Nuclear Engineering and Technology 54 (2022) 2067–2076

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Graded approach to determine the frequency and difficulty of safety culture attributes: The F-D matrix

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ARTICLE INFO

Article history:
Received 25 June 2021
Received in revised form
20 November 2021
Accepted 20 December 2021
Available online 23 December 2021

Keywords:
Nuclear safety culture
Harmonized safety culture model
Graded approach
Safety culture analysis
Analytic hierarchy process

ABSTRACT

The importance of safety culture has been emphasized to achieve a high level of safety. In this light, a systematic method to more properly deal with safety culture is necessary. Here, a decision-making tool that can apply a graded approach to the analysis of safety culture is proposed, called the F-D matrix, which determines the frequency and the difficulty of safety culture attributes recently defined by the IAEA. A hierarchical model of difficulty contributors was developed as a scoring standard, and its elements were weighted via expert evaluation using the analytic hierarchy process. The frequency of the attributes was derived by analyzing reported events from nuclear power plants in the Republic of Korea. Period-by-period comparisons with the F-D matrix can show trends in the change of the maturity level of an organization's safety culture and help to evaluate the effectiveness of previously implemented measures. In the evaluating the difficulty of the attributes in the recently developed harmonized safety culture model, the difficulties of Trending, Benchmarking, Resilience, and Documentation and Procedures were found to be relatively high, while the difficulties of Conflicts are Resolved, Ownership, Collaboration, and Respect is Evident were found to be relatively low. A case study was conducted with an analysis period of 10 years to attempt to reflect the many changes in safety culture that have been made following the Fukushima accident in March 2011. As a result of comparing two periods following the Fukushima accident, the overall frequency decreased by about 40%, providing evidence for the effects of the various improvements and measures taken following the increased emphasis on safety culture. The proposed F-D matrix provides a new analytical perspective and enables an in-depth analysis of safety culture.

1. Introduction

Remarkable safety achievements have been made in terms of technological aspects among the various factors that constitute safety in the nuclear field. Nevertheless, occasional abnormal events indicate the need for extensive efforts to improve safety beyond the technical aspects. One characteristic of some these cases is that certain elements related to the safety culture of the organization, such as the attitudes and perceptions of workers and organizational practices, have been revealed as the root cause or as contributing factors of the incidents [1–4]. Since nuclear power plants are designed, constructed, and operated by humans, human factors contribute in a broad sense to all failures, except for random equipment failures that occur probabilistically.

In the safety principles and recommendations of the International Atomic Energy Association (IAEA), the use of a graded approach is repeatedly emphasized. As two examples, the use of a graded approach should apply to the safety assessment of all facilities and activities [5] as well as to the development and application of management systems [6]. The IAEA Safety Glossary defines 'graded approach' as follows: "*For a system of control, such as a regulatory system or a safety system, a process or method in which the stringency of the control measures and conditions to be applied is commensurate, to the extent practicable, with the likelihood and possible consequences of, and the level of risk associated with, a loss of control*" [7]. A graded approach allows for valuable resources and attention to be focused on crucial activities. Also according to the safety principles of the IAEA, "Safety has to be achieved and maintained by means of an effective management system" [5]. It should be noted that management systems are both influenced by and also themselves influence the culture of an organization [8]. Therefore, management systems must take a holistic and systematic approach to safety culture.

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https://doi.org/10.1016/j.net.2021.12.028

Since a strong safety culture is requisite to achieve safety, the evaluation of a safety culture must also satisfy the requirements that safety evaluations are subjected to. Most safety culture assessment methods mainly focus on evaluating the maturity level of the organization's safety culture [4,9–11]. Although the importance of the graded approach is continuously emphasized elsewhere, there are at present no adequate methods for evaluating safety cultures in such a systematic way. In other words, a systematic decision-making tool using a graded approach is necessary. In applying a graded approach in safety assessment, according to the IAEA, the main factor taken into consideration should be the magnitude of the potential risk, while other relevant factors such as the maturity and complexity of the facility or activity should also be taken into account [12]. Complexity relates to the extent and difficulty of the efforts required to construct a facility or to implement an activity.

The main countermeasures to safety culture issues are deriving the weak safety culture-related elements from incidents or cases and preparing an improvement plan. Even though various efforts have been made to improve safety culture, evaluation of the effectiveness of the measures or strategies is insufficient. Typically, it is not easy to evaluate the effects of safety culture improvement measures because, not appearing instantly, they can only be captured through long-term observation. Therefore, for an efficacious approach to safety culture, it is necessary to analyze it from various perspectives. As the concept of safety culture is abstract, and its essence does not exist independently but rather can be traced throughout all activities of the organization, a holistic view of the organization is required to assess its safety culture.

Since various features appearing throughout the organization form its safety culture, an in-depth analysis of safety culture requires a detailed analysis of these various attributes. In addition, through a systematic analysis of actual cases, significant implications that the attributes of a safety culture have may possibly be derived. In this study, safety culture attributes are investigated through a past case analysis using the proposed frequency–difficulty matrix, or F-D matrix, that describes the degree of difficulty of safety culture elements and how often they appear in actual events. Here, the degree of difficulty is a generic term for the extent and difficulty of efforts made to meet safety culture principles. The F-D matrix is a tool that can compare the elements constituting a safety culture from a reductive point of view and allow changes over time to be observed. Conventionally, the general focus has simply been on the assumption that frequently problematic elements will pose many potential problems. By adding the concept of difficulty to this, the suggested tool enables a more in-depth analysis, making it possible to determine whether an element that occurs frequently is a problem because of a high difficulty level or whether it is a frequent problem despite a low difficulty level.

