1. Introduction

In the present manufacturing environment, difficult decisions are to be made in selecting appropriate materials for the required applications [1]. Similarly, in the construction industry, each stage involved is accompanied by numerous decision-making processes. In particular, numerous alternatives exist in regard to materials and construction methods in the early stages of construction, rendering selection more difficult. Because the selection problem involves various requirements, a multicriteria decision-making (MCDM) model is introduced in this study.

Multicriteria decision making (MCDM) analysis evaluates multiple conflicting criteria in decision-making in daily lives and/or in all areas. When evaluating options, the desired properties usually conflict. Decision-makers, for example, demand high quality at low cost.

In daily life, people typically weigh multiple criteria implicitly and may be comfortable with the consequences of decisions based on only intuition [2]. However, it is essential to structure the problem appropriately and evaluate multiple criteria explicitly when the stakes are high [3]. The construction and location of a nuclear power plant have many decision criteria, and the consequences of that choice will affect many people.
The following are the types of multi-criteria decision-making methods that can be easily found today. More decision-making methods are described in the paper in [1]. (1) graph theory and matrix approach (GTMA) [4], (2) multiobjective optimization techniques (MOOT) [5], (3) utility additive (UTA) [6], (4) linear assignment approach (LSA) [7], (5) Vlse Kriterijumska Optimizacija Kompromi sno Resenje method (VKOKRM) [8], (6) technique for order preference by similarity to ideal solution (TOPSIS) [9], (7) preference ranking-based methods (PRBM) [10], and (8) multiobject optimization on the basis of ratio analysis (MULTIMORA) [11].

Decision-making can be based on prior experience sometimes. In addition, the continual response and feedback of the alternatives to be decided will influence the decision. Typically, decision makers make decisions based on partial knowledge [12]. To solve the insufficiency and uncertainty problems caused by partial knowledge and incomplete information, more information analysis and decision-making experts are necessitated. For highly uncertain and subjective decision-making problems, either empirical feedback from experts or detailed information must be obtained. In decision-making studies, researchers typically use fuzzy membership function criteria to reflect uncertainties and solve subjective assessment problems. Palczewski and Salabun [13] have reviewed the status of research performed over 10 years in regard to the application of fuzzy criteria in MCDM problems. Further current fuzzy application in decision-making studies may refer to [14]. The most common problems occurring in MCDM are as follows [15].

First, the priority of multicriteria requirements depends on the subjective assessment by a person or group. Second, the more varied the user requirements, the more difficult it is to obtain and evaluate the requirements. Third, the evaluation criteria for the requirements are ambiguous and contain uncertainties. Fourth, regarding future requirements, the required resources and time depend on uncertain predictions. Finally, as new alternatives and options may be added, removed, or changed over time, nonoptimal alternatives may be selected in a changing environment [16].

Among the aforementioned problems arising during MCDM, this study focuses on the following problems: (1) incompleteness and uncertainty; (2) subjective assessment; (3) environmental change factors. The aim of this study is to solve these problems by obtaining the detailed information required for decision-making and using feedback information while considering a changing environment. Figure 1 presents a conceptual diagram of the approach used in this study.

An innovative MCDM TOPSIS method is proposed herein to overcome the limitations of incomplete, uncertain, and subjective evaluations that are inevitably caused by incomplete information and changing environments when making decisions. After initially selecting a construction method based on the first TOPSIS, a second decision is made by assessing technical characteristics that use the extended quality function deployment-failure mode effect analysis (QFD-FMEA) model to analyze the construction method’s “risk reduction rate” and “additional safety cost (increasing safety cost rate).”

The extended QFD-FMEA model can be used for quantitative assessments as well as for defining the uncertainty to ensure the safety of the construction method. Furthermore, it allows the safety environment to be changed by analyzing the risk reduction rate via the addition of safety options pertaining to hazardous technical characteristics. A case study is presented herein to illustrate a systematic approach that can support appropriate decision-making regarding a construction method via an interactive operation between the TOPSIS and extended QFD-FMEA models.

2. Research Method

In this study, preferences for applicable construction methods were analyzed using the MCDM TOPSIS model. In the subsequent secondary evaluation, detailed risks for safety requirements were evaluated for two of the most preferred construction methods. Additionally, the degree of risk reduction was evaluated based on safety measures, and the corresponding additional safety cost ratio was analyzed. To determine the best option, construction methods were analyzed based on the analysis results of risk reduction and the additional safety cost index from the second decision-making process. The degree of risk reduction and additional safety cost index were used in the second decision-making process to address changeable environments.

The concept of the quality function deployment (QFD) process was applied in this study to evaluate the risks involved in the selected construction method as well as to successively analyze risk reductions.

First the TOPSIS, QFD, and FMEA theories are briefly described. Subsequently, the extended QFD-FMEA model, which assesses risks and analyzes risk reductions using the QFD concept to explain the step-by-step process and mathematical logic, is described. In the case study, real construction data and virtual data were used to reproduce the entire decision-making process, and the model was validated by comparing the preference in both the initial and feedback-based second decision-making process. Figure 2 shows a conceptual diagram of the research structure.

3. Literature Review

Each subject pertaining to MCDM and risk assessment has been investigated extensively. The current status of conventional studies pertaining to the TOPSIS is as follows: AHP-TOPSIS was used to address supplier selection problems [17], where MCDM was performed to select qualified suppliers. The prequalification of suppliers in the construction supply chain indicates that the supplier’s capability is guaranteed. MCDM models for energy saving and the efficient use of energy resources were investigated to maintain sustainable operations at wastewater treatment plants [18].

In another study, the fuzzy TOPSIS method was used to identify the major risk criteria for construction projects. The riskiest and least risky projects were ranked in an analysis
based on five key criteria of construction projects in the fuzzy environment of projects: time, quality, cost, environment, and sustainability [19].

In another study, a method that combines QFD user requirements with the TOPSIS method was proposed. As the QFD user requirements correspond to the factors in the multi-criteria of TOPSIS, the combined QFD-TOPSIS model can effectively analyze the product preferences of users [20, 21].

A decision problem with contradictory and multiple criteria should be considered to evaluate the strategies implemented by governments. In fact, the abovementioned problem was applied to government strategies to manage the COVID-19 pandemic, and the priority of selection strategies was evaluated using the fuzzy TOPSIS method [22].

The appropriate process parameters must be selected to achieve cost reduction and quality improvement. When a decision entails the selection of suitable process parameters pertaining to various conflicting factors, it must be addressed using the MCDM method. In one study, MCDM was performed to select Mg alloys [23].

In another study, the TOPSIS was used to evaluate residents’ preferences for flexibility when selecting residential houses. User requirements were obtained using the Delphi method, and the TOPSIS was evaluated based on the house of quality (HOQ) [24].

Meanwhile, the TOPSIS was used in another study to evaluate smart city growth in various cities [25]. The basic dimensions of smart cities are generally evaluated based on regional competitiveness, transportation, information and communication technology, economy, natural resources, human and social capital, quality of life, and the participation of citizens in city management. The aim of the analysis is to enable a comparison between a city with another such that areas to be improved by policymakers can be identified.

Some previous studies pertaining to work risk assessment are briefly introduced as follows:

Failure mode effect analysis (FMEA) enables the identification of risks associated with an option in the manufacturing system design and implementation phases. Almannai et al. proposed a decision-making method that combines QFD and FMEA in an integrated computer manufacturing system [26].

Li et al. proposed an AHP-FMEA methodology was proposed to analyze the failure causes of floating offshore wind turbines [27].

Ribas et al. proposed an FMEA method to evaluate the mechanisms that trigger safety failures in hydroelectric power plants [28].

