comparison. Thus, the estimation of relative weights can be obtained from

$$A_{n \times n} W = \lambda_{max} W \tag{6}$$

where A is observed matrix of pair-wise comparisons, λ_{max} is the largest eigenvalue of A, and W is its right eigenvector. This is called the eigenvalue method (EM) of Saaty [13].

Finally, the weighting values of the respective decision factors at the bottom level of a hierarchy is computed by aggregating the relative weights of various elements in the hierarchy. For a complete hierarchy of AHP, the formula of computing the weighting value w_i of decision factor-i can be written as

$$w_i = w^{u_i/u-1} \times w^{u-1/u-2} \times \ldots \times w^{u-v/u_t} \tag{7}$$

where, we denote by $w^{u/u\text{-}1}$ the relative weight of decision element-(u) with respect to decision element-(u-1) which is the immediate higher level of and connected to decision element-(u), u_i represents that decision element-(u_i) is decision factor-i, v is the number of the levels between decision factor-i and the decision problem located in the top level of the hierarchy, and the decision problem is denoted by u_t

2.6 Final Categorization

The weighting values w_i and the updated probabilities $P(S_i=Hi)$ are integrated into the total probability $P(S_T=Hi)$, as follows:

$$P(S_T = Hi) = w_1 P(S_1 = Hi) + w_2 P(S_2 = Hi) + \ldots + w_l P(S_l = Hi) \tag{8}$$

where, l is the total number of the decision factors.

The final safety significance based on both the probabilistic and deterministic insights is represented as the total probability. Consequently, the final decisions in the RISSC are made according to the total probability $P(S_T=Hi)$: if the total probability of the target component is greater than 0.6, that component is categorized into Hi; if the total probability is smaller than 0.6 and greater than 0.4, that component is categorized into Po; if the total probability is smaller than 0.4, that component is categorized into Lo.

3. Applications and Results

In this section, the method for RISSC using the AHP and BBN was applied to the components, such as CC-V073, CV-V530, and SI-V644 in Ulchin Unit 3. The expert panel consisted of two PSA experts and one system design expert. The decision factors such as the importance analyses of the PSA were evaluated by two PSA experts, because the other expert had relatively poor expertise on PSA; and the decision factors such as the qualitative assessments based on the deterministic insight were evaluated by all the experts.

The main purpose of the qualitative assessments is to validate and complement the result of the PSA. To compare the categorization results based only on the PSA with those based only on the qualitative assessments, the categorizations based on the PSA and qualitative assessments were performed separately. The total probability for the categorization based only on the PSA is denoted by $P(S_{PT}=Hi)$ and the total probability only on the qualitative assessments is denoted by $P(S_{DT}=Hi)$. In the final integration step, $P(S_{PT}=Hi)$ and $P(S_{DT}=Hi)$ are integrated into $P(S_T=Hi)$ with even relative weights, that is, they are integrated into the average value. Before categorizing the components, the design basis functions, the simplified P & IDs, and the FV and the RAW values of the PSA were prepared for the experts' evaluations.

In the preliminary step, first, the decision factors considered in these applications were identified, as shown in Table 3.1 [7, 9].