2. Background

2.1. Safety culture and harmonized safety culture model

The concept of safety culture has been emphasized in industrial fields since the Chernobyl accident (1986) and is preemptively applied to improve safety in high-reliability industries such as the nuclear, aviation, and railway fields. Various definitions of the concept of safety culture have been suggested from different perspectives [13–19]. Generally, safety culture can be expressed as the commitment and responsibility of all members of an organization in terms of safety as related to their attitude, character, and behavior. In the nuclear field, safety culture has been defined as: *"That assembly of characteristics and attitudes in organizations and individuals which establishes that, as an overriding priority, nuclear plant safety issues receive the attention warranted by their significance"* [14]. Similarly, the World Association of Nuclear Operators (WANO) defines nuclear safety culture as: *"The core values and behaviours resulting from a collective commitment by leaders and individuals to emphasize safety over competing goals to ensure protection of people and the environment"* [20].

Like this, each organization strives to define and develop a safety culture as a basis or means for achieving safety. While operating agencies themselves set specific principles for their own organizational safety culture and make efforts to follow them, regulatory bodies also define the desired safety culture that operating agencies should have and check for their compliance. The safety culture models have similar intentions but different structures, so it is often challenging to comply with the safety culture guidelines; accordingly, the need to align the safety culture models has emerged. The IAEA, WANO, Institute of Nuclear Power Operations (INPO), U.S. Nuclear Regulatory Commission (USNRC), and other regulatory agencies have worked together to align the various safety culture models and created the harmonized safety culture (HSC) model [21]. This model is currently open as a Working Document of the IAEA. The HSC model provides the characteristics and attributes that an organization with a healthy safety culture should have. The HSC model consists of 10 broad traits, under which are a total of 43 attributes (Table 1).

2.2. Studies on safety culture

Early research on safety culture mainly explored the concept behind it and constructed models [22,23], while empirical research was also conducted to determine the components of safety culture and evaluate it [24–30]. Safety culture evaluation methods have several limitations as they mainly utilize subjective surveys, focus group interviews, field observations, and document reviews. In response, one study proposed a safety culture evaluation method through a probabilistic approach [31], and other studies focused on safety culture quantification using Bayesian networks [32–34]. Kim et al. presented a method to evaluate the work process including safety culture as a performance influencing factor used in human reliability analysis [35]. Otherwise, one study examined the correlation between the components of a safety culture model [36], and in another work, an attempt was made to quantify the effect of safety culture on nuclear power plant safety in terms of core damage frequency [37]. As such, research on safety culture has mainly involved model development, empirical studies such as developing and applying questionnaires, and quantifying the maturity level of safety culture. Research on decision-making tools or in-depth analysis tools to treat safety culture with a graded approach for inclusion in current management systems is lacking. With the recent introduction of the HSC model, all attributes of safety culture should be treated according to their importance and significance. For this, it is necessary to find an appropriate graded approach to analyze each attribute of safety culture in-depth. This paper develops such a method by defining *difficulty* as a unique characteristic of the safety culture attributes, thereby providing a new analysis perspective through the F-D matrix.

3. F-D matrix

The F-D matrix is a tool suggested to provide a new analytical perspective on safety culture. The safety culture attributes can each be analyzed according to their degree of difficulty and their frequency of appearance in actual abnormal events. Difficulty is derived from a developed model that first identifies the elements that contribute to the difficulty in meeting an attribute and then

Table 1
Harmonized safety culture model [21].

Traits	Attributes	Traits	Attributes
IR. Individual Responsibility	IR.1 Adherence IR.2 Ownership IR.3 Collaboration	WE. Respectful Work Environment	WE.1 Respect is Evident WE.2 Opinions are Valued WE.3 Trust is Cultivated WE.4 Conflicts are Resolved WE.5 Facilities Reflect Respect
QA. Questioning Attitude	QA.1 Recognize Unique Risks QA.2 Avoid Complacency QA.3 Question Uncertainty QA.4 Recognize and Question Assumptions	CL. Continuous Learning	CL.1 Constant Examination CL.2 Learning from Experience CL.3 Training CL.4 Leadership Development CL.5 Benchmarking
CO. Communication	CO.1 Free flow of information CO.2 Transparency CO.3 Reasons for Decisions CO.4 Expectations CO.5 Workplace Communication	PI. Problem Identification and Resolution	PI.1 Identification PI.2 Evaluation PI.3 Resolution PI.4 Trending
LR. Leader Responsibility	LR.1 Strategic Alignment LR.2 Leader Behavior LR.3 Employee Engagement LR.4 Resources LR.5 Field Presence LR.6 Rewards and Sanctions LR.7 Change Management LR.8 Authorities, Roles, and Responsibilities	RC. Raising Concerns	RC.1 Supportive Policies are Implemented RC.2 Confidentiality is Possible
DM. Decision-Making	DM.1 Systematic Approach DM.2 Conservative Approach DM.3 Clear Responsibility DM.4 Resilience	WP. Work Planning	WP.1 Work Management WP.2 Safety Margins WP.3 Documentation and Procedures

gives them weights. Frequency is derived from analyzing actual cases for the appearance of lacking safety culture attributes. Changes in attributes can be identified through a period-by-period comparison of the F-D matrix.

As the name suggests, the F-D matrix has axes of difficulty and frequency (Fig. 1). The difficulty axis represents the degree of difficulty to realize the safety culture attributes in the safety culture model, and the frequency axis represents their frequency in historical cases. There are various definitions of difficulty, and even for the same attribute, difficulty may be subjective and differ case by case. However, the concept of difficulty here is not subjective but rather a property of the target element that is found via its contributing factors. Because this study approaches safety culture from a reductive perspective, the F-D matrix treats the 43 safety culture elements (Table 1) as individual entities. While there should be correlations between the elements, they are assumed to be independent of each other here for simplicity.