Errors or failures occurring in the emergency department significantly affect the safety of patients and the goodwill of a hospital. In this regard, Chanamool and Naenna et al. proposed applying fuzzy FMEA for the prioritization and assessment of failures that are likely to occur in an emergency department [29].

Meanwhile, Balaraju et al. performed an FMEA using root cause analysis data obtained from underground mining machines. Additionally, recommendations for reducing failures were suggested [30].

FMEA and fault tree analysis (FTA) are two methods that are typically used for failure analysis. FMEA is a bottom-up method that is less structured and requires more expert knowledge compared with FTA, which is a top-down method.

Peeters combined FMEA and FTA to investigate the failure mechanism of an additive manufacturing system for metal printing [31].

Pipeline failure is typically predicted via FMEA owing to its ease of application.

Hassan et al. proposed a new approach, known as modified FMEA, which integrates the benefits of hybrid...
FMEA with a fuzzy rule base and FMEA with grey relations theory to overcome the identified drawbacks. Both fuzzy and grey theories were utilized to include experts’ diverse opinions, and a relative weighting was assigned to each assessment factor in the risk assessment. Subsequently, the risk assessment results were used to determine the risk priority and rank the failure modes under different conditions [32].

Based in literature review, these two subjects have been investigated extensively.

However, few studies have combined the two above-mentioned subjects to support safer and more complete decision-making while reducing uncertain situations in a decision-making environment.

Therefore, these two subjects should be combined, or the feedback information of a possible change environment should be supported, to reduce uncertainties in the decision-making process.

4. Review of Existing Theories

4.1. QFD. QFD is a customer-oriented product development process.

Yoji Akao, who established QFD, stated that QFD can be used to transform user requirements into technical features, determine the design quality of a finished product, and then systematically deploy each function pertaining to the quality of components or elements of the manufacturing process based on their relationships.

Mizuno and Akao [33] defined QFD as a specific step-by-step deployment of job competence or work that achieves quality in stages based on the purpose and method.

According to Nisson [34], QFD can be used when developing a new product or improving an existing product. Wassermann [35] stated that QFD is a technique in which an organization anticipates and prioritizes customer demands to define products or services provided to end consumers effectively.

QFD can be defined as a technique where user requirements are implemented as technical features, which implies that requirements gradually and continuously evolve into different dimensions.

For example, the HOQ has evolved by linking design and manufacturing processes in stages.

A study that used QFD to analyze the extent to which the requirements of green building performance are fulfilled demonstrated the application of QFD-HOQ [36].

As shown in Figure 3, QFD can be deployed continuously by linking it to the product design, component design, and production design in stages.

QFD involves transforming user requirements into specific goals at each stage via a series of processes, as described above. Finally, it implements the desired functions and product quality.

QFD does not involve a feedback process because the goal of QFD is achieved through the successful completion of the final product demanded by users. In fact, in QFD, the entire process of product design and production is completed via cascade processes based on the requirements of the previous stage.

4.2. TOPSIS Decision-Making Model. The TOPSIS is a multicriteria decision analysis method initially developed by Hwang and Yoon in 1981 [37]. Subsequently, it was further developed by Yoon in 1987 [38], and Hwang et al. in 1993 [39]. The TOPSIS is based on the concept that the alternative selected should have the shortest geometric distance from the positive ideal solution and the longest geometric distance from the negative ideal solution (NIS) [40].

In the TOPSIS method, two virtual solutions exist: the first is the ideal solution, which is the best virtual solution created using only the available information of the decision-making matrix. The other is the negative ideal solution, which is the worst solution obtained using only available information.

After creating these two solutions, the alternatives were evaluated. The best alternative is the one closest to the ideal solution and farthest from the negative ideal solution.

In this regard, the Euclidean distance or city-block distance is used as the distance measure.

As such, the TOPSIS is straightforward yet valid. The TOPSIS procedure comprises the following four steps.

1. Establishing an ideal solution (IS)
2. Establishing a negative ideal solution (NIS)
3. Measuring the distance between alternatives and the IS/NIS
4. Selecting the optimal alternative based on distance evaluation

4.3. FMEA Analysis Model. Failure mode and effects analysis (FMEA) is a review tool for systems, components, and assemblies to identify potential failure modes, causes, and effects [41].

The failure rate for each failure mode can be either statistically probable or subjective.

In addition, the FMEA can be extended to perform risk assessments for undesirable mechanical failures or human accidents.

A slightly more extended version of FMEA is FMECA (Failure Modes, Effects, and Critical Analysis).

Some definitions of specific terms are used to facilitate a better understanding of FMEA. The basic FMEA terms are as follows: [41].

A failure is a departure from an intended operation, function, or behavior.

Failure indicates a condition in which the system cannot perform a required function.

A failure mode is a way or condition in which a given system causes a failure.

A failure cause is different from a failure mode and is a process or mechanism that occurs before a failure mode occurs.

Failure effect is the effect that failure mode has on the functioning of a system.
A fault is an unwanted state due to a system failure. Faults can occur in multiple stages; faults can sometimes be in failure mode.

In FMEA, RPN (risk priority number) is an indicator of risk priority. It is calculated as:
\[
\text{RPN} = (\text{probability of occurrence}) \times (\text{rank of severity}) \times (\text{rank of detection}).
\]

5. Feedback Model for Decision-Making

The MCDM method relies on the information required for decision-making.

Most of the information required for decision making is measurable, whether subjective or objective, to determine the quality of the required performance or characteristics.

The scale for evaluating the required performance or characteristics can be defined as three-point, five-point, and seven-point scales, among others.

MCDM can be realized when the scale of the required characteristics has been determined and the scores have been measured.

However, the measured scores may change depending on the situation, over time, or under certain conditions.

In actual decision-making, this type of situation occurs frequently.

For example, when purchasing a particular product or machine, customer service may or may not be problematic depending on the region.

When purchasing a specific product, if the user’s residential region is changed, problems pertaining to customer service may occur in that region.

The decision-making method proposed herein is a model for decision making in a changing environment that uses specifically investigated information updates and feedback.

First, the construction method is selected using the TOPSIS method, and then the accident risks are analyzed comprehensively for the selected construction method.

Risk reduction measures have been established based on the analyzed risk factors, and the risk reduction ratio is calculated using a quantitative method in the newly changed environment.

The risk reduction ratio is accepted as a new requirement for the selection process of the construction method, and decision making is performed again.

Figure 4 shows the process of making a decision, in which the risk reduction information is fed back through extended QFD-FMEA. The integration process of the two models is illustrated in this diagram.

In the selection process of the construction method based on the TOPSIS, six steps are performed.

Step 1: The user requirements and technical characteristics of the construction method are defined as a 1:1 relationship.

Step 2: The importance of user-demanded functions is specified.

Step 3: The number applicable construction methods, \(m\), is specified and the technical characteristics of each construction method are measured based on the rating scale.

Step 4: The technical characteristic values of the construction method alternatives are normalized. The normalized value of the technical characteristics for each construction method alternative is the score that deviates the most from the non-ideal value.

Step 5: Importance weights are applied to the normalized values for each alternative construction method.

Step 6: The total preference score for each construction method is calculated, and the construction method alternatives are sorted by ranking.

The following is the detailed logic of the TOPSIS evaluation.

Corresponding <Step 1>: specify the “technical characteristics (TC)” of element technologies.

Here, \(X_{ij}\) represents the “technical characteristics (TC)” of the technological element. “Technical characteristics (TC)” indicates those up to \(k\). Here, \(x_{ij}\) represents the \(j\)-th “technology characteristic value (raw value)” in the element description \(A_i\).
Corresponding <Step 3>: specify the ideal and negative values of the technical characteristics.