Decision Factor (DF)				Description
DF_1	IA_1	Importance Analysis (IA)	Level 1 PSA	Basic analysis 1: single event failure (SEF)
DF_2	IA_2			Basic analysis 2: common cause failure (CCF)
DF_3	IA_3			Sensitivity analysis 1: without consideration of CCF
DF_4	IA_4			Sensitivity analysis 2: SEF, without recovery action
DF_5	IA_5			Sensitivity analysis 3: CCF, without recovery action
DF_6	IA_6			Sensitivity analysis 4: 95% value of SEF
DF_7	IA_7			Sensitivity analysis 5: 95% value of CCF
DF_8	IA_8		Level 2 PSA	Basic analysis 1: SEF
DF_9	IA_9			Basic analysis 2: CCF
DF_{10}	QA_1	Qualitative Assessment (QA)	Accident response function	Is the SSC required to shut down reactor and maintain if in safe shutdown condition?
DF_{11}	QA_2			Is the SSC required to maintain the reactor coolant pressure and fuel cladding boundaries?
DF_{12}	QA_3			Is the SSC required to remove atmospheric heat and radioactivity from containment and maintain containment integrity?
DF_{13}	QA_4			Is the SSC required to remove heat from the reactor?
DF_{14}	QA_5		Normal operations	Is the SSC required to provide primary side heat removal?
DF_{15}	QA_6			Is the SSC required for power conversion?
DF_{16}	QA_7			Is the SSC required for primary, secondary, or containment pressure control?
DF_{17}	QA_8			Is the SSC required to provide cooling water, component, or room cooling?

Table 3.1 Decision factors considered in the applications [7, 9]

Second, the conditional probabilities $P(S_i|C_{ij})$ were obtained from the experts and the required probabilities $P(C_{ij}|S_i)$ were computed using Bayes' theorem. And then the BBN models for the importance analyses and qualitative assessments were constructed by using the probabilities $P(C_{ij}|S_i)$.

In the implementation step, CC-V073, CV-V530, and SI-V644 were selected as the target components. And then, first, the decision factors that are available in the case of CC-V073 were identified and the decision hierarchy was revised. Second, the experts determined the criteria that CC-V073 falls in in the respective decision factors and the results were used to update the $P\,(S_i{=}Hi)$ as evidences. Third, the weighting values of the respective decision factors were computed by using the AHP. Finally, by using Eq. (8), the updated probabilities $P\,(S_i{=}Hi)$ and the weighting values w_i for each i were integrated into the total probabilities $P(S_{PT}{=}Hi)$, $P(S_{DT}{=}Hi)$, and $P\,(S_T{=}Hi)$, as follows:

$$P(S_{PT} = Hi) = w_1 P^{**}(S_1 = Hi) + w_2 P^{**}(S_2 = Hi) + \ldots + w_7 P^{**}(S_7 = Hi) \tag{9}$$

$$P(S_{DT} = Hi) = w_8 P^{***}(S_8 = Hi) + w_9 P^{***}(S_9 = Hi) + \ldots + w_{15} P^{***}(S_{15} = Hi) \tag{10}$$

$$P(S_T = Hi) = 0.5P(S_{PT} = Hi) + 0.5(S_{DT} = Hi) \tag{11}$$

In the similar manner, the total probabilities P($S_{PT}{=}Hi$), P($S_{DT}{=}Hi$), and P ($S_T{=}Hi$) for CV-V530 and SI-V644 were calculated and then the three components were categorized on the basis of the probabilities, as shown in Table 3.2.

	CC-V073		**CV-V530**		**SI-644**	
	Value	**Category**	**Value**	**Category**	**Value**	**Category**
$P(S_{PT}{=}Hi)$	**0.21**	**Lo**	**0.74**	**Hi**	**0.001**	**Lo**
$P(S_{DT}{=}Hi)$	**0.48**	**Po**	**0.57**	**Po**	**0.18**	**Lo**
$P(P_T{=}Hi)$	**0.35**	**Lo**	**0.66**	**Hi**	**0.09**	**Lo**

Table 3.2 The results of the applications

4. Discussions

In this section, we will discuss the results of the importance analyses of PSA first. The important decision factors among the importance analyses are the basic analyses based on CDF or LERF, because the sensitivity analyses are based on the events that hardly occur. If, however, the impact of the results of the sensitivity analyses on the safety of NPP is significant, the sensitivity analyses shall be considered significant for the safety significance categorization. Basic analysis 1 is based on the single event failure, but on the other hand, basic analysis 2 is based on CCF, that is, basic analysis 1 is based on the FV and RAW measures that include only the target component that has the single event failure, but basic analysis 2 is based on the FV and RAW measures that include all the components that have CCF. It seldom occurs that all the components that have CCF fail at the same time. However, if the impact of CCF is significant in NPP, the basic analysis 2 shall be considered significant for the safety significance categorization.