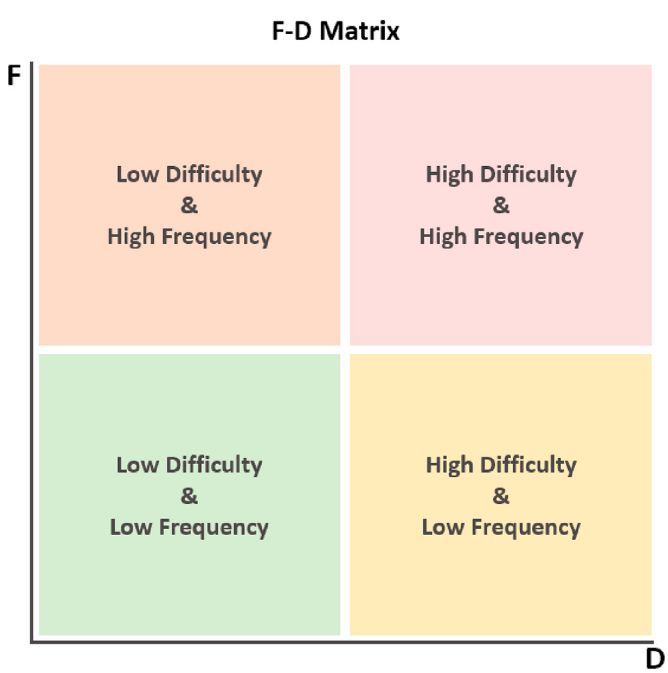

Fig. 1. F-D matrix.

The F-D matrix comprises four conceptual areas: the high F—high D (HFHD) zone, high F—low D (HFLD) zone, low F—high D (LFHD) zone, and low F—low D (LFLD) zone. The HFHD zone is for elements having a high degree of difficulty and appearing frequently; in other words, elements assigned to this area require a high level of attention because they are often troublesome to achieve in practice and appear frequently in abnormal event records. In contrast, the LFLD zone is a region for elements that have a low degree of difficulty to comply with and seldom appear, and therefore require a low level of attention. In general, it can be thought that elements with a high degree of difficulty will often appear as problems. However, the frequency of actual problems may appear differently depending on the maturity of the organization and the demand for the attributes in specific situations. Assuming that the demand level for the attributes is constant, then if an organization has a maturity level sufficient to realize a safety culture attribute with a high degree of difficulty, there will be fewer issues for that attribute. On the other hand, if the maturity level of the organization does not reach the difficulty level of an attribute, troubles related to that attribute will occur more frequently. In this way, the frequency can represent the gap between an organization's maturity and the difficulty of the corresponding attribute.

3.1. Safety culture factor frequency

Frequency is derived by selecting an analysis target period and identifying safety culture attributes from safety issues and safety-related events that occurred during that period. Abnormal events at nuclear power plants, near-miss events, etc., can be sources for analysis. In the case of events that have already occurred, safety culture-related factors should be derived based on existing records (e.g., incident investigation reports). If there is no appropriate standard, the quality of the results may vary depending on the analyst's competency or knowledge, so a standard for consistent analysis is needed. As a standard for deriving safety culture-related elements from an incident, the signs of deterioration in safety culture in the existing safety culture investigation guidelines can be referred to Refs. [14,17,19,20]. The frequency can be obtained by dividing the number of appearances of safety culture attributes by the period and the number of operating plants during the analysis period, as shown in the following equation.

$$frequency = \sum \frac{number\ of\ cases}{number\ of\ operating\ plants} \times years^{-1}$$

3.2. Safety culture attribute difficulty

Fig. 2 illustrates the approach to quantifying the difficulty of the safety culture attributes. First, in order to develop qualitative criteria, a hierarchical model is developed by deriving the factors that affect the difficulty to achieve the given attribute through literature research and expert advice. Second, an analytic hierarchy process (AHP) is performed by experts to set the weights for each factor. Relative weights are determined through pairwise comparison and confirming the reliability of the results through consistency tests. Results from all experts are then integrated to derive a final weight for each factor and normalize it. Third, each safety culture attribute is matched with corresponding difficulty contributors by qualitative analysis. Lastly, the degree of difficulty for each safety culture attribute is scored by reflecting the derived weights.

3.2.1. Difficulty contributor hierarchical model

The degree of difficulty in this work is defined as an intrinsic property that safety culture attributes have, describing how difficult it is to realize the attribute in practice. It is a quantitative expression of the abstract concept of difficulty used to compare safety culture attributes. For example, the degree of difficulty is high when a large amount of tangible and intangible resources or high expertise is required. The developed difficulty contributor hierarchical model (DCHM) does not identify all difficulty contributors but categorizes them as a means to quantify the degree of difficulty.

To prepare evaluation standards, various contributors to difficulty were derived by a literature review and expert consultation; the developed hierarchical model is shown in Fig. 3. Safety culture attributes can appear as artifacts such as behaviors, policies, and work results. Therefore, human factor analysis guidelines (e.g., assessing workload contributors) were referred [38–42]. Difficulty contributors can be divided into quantitative and qualitative aspects (Resources and Required Competencies in Fig. 3, respectively), where the first level criteria are the required tangible and intangible resources to assess the quantitative aspects and the required level of competency or capability to assess the qualitative aspects.

Subdividing the criteria and elements as much as possible may eliminate dependencies between the elements. However, considering too many factors may reduce the effectiveness of the analysis. Therefore, in this study, evaluation factors were grouped to optimize the number of items considered.