The ideal value $D^+$ and the negative value $D^-$ are defined as follows:

$$D^+ = \{ \max(x_{ij}^\prime i=1,2,\ldots,m) | j \in J^+ , \min(x_{ij}^\prime i=1,2,\ldots,m) | j \in J^- \}$$

$$D^-=\{ \min(x_{ij}^\prime i=1,2,\ldots,m) | j \in J^+ , \max(x_{ij}^\prime i=1,2,\ldots,m) | j \in J^- \}$$

$$J^+ = \{ j | j \text{is a factor related to augmentation} \}$$

$$J^- = \{ j | j \text{is a factor associated with reduction} \}$$

Corresponding <Step 4>: normalize the technical characteristics.

The technical characteristics of the different scales are normalized in the range of 0 to 1.

The mixed scale is normalized as follows:

$$r_{ij} = 1 - \frac{\max(x_{ij}^\prime) - x_{ij}^\prime}{\max(x_{ij}^\prime) - \min(x_{ij}^\prime)}.$$  \hspace{1cm} (3)

Corresponding <Step 2>, <Step 5>: provide the importance weight to the regularization matrix $R$.  \hspace{2.8cm} (4)
The weight is defined as \( w_j, \; (j = 1, 2, \ldots, k) \), and the weight range is 0–10.

The matrix \( V \) with weight applied to the intersection matrix \( R \) is as follows:

\[
V = \begin{bmatrix}
  w_{11}r_{11} & w_{12}r_{12} & \cdots & w_{1k}r_{1k} \\
  w_{21}r_{21} & w_{22}r_{22} & \cdots & w_{2k}r_{2k} \\
  \vdots & \vdots & \ddots & \vdots \\
  w_{m1}r_{m1} & w_{m2}r_{m2} & \cdots & w_{mk}r_{mk}
\end{bmatrix}
\]  

(5)

Corresponding <Step 6>: calculate the maximum value of \( v_{ik} \).

The maximum value \( A_{(\text{max})} \) is defined as

\[
A_{(\text{max})} = \{ \max (v_j); \; j = 1, 2, \ldots, k \} = \{ v_1^+, v_2^+, \ldots, v_k^+ \}.
\]  

(6)

\( A_{(\text{max})} \) shows the most preferred ideal technical characteristic.

Corresponding <Step 6>: calculation of the separation measure.

The interval from the ideal solution \( A_{(\text{max})} \) for each method alternative is defined as

\[
S_i^+ = \left[ \sum_{j=1}^{k} (v_{ij}^+ - v_{ij}^-) \right]^{1/2} \quad (i = 1, 2, \ldots, m, g, l).
\]  

(7)

The interval from the subideal solution (\( A^- \)) for each method alternative is defined as follows.

\[
S_i^- = \sum_{j=1}^{k} v_{ij}^- \quad (i = 1, 2, \ldots, m, g, l).
\]  

(8)

Corresponding <Step 6>: calculate the preference for each method.

The relative Closeness (\( C_i \)) of \( A_i \) to the ideal solution \( A_{(\text{max})} \) is defined as

\[
C_i = \frac{S_i^-}{(S_i^+ + S_i^-)} \quad 0 < C_i < 1 \quad (i = 1, 2, \ldots, m, g, l).
\]  

(9)

As \( C_i \) approaches 1, \( A_i \) approaches \( A^+ \) rather than \( A^- \).

Corresponding <Step 6-c>: sort the element description alternatives by the analyzed preference value \( C_i \).

The preference order is determined according to the size of \( C_i \).

5.1. The Extended QFD-FMEA. Original QFD-FMEA model involves a systematic procedure for assessing work risks.

Conventional FMEA analyses are limited to risk assessment, making it difficult to analyze the extent to which risk can be reduced quantitatively.

The original QFD-FMEA analyzes the risk factors that may arise during the operation of the construction method. Classification risk factors can facilitate risk reduction. Liu and Tsai applied the QFD concept to the FMEA model to propose a continuous relationship between construction items, hazard types, and hazard causes. The following Figure 5 is the original model of the QFD-FMEA [42].

The novel QFD-FMEA method proposed herein is based on the original QFD-FMEA model and extends the risk reduction ratio via QFD approach.

In other words, the extended QFD-FMEA is continuously and sequentially applied to the accident type, damage rating, occurrence frequency, risk level, direct risk causes, basic risk causes, risk reduction measures, risk reduction ratio, etc.

Figure 6 shows a basic conceptual diagram of the QFD-based FMEA extended model.

To perform extended QFD-FMEA, a questionnaire form is used to analyze the risk analysis and risk improvement level for each activity step of the applied method. Figure 7 shows basic questionnaire form for performing extended QFD-FMEA. The analysis results and data from this questionnaire form is applied to the case study.

The extended QFD-FMEA model involves 14 steps, as shown in Figure 8.

Steps 1–4 are the same as those of the conventional FMEA process.

In Steps 5–9, the accident types and basic causes are determined, and risk reduction measures are established.

In Steps 10–14, the subjective belief in risk reduction and the additional safety cost efficiency for risk reduction are quantified.

Figure 8 shows a detailed conceptual diagram of the deployment of the extended QFD-FMEA model.

5.1.1. Step 1. The accident type (AT) defines the possible failure mode and the corresponding effect of failure in each process of a construction method operation.

The accident type is defined as final result of possible hazards at each stage of work and is defined as falling, caught, collapsed, or submerged.

5.1.2. Step 2. Hazard factors (HF) are the causes of failure and the direct cause of accidents.

The direct causes of accidents can be defined from various perspectives, such as human error, unsafe behavior, and unsafe systems.

In this study, hazard factors (HF) were classified from two perspectives: unsafe behavior and unsafe systems.

Typical unsafe behaviors include the following:

(1) Access to dangerous locations; (2) removal of safety devices; (3) misuse of protection and protective equipment; (4) misuse of machinery; (5) maintenance of machinery while driving; (6) unsafe operation of speed; (7) careless handling of hazardous materials; (8) neglecting one state; (9) unsafe posture and behavior; (10) insufficient supervision and communication; (11) others.
The main types of unsafety conditions include the following:

1. Defects in material factors;
2. Defects in safety protection devices;
3. Defects in protective gear;
4. Defects in arrangement of physical factors and in the workplace;
5. Defects in working environment;
6. Defects in production process;
7. Defects in landmarks and equipment;
8. Others.

5.1.3. Step 3. The following matrix defines the relationship between AT and HF.

The relation value $x_{j,i}$ of $AT_j$ ranges from 0 to 1 and represents the proportion of risk.