With respect to CC-V073, the important decision factors were found to be DF-1 with w_1 0.2313, DF-2 with w_2 0.1391, DF-6 with w_6 0.2320, and DF-7 with w_7 0.1340. In the consideration of the weighting values of the decision factors w_i, $P(S_{PT}{=}Hi)$ was computed to be 0.21 quantitatively and the CC-V073 fell in Lo on the basis of PSA. Similarly, with respect to CV-V530, the important decision factor was found to be DF-3 with w_3 0.5858, $P(S_{PT}=Hi)$ was computed to be 0.74 quantitatively and the CV-V530 fell in Hi on the basis of PSA. With respect to SI-V644, the important decision factors were found to be DF-1 with w_1 0.2583 and DF-4 with w_4 0.4142, $P(S_{PT}=Hi)$ was computed to be 0.001 quantitatively and the SI-V644 fell in Lo on the basis of PSA. Consequently, the final decisions were made quantitatively and reasonably by using the proposed method.

Second, in a RISSC, the main purpose of the qualitative assessments is to validate and complement the results of the importance analyses of PSA. If the proposed method is reasonable, the results of the importance analyses and those of the qualitative assessments may be consistent or a little different in the numerous evaluations. In this work, when the decision criteria of the categorization in the importance analyses and the qualitative assessments are set to 0.5, the results of the importance analyses and those of the qualitative assessments are consistent in each evaluation. Although the decision criteria are set to 0.4 and 0.6 in consideration of uncertainty, only two categories are changed into Po. Because the Po is the intermediate category between Hi and Lo, we can say that the difference between the results is slight. Consequently, the qualitative assessments are found to be reasonable.

Third, the final decisions were made without discussion or adjustment of opinions of experts but by using BBN, the evaluations by the respective experts were reflected into the final evaluations. The evaluations in the respective decision factors were performed without an overlapping process, because the early participatory of the expert panel was introduced.

Fourth, in the qualitative assessment QA-1 for the RISSC of CC-V073, while expert-1 and expert-3 decided that CC-V073 fell in c_2, expert-2 decided that CC-V073 fell in c_3, that is, there were differing opinions. The evaluations performed by the respective experts, however, were reflected in the final result $P^{***}(S_i=Hi)$ by using BBN. In the importance analyses IA-3 and IA-4 for the RISSC of CC-V073, there might be differing opinions if the conventional qualitative evaluation through discussion was applied. While expert-1 might decide that decision factor IA-4 was more important than IA-3, expert-2 might decide that decision factor IA-3 was more important than IA-4. It might be time-consuming and difficult to resolve the differing opinions, because the evaluations were performed qualitatively. In this work, the weighting values of IA-3 and IA-4 were evaluated quantitatively by using the AHP. Expert-1 evaluated the weighting value of IA-3 as 0.0696 and that of IA-4 0.0888. Expert-2 evaluated the weighting value of IA-3 as 0.1592 and that of IA-4 as 0.0896. The integrated weighting value of IA-3 was 0.1101 and that of IA-4 was 0.0930. Consequently, the weighting value of IA-3 was 0.0171 more important than that of IA-4. The differing opinions of experts could be resolved through the quantitative process of the proposed method.