3.2.2. DCHM – dimension of resources

The required resource types were classified into time resources, material resources, and human resources to assess the quantitative aspects of each contributor. As time resources were evaluated in terms of duration and frequency, the criteria for the dimension of resources are the following: duration, frequency, material resources, and human resources. First, duration refers to the amount of time required to comply with the relevant safety culture attribute, and is graded High, Mid, Low, or N/A according to its level. Second, regularity indicates how often the relevant attribute is required in a daily work environment, and is also graded High, Mid, or Low according to its level. Third, material resources represent whether material or economic resources such as budget allocation

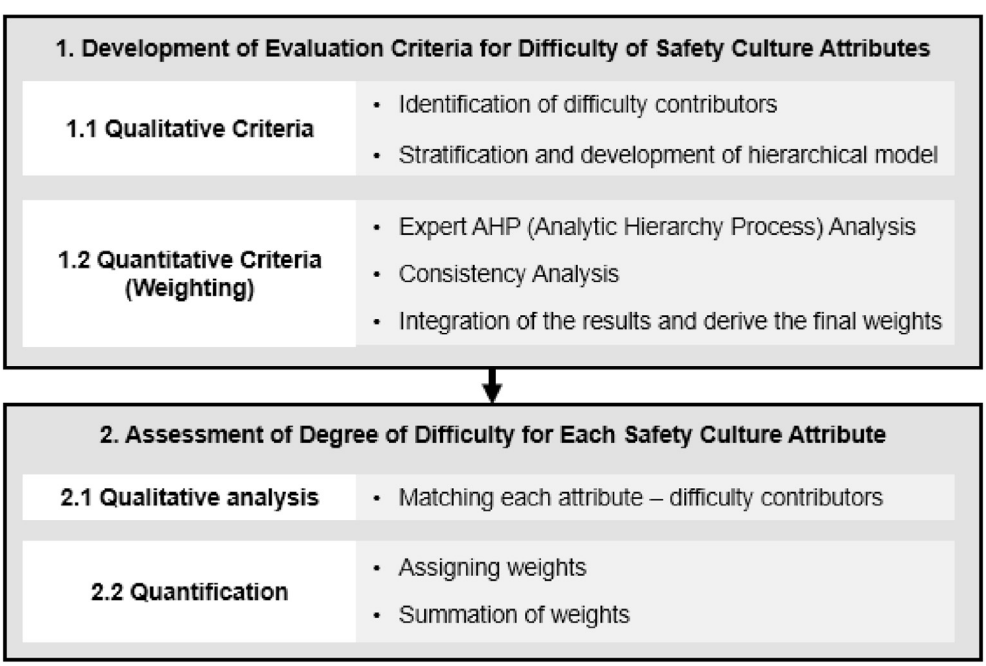

Fig. 2. Process to quantify the degree of difficulty of the safety culture attributes.

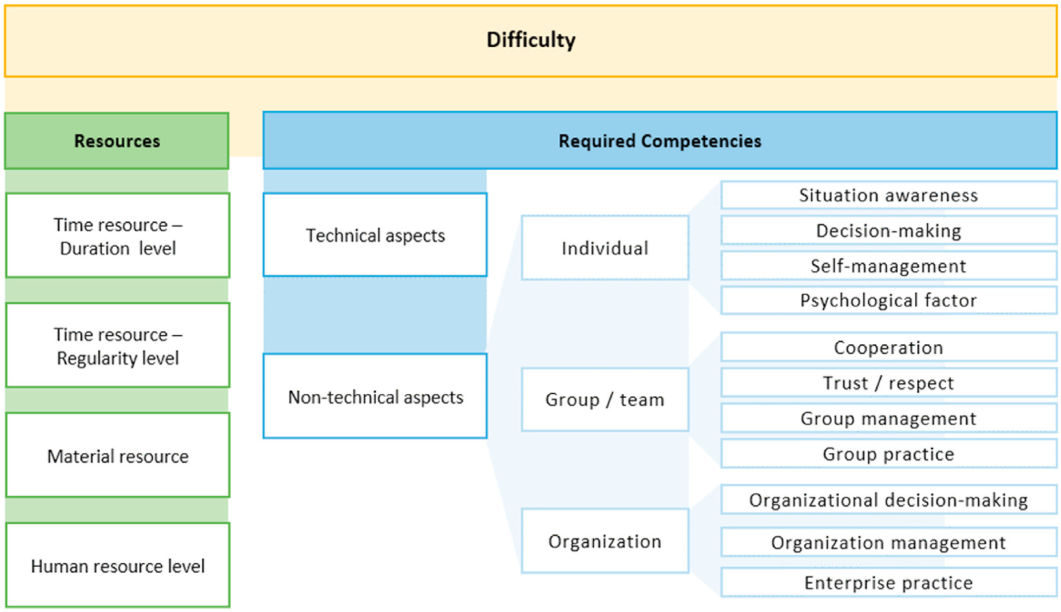

Fig. 3. Difficulty contributor hierarchical model (DCHM).

are needed for the safety culture attribute. This criterion does not consider the required quantity but only the necessity. Finally, human resources represent the required level of manpower, and is graded by Enterprise, Division, Group, and Individual levels.

3.2.3. DCHM – dimension of competency

The required competency is categorized into technical aspects and non-technical aspects to evaluate the qualitative aspects of each contributor. Technical aspects indicate the requirements that directly affect specific task performance, such as professional knowledge, technology, or know-how. On the other hand, non-technical aspects refer to the required non-technical capabilities supplementing the technical aspects. The division between the two here is based on the non-technical skills concept used in aviation and medical fields [43]. Since safety culture mostly involves non-technical characteristics by definition, the non-technical aspects were divided into individual competence, group competence, and organizational competence, as detailed below.