In any $AT_j$, the sum of all relation values $x_{1,1}$, $x_{2,2}$, ..., $x_{j,n}$ of HF becomes 1.0.

$$
AT_1 \begin{bmatrix} HF_1 & HF_2 & \cdots & HF_n \end{bmatrix} \begin{bmatrix} x_{1,1} & x_{1,2} & \cdots & x_{1,n} \\
 x_{2,1} & x_{2,2} & \cdots & x_{2,n} \\
 \cdots & \cdots & \cdots & \cdots \\
 x_{m,1} & x_{m,2} & \cdots & x_{m,n} \\
\end{bmatrix} \begin{bmatrix} HF_1 \end{bmatrix} (j = 1, \ldots, m) \quad (10)
$$

$\sum_{i=1}^{n} x_{j,i} = 1$

5.1.4. Step 4. The severity level (based on personal injury) is defined in Table 1.
The frequency of accidents is calculated by dividing the number of accidents per year by the total number of workers employed. The occurrence frequency is determined based on Table 2:

The risk index of an accident type is defined as criticality, and is calculated by multiplying the severity value (SV) and occurrence value (OV) of AT(j):

\[ C_{AT(j)} = SV_{AT(j)} \times OV_{AT(j)} \]  \hspace{1cm} (11)

The grade value of the risk index is defined as the criticality rank and is calculated as follows:

In any accident type, the criticality index (CI) is denoted as \( C_{AT(j)} \):

\[ CI_{AT(j)} = \frac{SV_{AT(j)} \times OV_{AT(j)}}{SV_{max} \times OV_{max}} \times 10. \]  \hspace{1cm} (12)

The total number of possible risk scores in the construction method is the total criticality index (TCI), which is calculated using the following formula:

\[ TCI = \sum_{j=1}^{m} CI_{AT(j)}. \]  \hspace{1cm} (13)
Table 1: Criteria for severity rating.

| Severity rating     | Evaluation value |
|---------------------|------------------|
| Dead                | 5 (A)            |
| Serious wound       | 4 (B)            |
| Minor injuries      | 3 (C)            |
| Very minor injuries | 2 (D)            |
| None                | 1 (E)            |

Table 2: Evaluation criteria for accident frequency.

| Occurrence frequency | Evaluation value |
|----------------------|------------------|
| ~1/10,000 (very frequent) | 5 |
| ~1/100,000 (frequent) | 4 |
| ~1/1,000,000 (occasionally) | 3 |
| ~1/10,000,000 (rarity) | 2 |
| ~1/100,000,000 (very rare) | 1 |
5.1.5. Step 5. The basic causes (BC) of the direct causes are as follows:

1. Man: human factors that cause errors
2. Machine: physical factors, such as defects and breakdown of machinery and equipment
3. Media (work information): factors such as work information, method, and environment
4. Management: management factors

5.1.6. Step 6. The following matrix defines the relationship (indicated by y) between the direct risk and basic cause.

\[ \begin{align*}
\text{BC}_{(1,2,3,4)} &= \begin{bmatrix}
\text{CI}_{(1)} \times x_{1,1} & \text{CI}_{(2)} \times x_{1,2} & \cdots & \text{CI}_{(m)} \times x_{1,m} \\
\star y_{1,(1,2,3,4)} & \star y_{1,(1,2,3,4)} & \cdots & \star y_{1,(1,2,3,4)} \\
\text{CI}_{(1)} \times x_{2,1} & \text{CI}_{(2)} \times x_{2,2} & \cdots & \text{CI}_{(m)} \times x_{2,m} \\
\star y_{2,(1,2,3,4)} & \star y_{2,(1,2,3,4)} & \cdots & \star y_{2,(1,2,3,4)} \\
\cdots & \cdots & \cdots & \cdots \\
\text{CI}_{(1)} \times x_{n,1} & \text{CI}_{(2)} \times x_{n,2} & \cdots & \text{CI}_{(m)} \times x_{n,m} \\
\star y_{n,(1,2,3,4)} & \star y_{n,(1,2,3,4)} & \cdots & \star y_{n,(1,2,3,4)}
\end{bmatrix}
\end{align*} \]

\[ \text{BC}_1 = \text{CI}_{(1)} \sum x_{j,i} \times y_{1,j} \quad (j = 1, \ldots, m, i = 1, \ldots, n), \]

\[ \text{BC}_2 = \text{CI}_{(2)} \sum x_{j,i} \times y_{1,j} \quad (j = 1, \ldots, m, i = 1, \ldots, n), \]

\[ \text{BC}_3 = \text{CI}_{(3)} \sum x_{j,i} \times y_{1,j} \quad (j = 1, \ldots, m, i = 1, \ldots, n), \]

\[ \text{BC}_4 = \text{CI}_{(4)} \sum x_{j,i} \times y_{1,j} \quad (j = 1, \ldots, m, i = 1, \ldots, n). \]

5.1.7. Step 7. The criticality index (CI) of BC₁, BC₂, BC₃, and BC₄ for each basic cause is the sum of the contributions of the HF for all AT and is calculated as follows:

5.1.8. Steps 8 and Step 9. According to the BC type, which is the basic cause, we set a 1:1 risk reduction measure (RRM) relationship for each HF. Here, RRM is a precautionary safety management parameter for risk reduction.

\[ \text{BC}_1 \rightarrow \text{HF}_{(1,\ldots,n')} \quad \rightarrow^{1:1} M_1 \text{RRM}_{(1,\ldots,n')}, \]

\[ \text{BC}_2 \rightarrow \text{HF}_{(1,\ldots,n')} \quad \rightarrow^{1:1} M_2 \text{RRM}_{(1,\ldots,n')}, \]

\[ \text{BC}_3 \rightarrow \text{HF}_{(1,\ldots,n''')} \quad \rightarrow^{1:1} M_3 \text{RRM}_{(1,\ldots,n'''}), \]

\[ \text{BC}_4 \rightarrow \text{HF}_{(1,\ldots,n''')} \quad \rightarrow^{1:1} M_4 \text{RRM}_{(1,\ldots,n'''}), \]

5.1.9. Step 10. Prevention measures for the basic causes of industrial accidents can be established based on the following 4 safety elements:

1. Education: applying safety technology to engineering information data, equipment, etc.
2. Technology: build knowledge and skills
3. Management: achieving and implementing safety standards, checking results
4. Individual: health monitoring of workers, personal skill level, personal safety level

The weight \( y_{i,k} \) of BC ranges between 0 and 1.0. In \( HF_i \), the sum of all 4M relational values \( y_{1,1}, y_{1,2}, y_{1,3}, y_{1,4} \) becomes 1.0.
The weight of the safety efficiency (SE) ranges between 0 and 1.
SE₁ = SE (education) SE₂ = SE (technology)
SE₃ = SE (management) ASE₄ = SE (individual)

5.1.10. Steps 11 and 12. The weighting matrix of the SE for the RRM is as follows: The risk reduction rate (RRR) is expressed as shown in equation (19).

\[ RRR_u = 1 - \left( \frac{w_{(u,1)} \ast SE_{(1)} + \frac{w_{(u,2)} \ast SE_{(2)}}{w_{m,n}} + \frac{w_{(u,3)} \ast SE_{(3)}}{w_{m,n}} + \frac{w_{(u,4)} \ast SE_{(4)}}{w_{m,n}}}{\sum_{j=1}^{m} CI_{AT(j)} \ast x_{j,n}} \right) \ast y_{n,k} (n = 1, 2, 3, 4), \]

The CI reflecting the RRRᵢ for any accident type is defined as reduction criticality index (RCI) RCIₐₗₐₜᵢ(j).
The modified risk index criticality RCIₐₗₐₜᵢ(j) with the RRRᵢ reflected is calculated using (22).

\[ RCI_{AT(j)} = \sum CI_{AT(j)} \ast x_{j,n} \ast y_{n,k} \ast RRR_u. \]

5.1.11. Step 13. The risk reduction measures (RRM) for the HF by the AT are defined by the following matrix, and the risk index as the CIₐₗₐₜᵢ(j) of the accident type is calculated using equation (25).

\[ RRM_u = 1 - \left( \frac{w_{(u,1)} \ast SE_{(1)} + \frac{w_{(u,2)} \ast SE_{(2)}}{w_{m,n}} + \frac{w_{(u,3)} \ast SE_{(3)}}{w_{m,n}} + \frac{w_{(u,4)} \ast SE_{(4)}}{w_{m,n}}}{\sum_{j=1}^{m} CI_{AT(j)} \ast x_{j,n}} \right) \ast y_{n,k} (n = 1, 2, 3, 4), \]

5.1.12. Step 14. The total criticality index (TCI) is calculated using

\[ TCI = \sum_{j=1}^{m} CI_{AT(j)}. \]

The total reduction criticality index (TRCI) is calculated using

\[ TRCI = \sum_{j=1}^{m} R \ast CI_{AT(j)}. \]

The total risk reduction rate (TRRR) is calculated using

\[ TRRR(\%) = 1 - \frac{TCI}{TRCI}. \]

6. Case Study

A case study was performed in the current study to quantitatively analyze the risk reduction vs. cost increase using extended QFD-FMEA.