5. Conclusions

A risk-informed safety significance categorization (RISSC) is to categorize the SSCs of a NPP into two or more groups, according to their safety significance using both probabilistic and deterministic insights [4, 5]. In this work, a method for risk-informed safety significance categorization (RISSC) using the AHP and BBN is proposed to overcome the demerits of the conventional methods and to effectively arrive at a final decision (or categorization). The demerits seemed to result from the process of qualitative and linear decision-making through discussion and adjustments of opinions. Hence, to improve the overall decision-making process and perform an integrated evaluation quantitatively, the early participatory of the expert panel using the AHP and BBN is introduced to the RISSC. The early participatory of the expert panel is applied to perform the RISSC in an early stage on the basis of the expert's knowledge and experience; the AHP to structure the decision problem RISSC with the decision factors and to obtain the relative importance of the decision factors, that is, the weighting values of the decision factors; the BBN to evaluate the probabilities that a component falls in *Hi (high safety significant category)* in the respective decision factors as safety significances in the respective decision factors. The weighting values of the decision factors and the probabilities that a component falls in *Hi* in the respective decision factors are integrated into the total probability. The total probability is utilized as the final safety significance for the decision-making in the RISSC. According to that safety significance, SSCs are quantitatively categorized into three categories such as high safety significant category (Hi), potentially safety significant category (Po), or low safety significant category (Lo). In order to demonstrate the utility of the proposed method, it was applied to the components, such as CC-V073, CV-V530 and SI-V644 in Ulchin Unit 3. By using this method, we could categorize the components quantitatively on the basis of experts' knowledge and experience in an early stage. From the results of the applications, the proposed method was shown to be able to overcome the abovementioned demerits of the conventional methods; we could arrive at final decisions effectively; and the application results show that the method is reasonable. Consequently, we conclude that the method proposed in this work is reasonable and useful.

A NPP consists of a large number of components. Some of the components are modeled in PSA, the others not modeled in PSA. As it is likely to take much time and effort to categorize the components with the conventional RISSC method, the proposed method will be useful. However, because the probabilistic and deterministic insights used in this method are based only on level 1 and 2 internal event PSA and normal operating conditions, the study on other conditions should be followed in order to perform the RISSC based on all the conditions of a NPP.

References

[1] NEI Risk Applications Task Force and NEI Risk-Informed Regulatory Working Group. Option 2 Implementation Guideline. NEI/NEI 00-04 (DRAFT-Revision A2), 2000.

[2] Ian B. Wall, John. J. Haugh, David. H. Worlege. Recent Application of PSA for Managing Nuclear Power Plant Safety. Progress in Nuclear Energy, Vol. 39, No. 3-4, pp. 367-425, 2001.

[3] B. John Garrick, Robert F. Christie. Probabilistic Risk Assessment Practices in the USA for Nuclear Power Plants. Safety Science, Vol. 40, pp. 177-201, 2002.

[4] Michael C. Cheok, Gareth W. Parry, Richard R. Sherry. Use of Importance measures in risk-informed regulatory applications. Reliability Engineering and System Safety, Vol. 60, pp.

213-226, 1998.

[5] ASME OMN-3 Code Case. Requirements for Safety Significance Categorization of Pump and Valve Components Using Risk Insights for Inservice Testing of LWR Power Plants. 1998.

[6] Aniello Amendola. Recent paradigms for risk-informed decision making. Safety Science, Vol. 40, pp. 17-30, 2001.

[7] D. I. Kang. Risk-Informed Importance Analysis of In-Service Testing Components for Ulchin Unit 3. KAERI/TR-1927, 2001.

[8] W. J. Parkinson. Risk-Based In-Service Testing Program for Comanche Peak Steam Electric Station. EPRI/TR-105870, 1995.

[9] Nuclear Energy Institute. Industry Guideline for Monitoring the Effectiveness of Maintenance at Nuclear Power Plant. NUMARC 93-01 (Revision 2), 1996.

[10] Nuclear Generation Group Nuclear Engineering Standard NES-G-15.02. Maintenance Rule: Risk Significance Determination Standard. ComEd, 2000.

[11] T. L. Saaty. The Analytic Hierarchy Process. McGraw-Hill, 1980.

[12] Finn V. Jensen. An Introduction to Bayesian Networks. Springer-Verlag New York, Inc., 1996.

[13] F. Zahedi. The Analytic Hierarchy Process: a survey of the method and its applications. Interfaces, 16, pp.96-108, 1986.