First, individual competence refers to an individual's competency or a qualitative level and consists of the following: situational awareness, decision-making, self-management, and psychological factors. Self-management here includes all related capabilities such as fitness-for-duty (e.g., fatigue management, drug and alcohol restrictions), stress management, and personal work management. Psychological factors include various psychological characteristics such as values or consciousness level, recognition of authority and duty, and work-related attitudes and individual characteristics.

Second, group competence is the set of competencies that teams or departments should possess: collaboration and cooperation, mutual respect and trust, group management, and group practice. Group management here can include all kinds of capabilities such as various management systems (task management, quality management, conflict resolution, etc.) and leadership within a group or department.

Lastly, organizational competence includes aspects beyond the level of employee authority. First, organizational decision-making refers to when the safety cultural attribute requires an organizational-level decision-making method or system. Organizational management is the case when a safety cultural attribute requires various organizational management processes or systems, including document management, performance management, personnel management, resource management, evaluation management, etc. The last category is enterprise practice, referring to when the safety culture attribute requires or is related to an enterprise-wide practice or climate.

3.3. Weighting process

3.3.1. Analytic hierarchy process (AHP)

In this paper, weights of the difficulty contributors were derived through an AHP with experts to make guidelines for evaluating the degree of difficulty. AHP is a method of prioritizing alternatives in a decision-making process with multiple criteria [44]. It is an approach that can solve complex decision-making problems logically and simply by judging via a pairwise comparison method between factors constituting a decision-making hierarchy. The AHP technique has a strength in that it can be usefully applied to obtain the weight or importance of the factors to be evaluated using the qualitative knowledge of experts in cases when quantitative analysis is intricate. Because of these advantages, the AHP technique is widely used in various studies.

The AHP technique generally goes through the following four steps.

1) Decision-making stratification model construction
2) Collection of pairwise comparison data between decision-making factors
3) Verification of the consistency of the comparison data
4) Integration of the relative weights of the decision factors

Through these steps, AHP stratifies the decision-making problem with the various criteria considered by the decision-maker, compares the alternatives according to the criteria, evaluates the importance relative to each other, and calculates the weight for each factor by integrating the results. The basic scale used for pairwise comparison is a ratio scale that shows the relative importance on a scale from 1 to 9 with 17 options. The different scale types previously suggested to apply to this ratio are shown in Table 2. Quantitative weights can be derived by assigning judgement scales and weights to the qualitative comparison results using

AHP.

In this work, expert evaluation using AHP was performed during the period from June 1 to June 19, 2021, to assign weights to the contributors. Weighting was carried out with the consultation of one expert each from a research institute, regulatory agency, operating agency, and university in the Republic of Korea (ROK). Quantitative weights were derived by assigning a judgement scale to obtain weights for the qualitative pairwise comparison results originally on a 1–9 scale. To determine the appropriate judgement scale, various scale types were reviewed (Table 2). In general applications of AHP, the linear scale is most commonly used. However, inadequate results can arise from deviation from the intention of the respondents, due to the large difference between each scale value in the linear scale. For example, for A, B, and C, consider that A is only slightly more important than B (A:B = 2:1) and that B is only slightly more important than C (B:C = 2:1). Applying the linear ratio scale, A is twice as important as B, and B is twice as important as C, and therefore A is four times more important than C, resulting in a ratio of A:B:C = 4:2:1. As such, in applying the linear scale in the present work, it was found to be unsuitable for the weight distribution of the evaluation criteria of difficulty. As a result of examining the other scale types in Table 2, the root square scale, inverse linear scale, and asymptotical scale were found to be suitable types to obtain weights. Of these, the inverse linear scale was chosen, where $x \in \{1, 2, 3, \ldots, 9\}$ is (1: equal, 3: slightly important, 5: important, 7: very important, 9: critically important), with ratio scale values of <1; 1.13; 1.29; 1.5; 1.8; 2.25; 3; 4.5; 9>.

With this scale, the pairwise comparison was conducted. To verify the consistency of the results, a consistency test was performed, which is a process that calculates the ratio of the random index (RI) and the consistency index (CI), called the consistency ratio (CR). Here, CI is calculated using the number of comparison items (n) with the largest eigenvalues in the comparison matrix, and RI is calculated using the CI derived from random responses in the comparison matrix. If the CI of the matrix does not exceed 10% of the RI (CR < 0.1), it is generally possible to determine that the consistency of the response is sufficient. In this work, since the inverse linear scale was used, the values in Table 3 were used as the RI values.

4. Case study

4.1. HSC attribute appearance frequency

The frequencies of the HSC attributes of safety culture were derived from records of nuclear power plant abnormal events in the ROK. From the event records, reported cases of events such as unplanned plant shutdowns provided by the OPIS (operational performance information system, a source of information on nuclear power plants in the ROK) were analyzed, and the related safety culture factors were derived from the cause, progress, and response process of the event as indicated in the event report. In order to reduce the subjectivity of the analyst as much as possible, the only cases interpreted were those in which the indicators indicating the deterioration of an attribute are directly described. From the period April 2011 to March 2021, a total of 119 abnormal events were reported and rated according to the international nuclear and radiological event scale developed by the IAEA and the OECD Nuclear Agency [53]. Among all events, this study analyzed the internal events, of which 19 cases were rated level 1 or higher and 62 cases were rated level 0 or were not rated. By considering this particular period, the various improvements and measures taken following the increased emphasis on safety culture after the Fukushima accident (March 11, 2011) could be analyzed in terms of their effects on safety culture.