The TOPSIS analysis in the case study indicated a changed preference method by combining the TOPSIS and extended QFD-FMEA processes.

The construction method used in the case study is the dismantling method for the facility.

Five methods were selected for the case study: the large breaker, crushing, diamond cutter, crushing, overturning, and steel ball methods, which are most typically used methods for dismantling.
Random numbers were designated to these construction methods. As the objective of this study was to verify the general decision-making process, the general possibility of industrial application, and the validity of the proposed model, preference analysis results for the actual dismantling method used in construction sites were not required.

### Table 3: Technology characteristic values of 5 alternative methods and importance weights of TC.

| Main category | Characteristic name | Importance (TC) | A001 | A002 | A003 | A004 | A005 |
|---------------|---------------------|-----------------|------|------|------|------|------|
| **Economics** | Low cost            | 9               | 5    | 4    | 3    | 3    | 2    |
|               | Low noise           | 7               | 3    | 3    | 4    | 5    | 5    |
| **Environmental** | Low dust          | 6               | 4    | 3    | 4    | 5    | 3    |
|               | Waste reduction     | 10              | 3    | 5    | 5    | 4    | 1    |
|               | CO2 reduction       | 8               | 5    | 4    | 3    | 4    | 4    |
| **Safety**    | Safety              | 10              | 3    | 3    | 2    | 3    | 3    |

### Table 4: The preference values of each construction method.

| Main category | Characteristic details | Economics | Environmental | Safety | Weighted sum | Total value | Preference ranking |
|---------------|------------------------|-----------|----------------|--------|--------------|-------------|-------------------|
|               |                        | Low cost  | Low noise      | Low dust| Waste reduction| CO2 reduction| Safety            |
|               |                        | Weighted | 45             | 21     | 24           | 30          | 30               |
| **A001**      | Normalized score       | 5        | 3              | 4      | 3            | 5           | 3                | 190              | 7.60  | 2    |
|               | Weighted               | 45       | 21             | 24     | 30           | 30          | 30               |
| **A002**      | Normalized score       | 4        | 3              | 3      | 5            | 4           | 3                | 187              | 7.48  | 3    |
|               | Weighted               | 36       | 21             | 18     | 50           | 32          | 30               |
| **A003**      | Normalized score       | 3        | 4              | 4      | 5            | 3           | 2                | 173              | 6.92  | 4    |
|               | Weighted               | 27       | 28             | 24     | 50           | 24          | 20               |
| **A004**      | Normalized score       | 3        | 5              | 5      | 4            | 4           | 3                | 194              | 7.76  | 1    |
|               | Weighted               | 27       | 35             | 30     | 40           | 32          | 30               |
| **A005**      | Normalized score       | 2        | 5              | 3      | 1            | 4           | 3                | 143              | 5.72  | 5    |
|               | Weighted               | 18       | 35             | 18     | 10           | 32          | 30               |

*: 10-point scale weights.

### Table 5: Technical characteristics for priority 1~2 alternatives on 2nd TOPSIS evaluation.

| Main category | Characteristic name | Importance | A001 | A004 |
|---------------|---------------------|------------|------|------|
| **Economics** | Low cost            | 9          | 5    | 3    |
|               | Additional low safety cost | 9      | 5    | 4    |
| **Environmental** | Low noise          | 7          | 3    | 5    |
|               | Low dust            | 6          | 4    | 5    |
|               | Waste reduction     | 10         | 3    | 4    |
|               | CO2 reduction       | 8          | 5    | 4    |
| **Safety**    | Safety              | 10         | 3    | 3    |
|               | Risk reduction (total) | 10     | 4    | 3    |

*: 10-point scale weights (importance, total value)

### Table 6: 2nd TOPSIS evaluation result for priority 1~2 alternatives.

| Main category | Characteristic details | Economics | Additional low safety | Environmental | CO2 reduction | Safety | Risk reduction | Weighted sum | Total value | Preference ranking |
|---------------|------------------------|-----------|-----------------------|---------------|--------------|--------|---------------|--------------|-------------|-------------------|
|               |                        | Low cost  | Low noise             | Low dust      | Waste reduction|        |               |              |             |                   |
| **Weight**    |                        | 9         | 7                     | 6             | 10           | 8      | 10            |              |             |                   |
| **A001**      | Normalized score       | 5         | 5                     | 3             | 4            | 3      | 4             |              |             |                   |
|               | Weighted               | 45        | 45                    | 24            | 30           | 30     | 30            | 275          | 7.97        | 1                 |
| **A004**      | Normalized score       | 3         | 4                     | 5             | 4            | 4      | 3             |              |             |                   |
|               | Weighted               | 27        | 36                    | 35            | 30           | 32     | 30            | 260          | 7.54        | 2                 |

*: 10-point scale weights (importance, total value)
| Number  | Composition ratio (%) | Accident type | Frequency (years) | H_01 | H_02 | H_03 | H_04 | H_05 | H_06 | H_07 | H_08 | H_09 | H_10 | H_11 | H_12 | H_13 | H_14 | Sum |
|---------|----------------------|---------------|-------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|-----|-----|
| A01_01  | 13.5                 | A             | 12                | 0    | 0    | 0    | 0.5  | 0    | 0    | 0    | 0.5  | 0    | 0    | 0    | 0    | 0    | 1.0 |
| A01_02  | 6.7                  | A             | 6                 | 0    | 0    | 0.3  | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0.7  | 0    | 0    | 1.0 |
| A01_03  | 22.5                 | A             | 20                | 0    | 0    | 0    | 0.3  | 0    | 0    | 0    | 0    | 0    | 0    | 0.2  | 0    | 0    | 0    | 1.0 |
| A01_04  | 3.4                  | A             | 3                 | 0    | 0    | 0    | 1.0  | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 1.0 |
| A01_05  | 16.9                 | B             | 15                | 1.0  | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 1.0 |
| A01_06  | 25.8                 | B             | 23                | 0    | 0    | 1.0  | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 1.0 |
| A01_07  | 5.6                  | C             | 5                 | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0.7  | 0    | 0    | 0    | 0    | 0    | 0.3 | 1.0 |
| A01_08  | 5.6                  | C             | 5                 | 0    | 0    | 0    | 0    | 0    | 0    | 0.5  | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 1.0 |
### Table 8: Risk assessment and risk reduction ratio analysis table by QFD-FMEA logic at A001.

| Accident number | Accident type | H_main | H_sub (1) | H_sub (2) | Severity | Frequency | Risk | CI | RCI |
|-----------------|---------------|--------|-----------|-----------|----------|-----------|------|----|-----|
| A01_01          | A             | 5      | 5         | 0         | 5        | 3         | 15   | 6.00| 2.87|
| A01_02          | A             | 7      | 3         | 0         | 3        | 2         | 6    | 2.40| 0.86|
| A01_03          | A             | 5      | 3         | 2         | 5        | 4         | 20   | 8.00| 3.25|
| A01_04          | A             | 10     | 0         | 0         | 5        | 1         | 5    | 2.00| 0.68|
| A01_05          | B             | 10     | 0         | 0         | 3        | 3         | 9    | 3.60| 1.37|
| A01_06          | B             | 10     | 0         | 0         | 4        | 5         | 20   | 8.00| 3.36|
| A01_07          | C             | 7      | 3         | 0         | 2        | 1         | 2    | 0.80| 0.33|
| A01_08          | C             | 5      | 5         | 0         | 5        | 1         | 5    | 2.00| 1.04|

TRRR: 58.1%

**Table 9: Alternative A001 basic cause ratio analysis table by accident type (Step 5 of extended QFD-FMEA).**

| Number | Hazard factors M1 | M2 | M3 | M4 | Component value (sum) |
|--------|-------------------|----|----|----|------------------------|
| A01_01 | H_04 (0.50)       | 0.50 | 0.50 | 0.00 | 1.00 |
|        | H_06 (0.50)       | 0.00 | 0.00 | 1.00 | 1.00 |
|        | Configuration value | 1.50 | 1.50 | 3.00 | 6.00 |
|        | Composition ratio  | 0.25 | 0.25 | 0.50 | 1.00 |
| A01_02 | H_08 (0.30)       | 0.00 | 0.70 | 0.30 | 1.00 |
|        | H_12 (0.70)       | 0.80 | 0.00 | 0.00 | 1.00 |
|        | Configuration value | 1.34 | 0.50 | 0.22 | 2.00 |
|        | Composition ratio  | 0.56 | 0.21 | 0.09 | 1.00 |
| A01_03 | H_04 (0.30)       | 0.00 | 0.30 | 0.70 | 1.00 |
|        | H_08 (0.20)       | 1.00 | 0.00 | 0.00 | 1.00 |
|        | H_12 (0.50)       | 0.00 | 0.00 | 1.00 | 1.00 |
|        | Configuration value | 1.60 | 0.72 | 1.68 | 4.00 |
|        | Composition ratio  | 0.20 | 0.09 | 0.21 | 0.50 |
| A01_04 | H_05 (1.00)       | 0.00 | 0.00 | 0.50 | 1.00 |
|        | Configuration value | 0.00 | 0.00 | 1.00 | 1.00 |
|        | Composition ratio  | 0.00 | 0.00 | 0.50 | 1.00 |
| A01_05 | H_01 (1.00)       | 0.00 | 0.00 | 1.00 | 1.00 |
|        | Configuration value | 0.00 | 0.00 | 3.60 | 3.60 |
|        | Composition ratio  | 0.00 | 0.00 | 1.00 | 1.00 |
| A01_06 | H_03 (1.00)       | 0.00 | 0.00 | 1.00 | 1.00 |
|        | Configuration value | 0.00 | 0.00 | 8.00 | 8.00 |
|        | Composition ratio  | 0.00 | 0.00 | 1.00 | 1.00 |
| A01_07 | H_08 (0.70)       | 0.00 | 0.40 | 0.60 | 1.00 |
|        | H_14 (0.30)       | 1.00 | 0.00 | 0.00 | 1.00 |
|        | Configuration value | 0.24 | 0.22 | 0.34 | 0.80 |
|        | Composition ratio  | 0.30 | 0.28 | 0.42 | 0.80 |
| A01_08 | H_06 (0.50)       | 1.00 | 0.00 | 0.00 | 1.00 |
|        | H_08 (0.50)       | 0.00 | 0.00 | 1.00 | 1.00 |
|        | Configuration value | 1.00 | 0.00 | 1.00 | 1.00 |
|        | Composition ratio  | 0.50 | 0.00 | 0.50 | 1.00 |

**Table 10: Table of analysis of hazard factors and risk reduction measures by basic causes of A001 alternative (Steps 7, 8, 9 of extended QFD-FMEA).**

| BC rate | Hazard factors | HF - CI | Composition rate | Rate of HF | Accident type (AT) | Risk score | Risk reduction measures (RRM) | Priority | Risk reduction rate (RRR) | Reduction criticality index (RCI) |
|---------|----------------|---------|------------------|-----------|-------------------|------------|-------------------------------|----------|--------------------------|----------------------------------|
| M1 0.17 | H_04           | 1.50    | 26.4%            | 4.6%      | A01_01            | 15         | Risk reduction measure 01     | 2        | 0.34                     | 0.51                             |
|         | H_06           | 1.00    | 17.6%            | 3.0%      | A01_08            | 5          | Risk reduction measure 02     | 5        | 0.52                     | 0.52                             |
|         | H_08           | 1.60    | 28.1%            | 4.9%      | A01_03            | 20         | Risk reduction measure 03     | 1        | 0.52                     | 0.83                             |
|         | H_12           | 1.34    | 23.6%            | 4.1%      | A01_02            | 6          | Risk reduction measure 04     | 4        | 0.34                     | 0.46                             |
|         | H_14           | 0.24    | 4.2%             | 0.7%      | A01_07            | 2          | Risk reduction measure 05     | 6        | 0.34                     | 0.08                             |
|         | Sum            | 5.68    | 100%             | —         | —                 | 2          | Sum                           | 2.40     |                          |                                   |
In the case study, five construction methods were evaluated in terms of the following aspects: economic feasibility, environmental performance, and safety. According to the requirements of the dismantling method, technical characteristics of economic feasibility, low noise, low dust, low waste, CO2 reduction, and safety were evaluated on a five-point scale.

Subsequently, the scores assigned were normalized and weighted to calculate the preference for the five methods. Extended QFD-FMEA analysis was applied to two of the five methods that indicate the highest preference.

In extended QFD-FMEA, the risk factors for the methods with the highest preference, degree of risk reduction, and degree of increased safety costs are analyzed.

| BC rate | Hazard factors | HF- CI | Composition rate | Rate of HF | Accident type (AT) | Risk score | Risk reduction measures (RRM) | Priority | Risk reduction rate (RRR) | Reduction criticality index (RCI) |
|---------|----------------|--------|------------------|-----------|--------------------|-----------|-----------------------------|----------|--------------------------|---------------------------------|
| M2 0.33 | H_03           | 8.50   | 77.7%            | 25.9%     | A01_02, A01_06     | 20        | Risk reduction measure 06   | 1        | 0.42                     | 3.57                             |
|         | H_04           | 2.22   | 20.3%            | 6.8%      | A01_01, A01_03     | 20        | Risk reduction measure 07   | 1        | 0.53                     | 1.18                             |
|         | H_08           | 0.22   | 2.0%             | 0.7%      | A01_07             | 2         | Risk reduction measure 08   | 6        | 0.34                     | 0.08                             |
|         | H_01           | 10.95  | 100%             | —         | —                  | —         | Risk reduction measure 09   | 3        | 0.38                     | 1.37                             |
|         | H_03           | 0.22   | 2.0%             | 0.7%      | A01_02             | 6         | Risk reduction measure 10   | 4        | 0.38                     | 0.08                             |
|         | H_04           | 1.68   | 15.5%            | 5.1%      | A01_03             | 20        | Risk reduction measure 11   | 1        | 0.40                     | 0.67                             |
|         | H_05           | 1.00   | 9.2%             | 3.0%      | A01_04             | 5         | Risk reduction measure 12   | 5        | 0.34                     | 0.34                             |
|         | H_08           | 4.34   | 40.0%            | 13.2%     | A01_01, A01_07, A01_08 | 15        | Risk reduction measure 13   | 2        | 0.52                     | 2.25                             |
| M3 0.33 | H_01           | 10.83  | 100%             | —         | —                  | —         | Risk reduction measure 14   | 5        | 0.34                     | 0.34                             |
|         | H_03           | 1.00   | 18.7%            | 3.0%      | A0act1_04          | 5         | Risk reduction measure 15   | 1        | 0.34                     | 1.47                             |
|         | H_12           | 4.34   | 81.3%            | 13.2%     | A01_02, A01_03     | 20        | Risk reduction measure 16   | 6        | 0.34                     | 1.81                             |
|         | Sum            | 5.336  | 100%             | —         | —                  | —         | Sum                         | 5.9      | —                        | —                               |