To express the frequency of the safety culture attributes that appeared as a result of the analysis of the event reports, the number of operating units (Table 4) when the event occurred was divided and summed. A list of the frequencies of the 43 attributes is shown in Table 5.

4.2. HSC attribute difficulty quantification

4.2.1. Weighting results for the difficulty contributors

Expert evaluation using AHP was performed to evaluate the weights of each difficulty contributor. For this, “HSC Difficulty-AHP” software was developed and used, and the inverse linear scale was selected as the scale type. Fig. 4 shows the normalized weight for each element, represented by width. Weights for the duration and demand regularity are determined depending on their High, Mid, and Low grades, while the weights for the material resource and technical aspects are not decomposed. For the rest, the stratified evaluation elements are decomposed as shown in Fig. 4, and the degree of difficulty is calculated by summing all the weights of the relevant elements. For example, the lowest possible score for a given attribute according to these weighting results would be 0.0832 points, determined as follows: duration: N/A; demand regularity: low; material resource: none; and human resource: none, giving 0.06638 points in the Resource category, and then technical aspects: none, and individual self-management: 0.01682 points as the lowest weight among the non-technical aspects in the Required Competencies category. To qualitatively evaluate the

Table 2
Judgement scales for the AHP method.

Scale type	Mathematical description	Parameters	Approximate scale values
Linear [45]	$s = x$	$x = \{1, 2, \ldots, 9\}$	1; 2; 3; 4; 5; 6; 7; 8; 9
Power [46]	$s = x^2$	$x = \{1, 2, \ldots, 9\}$	1; 4; 9; 16; 25; 36; 49; 64; 81
Root square [46]	$s = \sqrt{x}$	$x = \{1, 2, \ldots, 9\}$	1; $\sqrt{2}$; $\sqrt{3}$;2; $\sqrt{5}$ $\sqrt{6}$; $\sqrt{7}$; $\sqrt{8}$;3
Geometric [47]	$s = 2^{x-1}$	$x = \{1, 2, \ldots, 9\}$	1; 2; 4 ; 8 ; 16; 32; 64; 128; 256
Inverse linear [48]	$s = \frac{9}{10 - x}$	$x = \{1, 2, \ldots, 9\}$	1; 1.13; 1.29; 1.5; 1.8; 2.25; 3; 4.5; 9
Asymptotical [49]	$s = \tanh^{-1}\frac{\sqrt{3}(x-1)}{14}$	$x = \{1, 2, \ldots, 9\}$	0; 0.12; 0.24; 0.36; 0.46; 0.55; 0.63; 0.7; 0.76
Balanced [50]	$s = \frac{w}{1 - w}$	$w = \{0.5, 0.55, 0.6, \ldots, 9\}$	1; 1.22; 1.5; 1.86; 2.33; 4; 5.67; 9
Logarithmic [51]	$s = \log_2(x+1)$	$x = \{1, 2, \ldots, 9\}$	1; 1.58; 2; 2.2; 2.58; 2.81; 3; 3.17; 3.32

Table 3
Random index (RI) for the judgement scale of the inverse linear type used in AHP.

n	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.205	0.333	0.417	0.475	0.517	0.547	0.572	0.590	0.605	0.617	0.627	0.636	0.643

Source: Franek and Kresta [52].

Table 4
Total number of operating plants in the ROK by new plants.

New unit operation start date	Plant name	Total number of operating plants	New unit operation start date	Plant name	Total number of operating plants
1977-06-19	Kori-1	1	1998-02-19	Wolsong-3	14
1982-11-21	Wolsong-1	2	1998-12-14	Hanul-4	15
1983-04-09	Kori-2	3	1999-04-10	Wolsong-4	16
1985-01-01	Kori-3	4	2001-11-24	Hanbit-5	17
1985-10-26	Kori-4	5	2002-09-01	Hanbit-6	18
1986-01-31	Hanbit-1	6	2003-11-28	Hanul-5	19
1986-10-15	Hanbit-2	7	2004-12-16	Hanul-6	20
1988-02-25	Hanul-1	8	2010-07-15	Shin-Kori-1	21
1989-02-25	Hanul-2	9	2011-12-27	Shin-Kori-2	22
1994-10-13	Hanbit-3	10	2012-01-07	Shin-Wolsong-1	23
1995-07-07	Hanbit-4	11	2015-02-08	Shin-Wolsong-2	24
1997-01-29	Wolsong-2	12	2015-12-29	Shin-Kori-3	25
1997-12-21	Hanul-3	13	2019-04-08	Shin-Kori-4	26

Table 5
Frequencies of the HSC attributes.

Attribute	IR.1	IR.2	IR.3	QA.1	QA.2	QA.3	QA.4	CO.1	CO.2
Appearances	15	6	1	1	15	4	0	1	0
Frequency	0.06316	0.02565	0.00435	0.00435	0.06382	0.01619	0	0.00435	0
Attribute	CO.3	CO.4	CO.5	LR.1	LR.2	LR.3	LR.4	LR.5	LR.6
Appearances	4	1	4	2	0	0	2	0	0
Frequency	0.01730	0.00385	0.01746	0.00861	0	0	0.00817	0	0
Attribute	LR.7	LR.8	DM.1	DM.2	DM.3	DM.4	WE.1	WE.2	WE.3
Appearances	10	5	21	12	1	8	0	0	0
Frequency	0.04276	0.02005	0.08729	0.05026	0.00385	0.03381	0	0	0
Attribute	WE.4	WE.5	CL.1	CL.2	CL.3	CL.4	CL.5	PI.1	PI.2
Appearances	0	10	5	21	14	0	13	22	6
Frequency	0	0.04147	0.02071	0.08962	0.05736	0	0.05417	0.09309	0.02504
Attribute	PI.3	PI.4	RC.1	RC.2	WP.1	WP.2	WP.3		
Appearances	7	0	0	0	30	3	33		
Frequency	0.02939	0	0	0	0.12620	0.01276	0.13657		