Table 10: Continued.

| Risk reduction measures (RRM) | Reduction measures priority | Education (SE1) 0.7 | Safety efficiency (SE) | Technology (SE2) 0.5 | Management (SE3) 0.4 | Personal (SE4) 0.3 | Risk reduction rate (RRR) | Increasing safety cost rate (ISCR) (%) |
|------------------------------|-----------------------------|---------------------|------------------------|----------------------|----------------------|-------------------|--------------------------|----------------------------------------|
| Risk reduction measures 01   | 2                           | 0.9                 | 0.1                    | 0.34                 | 0.01                 | 0.01              | 1.0                     |                                       |
| Risk reduction measures 02   | 5                           | 0.9                 | 0.1                    | 0.52                 | 1.10                 | 1.10              | 0.1                     |                                       |
| Risk reduction measures 03   | 1                           | 0.9                 | 0.1                    | 0.52                 | 0.10                 | 0.10              | 0.1                     |                                       |
| Risk reduction measures 04   | 4                           | 0.9                 | 0.1                    | 0.34                 | 0.15                 | 0.15              | 0.1                     |                                       |
| Risk reduction measures 05   | 6                           | 0.9                 | 0.1                    | 0.34                 | 0.30                 | 0.30              | 0.3                     |                                       |
| Risk reduction measures 06   | 1                           | 0.5                 | 0.1                    | 0.42                 | 0.10                 | 0.10              | 0.1                     |                                       |
| Risk reduction measures 07   | 1                           | 0.8                 | 0.1                    | 0.53                 | 0.20                 | 0.20              | 0.2                     |                                       |
| Risk reduction measures 08   | 6                           | 0.9                 | 0.1                    | 0.34                 | 0.80                 | 0.80              | 0.8                     |                                       |
| Risk reduction measures 09   | 3                           | 0.8                 | 0.1                    | 0.38                 | 0.80                 | 0.80              | 0.8                     |                                       |
| Risk reduction measures 10   | 4                           | 0.7                 | 0.2                    | 0.38                 | 0.30                 | 0.30              | 0.3                     |                                       |
| Risk reduction measures 11   | 1                           | 0.7                 | 0.2                    | 0.40                 | 0.40                 | 0.40              | 0.4                     |                                       |
| Risk reduction measures 12   | 5                           | 0.9                 | 0.1                    | 0.34                 | 0.10                 | 0.10              | 0.1                     |                                       |
| Risk reduction measures 13   | 2                           | 0.9                 | 0.1                    | 0.52                 | 1.00                 | 1.00              | 1.0                     |                                       |
| Risk reduction measures 14   | 5                           | 0.9                 | 0.1                    | 0.34                 | 0.05                 | 0.05              | 0.05                     |                                       |
| Risk reduction measures 15   | 1                           | 0.9                 | 0.1                    | 0.34                 | 0.50                 | 0.50              | 0.5                     |                                       |

Table 11: Analysis table of subjective beliefs about risk reduction and additional costs corresponding to steps 11 and 12 of extended QFD-FMEA at A001.
Preference is analyzed again based on the performance of the method in increasing the safety cost and reducing risk in the second decision-making.

In the case study, Method #4 was prioritized, followed by Method #1 in the first decision-making process. However, in the second decision-making process, Method #1 was regarded as the highest priority.

This is because Method #1 exhibits better risk reduction performance and a lower cost for added safety compared with Method #4.

Furthermore, Method #1 exhibits a lower tradeoff in terms of risk reduction and the corresponding safety cost compared with Method #4.

Below Table 3 shows the technical characteristic values through the 5-point scale of each construction method.

Table 4 shows the preference values of each construction (dismantling) method by TOPSIS logic. As a result of the preference analysis, the A004 alternative was analyzed as the first and the A001 alternative as the second.
| Number  | Composition ratio (%) | Accident type | Frequency (years) | H_01 | H_02 | H_03 | H_04 | H_05 | H_06 | H_07 | H_08 | H_09 | H_10 | H_11 | H_12 | H_13 | H_14 | Sum |
|---------|-----------------------|---------------|-------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| A01_01  | 11.6                  | A             | 10                | 0.3  | 0    | 0    | 0    | 0    | 0    | 0.7  | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 1.0 |
| A01_02  | 10.5                  | A             | 9                 | 0    | 0    | 0    | 0.3  | 0    | 0    | 0    | 0    | 0    | 0.3  | 0    | 0.4  | 0    | 0    | 1.0 |
| A01_03  | 7.0                   | A             | 6                 | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 1    | 0    | 0    | 0    | 0    | 0    | 0    | 1.0 |
| A01_04  | 31.4                  | B             | 27                | 0    | 0    | 1    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 1.0 |
| A01_05  | 26.7                  | C             | 23                | 0    | 0    | 0    | 0    | 0.7  | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0.3 | 1.0 |
| A01_06  | 12.8                  | C             | 11                | 0.5  | 0    | 0    | 0    | 0    | 0    | 0.5  | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 1.0 |
Table 5 shows the results of re-evaluating the preference for the A004 and the A001 alternative through the TOPSIS evaluation.

The technical characteristics of feedback items for secondary decision-making are the risk reduction and the additional safety cost for risk reduction.

Table 6 below shows the preference analysis results of A004 and A001 for the alternative construction (dismantling) method, and the ranking changed differently from the first evaluation.

In secondary decision-making, A001 shows a higher preference value than A004.

This result is because A001 has more risk reduction potential than A004 in risk reduction, and A001 has more economical technical characteristics than A004 in terms of added safety and low cost.

Therefore, in the final decision making, it can be recommended that the construction method be selected as A001 as a more suitable alternative.

Table 7 is a fundamental analysis table of accident types and risk factors for the A001 alternative for extended QFD-FMEA evaluation.

Table 8 is a table of CI, RCI analysis through extended QFD-FMEA of the A001.

Table 9 is a table of basic cause ratio by hazard factors through extended QFD-FMEA of the A001.

Table 10 defines risk reduction measures according to the classification system of basic causes and hazard factors, and then the risk reduction ratio was derived from the results in Table 11.

Table 11 below lists risk reduction measures (RRM), risk reduction rate (RRR), and increasing safety cost rate (ISCR) of alternative A001.

Below Figure 9 shows the flow chart of case data for risk assessment, basic cause analysis, safety measures, and risk reduction ratio using extended QFD-FMEA.

Below Table 12 shows the basic analysis table for the accident types and risk factors of the A004 alternative for extended QFD-FMEA evaluation.

Table 13 is a table analyzing CI, RCI using extended QFD-FMEA for the A004 alternative.

Table 14 is a table of basic cause ratio by hazard factors through extended QFD-FMEA of the A004.
Table 15: Table of analysis of hazard factors and risk reduction measures by basic causes of A004 alternative (Step 7, 8, and 9 of extended QFD-FMEA).

| BC  | Hazard factors | HF-CI Composition rate | Rate of HF | Accident type (AT) | Risk score | Risk reduction measures (RRM) | Priority | Risk reduction rate (RRR) | Reduction criticality index (RCI) |
|-----|----------------|-------------------------|------------|-------------------|------------|-------------------------------|----------|--------------------------|----------------------------------|
| M1  | 0.32           | H_01 0.48 5.2% 1.7%     | A01_01     | 8                 | 0.46       | Risk reduction measure 01     | 3        | 0.46                     | 0.22                             |
|     |                | H_03 6 65.2% 21.1%      | A01_04     | 15                | 0.56       | Risk reduction measure 02     | 2        | 0.56                     | 3.36                             |
|     |                | H_05 2.24 24.3% 7.9%    | A01_05     | 20                | 0.64       | Risk reduction measure 03     | 1        | 0.64                     | 1.43                             |
|     |                | Sum 9.2 100% -           | -          | -                 | -          | Sum                           | 5.31     |                          |                                  |
|     |                | H_04 0.6 5.3% 2.1%      | A01_02     | 10                | 0.62       | Risk reduction measure 04     | 2        | 0.62                     | 0.30                             |
|     |                | H_05 3.36 29.9% 11.8%   | A01_05     | 20                | 0.66       | Risk reduction measure 05     | 1        | 0.66                     | 2.22                             |
| M2  | 0.39           | H_07 3.744 33.4% 13.2%  | A01_01, A01_03 | 6 | Risk reduction measure 07     | 4        | 0.65                     | 2.43                             |
|     |                | H_12 1.12 10.0% 3.9%    | A01_02     | 10                | 0.50       | Risk reduction measure 08     | 2        | 0.50                     | 0.56                             |
|     |                | H_14 2.4 21.4% 8.5%     | A01_05     | 20                | 0.67       | Risk reduction measure 09     | 1        | 0.67                     | 1.43                             |
|     |                | Sum 11.22 100% -        | -          | -                 | -          | Sum                           | 7.07     |                          |                                  |
|     |                | H_01 0.48 11.0% 1.7%    | A01_01     | 8                 | 0.68       | Risk reduction measure 10     | 3        | 0.68                     | 0.33                             |
|     |                | H_04 0.6 13.7% 2.1%     | A01_02     | 10                | 0.52       | Risk reduction measure 11     | 2        | 0.52                     | 0.31                             |
| M3  | 0.15           | H_07 0.896 20.5% 3.2%   | A01_01     | 8                 | 0.62       | Risk reduction measure 12     | 3        | 0.62                     | 0.56                             |
|     |                | H_08 2.4 54.8% 8.5%     | A01_06     | 12                | 0.60       | Risk reduction measure 13     | 3        | 0.60                     | 1.44                             |
|     |                | Sum 4.38 100% -         | -          | -                 | -          | Sum                           | 2.63     |                          |                                  |
|     |                | H_01 2.4 66.7% 8.5%     | A01_06     | 12                | 0.68       | Risk reduction measure 14     | 3        | 0.68                     | 1.63                             |
| M4  | 0.12           | H_10 1.2 33.3% 4.2%     | A01_02     | 10                | 0.62       | Risk reduction measure 15     | 2        | 0.62                     | 0.74                             |
|     |                | Sum 3.60 100% -         | -          | -                 | -          | Sum                           | 2.38     |                          |                                  |

Table 16: Analysis table of subjective beliefs about risk reduction and additional costs corresponding to Steps 11 and 12 of extended QFD-FMEA at A004.

| Risk reduction measures (RRM) | Reduction measures priority | Education (SE1) 0.7 | Safety efficiency (SE) Technology (SE2) 0.5 | Management (SE3) 0.4 | Personal (SE4) 0.3 | Risk reduction rate (RRR) | Increasing safety cost rate (ISCR) (%) |
|-------------------------------|------------------------------|---------------------|---------------------------------------------|----------------------|------------------|------------------------|-------------------------------------|
| Risk reduction measures 01    | 3                            | 0.4                 | 0.4                                         | 0.2                  | 0.46             | 0.10                   |
| Risk reduction measures 02    | 2                            | 0.4                 | 0.4                                         | 0.1                  | 0.56             | 2.10                   |
| Risk reduction measures 03    | 1                            | 0.6                 | 0.4                                         | 0.64                 | 0.10             |
| Risk reduction measures 04    | 2                            | 0.8                 | 0.8                                         | 0.62                 | 0.30             |
| Risk reduction measures 05    | 2                            | 0.8                 | 0.8                                         | 0.62                 | 0.90             |
| Risk reduction measures 06    | 1                            | 0.8                 | 0.8                                         | 0.66                 | 0.10             |
| Risk reduction measures 07    | 4                            | 0.5                 | 0.5                                         | 0.65                 | 0.70             |
| Risk reduction measures 08    | 2                            | 0.5                 | 0.5                                         | 0.5                  | 1.60             |
| Risk reduction measures 09    | 1                            | 0.2                 | 0.8                                         | 0.62                 | 2.10             |
| Risk reduction measures 10    | 3                            | 0.2                 | 0.8                                         | 0.68                 | 1.20             |
| Risk reduction measures 11    | 2                            | 0.3                 | 0.6                                         | 0.52                 | 0.40             |
| Risk reduction measures 12    | 3                            | 0.2                 | 0.8                                         | 0.62                 | 2.10             |
| Risk reduction measures 13    | 3                            | 0.5                 | 0.6                                         | 0.6                  | 3.10             |
| Risk reduction measures 14    | 3                            | 0.2                 | 0.8                                         | 0.68                 | 0.20             |
| Risk reduction measures 15    | 2                            | 0.2                 | 0.8                                         | 0.62                 | 1.40             |
| Sum                           | 16.4                         |                     |                                             |                      |                  |                        |

Table 15 shows risk reduction measures according to the classification system of basic causes and hazard factors, and then the risk reduction ratio was derived from the results in Table 16. Table 16 lists risk reduction measures (RRM), risk reduction rate (RRR), and increasing safety cost rate (ISCR) of alternative A004.
7. Conclusions

One of the problems in MCDM is the low productivity of the project caused by insufficient relevant experience, information, and knowledge. A decision-making method and a systematic approach for selecting construction methods based on risk analysis and expert feedback were proposed herein. Factors to reduce risks were identified using the extended QFD-FMEA in MCDM to improve limited and incomplete information. The extended QFD-FMEA model proposed in this research supports the re-evaluation of construction methods based on a changing safety environment by providing the rate of risk reduction and increased safety cost owing to the reduced risks of alternative construction methods.

A step-by-step decision-making process for construction method selection was presented and verified via a case study. The preferences for five alternate construction methods were evaluated using simulated data. The first decision-making based on the TOPSIS yielded the two most preferred alternatives among the five alternate methods. Subsequently, the extended QFD-FMEA was performed for the two most preferred alternatives to analyze the tradeoff between risk reduction and safety costs.

Among the five alternatives, Method #4 was selected in the initial TOPSIS review stage of the case study; however, in the second round of the TOPSIS assessment, Method #1 was selected. The construction method preference results changed after feedback was provided from the extended QFD-FMEA analysis. This indicates that preferences can be changed through feedback during the review process. This is the main contribution of this study, i.e., a decision-making procedure that can determine the most appropriate construction method, from construction method selection to risk mitigation and planning.

The feedback-based TOPSIS model presented herein was extended to a generalized decision-making area. When the...
required characteristic items in MCDM exhibit high uncertainty, tradeoff characteristics, and high sensitivity, the decision-making model will effectively manage the MCDM problems. The limitation of this study is that simulated data were used to validate the extended QFD-FMEA procedure. In a future study, we will apply extended QFD-FMEA to an actual project based on empirical risk assessment at actual construction sites.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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