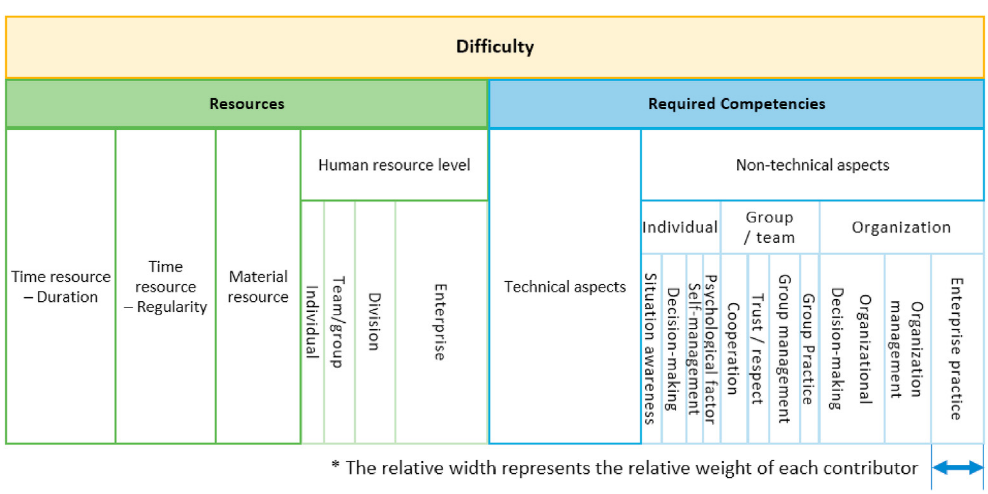

Fig. 4. Difficulty contributor weighting results.

difficulty of the HSC attributes, the difficulty contributors accompanying each attribute were qualitatively derived and collected, and then the assigned weights were summed. The authors did not evaluate the difficulty contributors themselves. Fig. 5 shows the scoring results for the 43 HSC attributes. As a result of evaluating the difficulty of the HSC attributes, the difficulties of Trending,

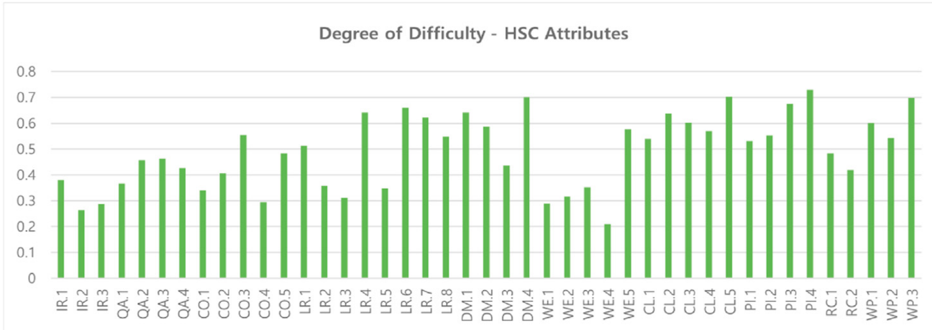

Fig. 5. HSC attribute difficulty scoring results.

Benchmarking, Resilience, and Documentation and Procedures were found to be relatively high, and the difficulties of Conflicts are Resolved, Ownership, Collaboration, and Respect is Evident were found to be relatively low.

4.3. F-D matrix application

Fig. 6 shows the analysis results for level ≥1 and ≤ 0 cases that occurred at nuclear power plants in the ROK (see Sect. 4-1). As can be seen, the distribution of frequencies expands as the difficulty increases. Although the frequency may increase as the difficulty increases, this is a result of the combination of various environmental and situational factors and the maturity of the organization's safety culture. In addition, since the case study analyzed only the contents revealed in the case reports, some attributes were not found.

Fig. 7 shows a period-by-period comparison for two periods from April 2011–March 2021. As can be seen, most attributes tended to decrease in frequency. The sum of the frequencies of all attributes showed a decrease of about 40% from 1.43992 to 0.88338. As described above, if the demand for an attribute is constant, the frequency may indicate a gap between difficulty and maturity. When the maturity level exceeds the difficulty level, large gaps between the two lead to fewer problem occurrences. However, if the maturity is insufficient in terms of the difficulty level, large gaps lead to more problem occurrences. Therefore, if the frequency increases, the maturity of the related attribute might have decreased, while if the frequency decreases, the maturity of the related trait might have increased. Observing such changes in frequency can reveal trends in safety culture maturity. In addition, the effectiveness of the implemented measures can be assessed indirectly. Hence, this result proves that efforts for improving the safety culture in the ROK after the Fukushima accident have been effective. The attributes showing the largest reductions are PI1, CL2, and WP1, which indicates that the organization's maturity level related to recognizing safety-related issues, reflecting experience, and work-management, respectively, may have achieved the greatest improvement.

In general, more efforts are necessary to improve the maturity of an organization for attributes with high difficulty. Among multiple attributes with similar changes in frequency, it can be said that the actions related to the attributes with higher difficulty show greater effectiveness. For example, IR.1 and QA.2 show a similar drop in frequency, but as QA.2 has a higher difficulty, the measures related to QA.2 seem to have had a greater impact than the measures for IR.1. In the case of the attributes that have a small increase in frequency or other slight changes, the cause could be because 1) the maturity of the organization has already reached close to its development limit (i.e., the frequency is dominated by situation occurrences), or 2) the effectiveness of the relevant measures may have been relatively small (i.e., the maturity has not changed). If the frequency is low enough, the former is more likely, while the possibility of the latter should be considered as well.

5. Conclusion

Achieving a high level of safety requires a strong safety culture as an important basis. For the formation and improvement of safety culture, organizations' management systems should continuously strive to improve safety culture. To effectively deal with safety culture in management systems, an in-depth analysis tool using a graded approach is necessary. In this paper, the F-D matrix was introduced to give a new analytical perspective on safety culture. The F-D matrix can help elucidate whether a safety issue occurs because complying with the related safety culture principle is difficult or whether the issue occurs regardless of this difficulty level. While safety issues that arise frequently have more opportunities to be checked and compensated, infrequent issues can be easy to overlook. Considering the degree of difficulty inherent in each safety culture element can give weight to safety culture improvements and help to establish a differential strategy for efficient resource allocation. In addition, comparisons of safety issues by period with the F-D matrix can show trends in the change of the maturity level of an organization's safety culture and help to evaluate the effectiveness of measures implemented in the past.

This study utilized the HSC attributes suggested by the IAEA as the main parameter. In the future, it is necessary to set the operational definition of each attribute more strictly. This study did not propose a meticulous difficulty model. It should also be noted that the difficulty contributors may vary by the target organization, as can their required levels of competency and resources, etc., which is not reflected in this study. To test the validity of the model, a practical application should be conducted. Due to the limitations of available data, a case study was conducted in this work using reported events in the form of data disclosed in the OPIS. More useful results can be derived if operational data or undisclosed case data are analyzed extensively, including near-miss cases. In addition, a more systematic methodology should be developed to derive the frequencies of the attributes from the cases to obtain more objective results. If a systematic method for deriving the frequency of safety culture attributes through event analysis is prepared through future research, high-quality analysis with less dependency on the competency or knowledge of analysts will be possible.

As mentioned above, there are still some issues to address before applying the F-D matrix in practice. However, as the interest in safety culture increases, this study with its graded approach can contribute to promoting more focused safety culture improvements. For instance, it may support organizations that want to

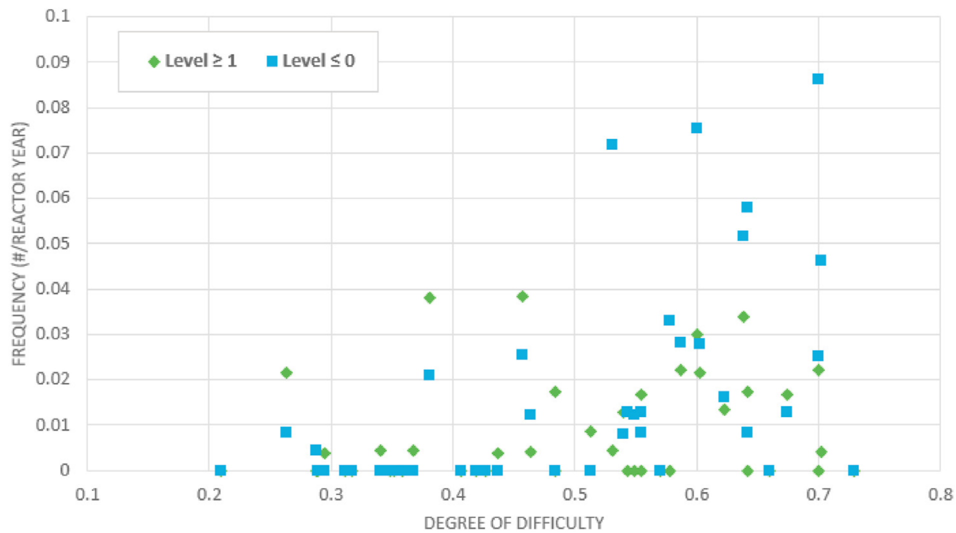

Fig. 6. F-D Matrix for level ≥1 and ≤ 0 cases.

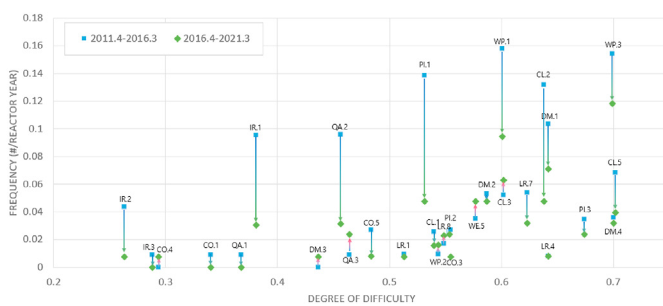

Fig. 7. F-D comparison by period.

promote a safety culture in allocating appropriate levels of resources to the establishment of relevant strategies. Since a high level of difficulty means that extensive tangible and intangible resources are required, a graded strategy can be established according to the relative difficulty level. By considering the contribution and the severity of a safety culture attribute, its consequence can be more clearly understood. In future work, such attribute consequences will be derived and integrated with their frequency to determine their importance in terms of safety.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety (KoFONS) using a financial resource granted by the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea (No. 2003011).

Appendix

Abbreviation

International Atomic Energy Association (IAEA)
World Association of Nuclear Operators (WANO)
Institute of Nuclear Power Operations (INPO)
U.S. Nuclear Regulatory Commission (USNRC)
Harmonized safety culture (HSC)
Republic of Korea (ROK)
Analytic hierarchy process (AHP)
Difficulty contributor hierarchical model (DCHM)
Random index (RI)
Consistency index (CI)
Consistency ratio (CR)

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