Application of Fuzzy TOPSIS in Selecting Cutting Technology for Radioactive Waste Metal Melting Facility

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1. Introduction

In the process of decommissioning nuclear power plants, it is important to minimize the amount of radioactive waste generated and reduce the cost of disposal. One technology for the volume reduction of waste is the recycling of waste using metal melting. Facilities like Simpelkamp in Germany and Studsvik in Sweden have demonstrated that operating metal melting facilities for low-level radioactive waste recycling is both environmentally beneficial and economically viable [1].

The take-over conditions for the melting facility include exempt, very low-level, and low-level waste unless additional decontamination facilities are considered. And size of the waste received for acquisition cannot be adjusted. Therefore, to apply a melting facility to the waste received after nuclear power plant decommissioning, additional cutting facilities are required.

The cutting facility applied to the melting facility differs from nuclear decommissioning cutting technologies. Firstly, it must consider the activities of workers for low-level radioactive waste. Secondly, it must consider cutting in the atmosphere. Thirdly, it must select the most efficient cutting technology that has been commercialized and is available (in terms of performance, risk, cost, etc.). Therefore, this study aims to construct a Multi-Criteria Decision-Making Model and integrate fuzzy set theory to select the optimal cutting technology for the melting facility.

When comparing results obtained from various sources, ambiguity may accompany the process. In such cases, employing linguistic variables, such as fuzzy set theory, can be more practical than precise numerical comparisons [2]. In this study, Triangular Fuzzy Numbers are integrated into MCDM to comparatively assess previous research data. Furthermore, the TOPSIS methodology is utilized to calculate the closeness coefficient and determine the ranking of cutting technologies.

2. Methods

In this study, the algorithm structure was based on the methodology proposed by V. Kukreja in 2023 to evaluate metal-cutting processes for a metal melting facility for radioactive metal waste [3]. The algorithm structure proposed analysis is shown in Fig. 1

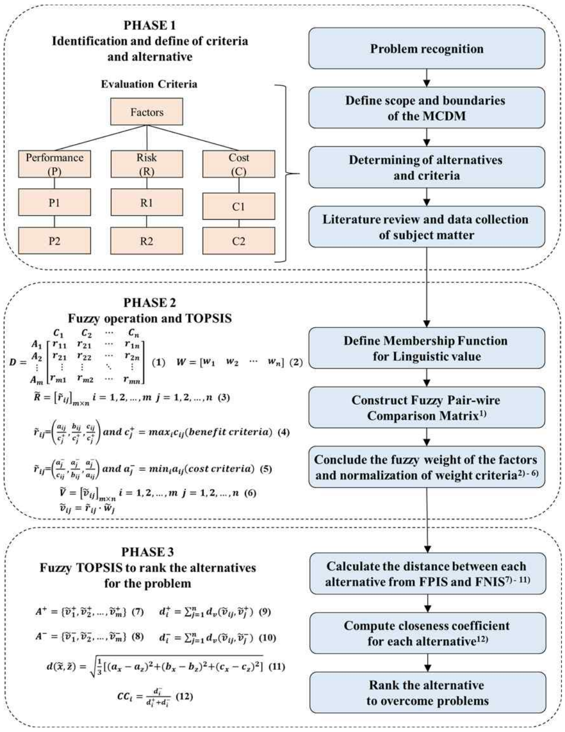

Fig. 1. Functional diagram of Fuzzy TOPSIS method

2.1 Phase 1: Identification and definition of criteria and alternative

For radioactive waste, the performance evaluation criteria for metal-cutting technology proposed by L.E. Boing in 1989 and G.R. Lee in 2022 are referenced [4, 5]. Additionally, for exempt waste, the evaluation criteria for cutting technology used in shipyards proposed by S. Cebi in 2016 are referenced [6]. The determined MCDM is shown in Fig 2. The determined criteria are six sub-attributes under Performance, Risk, and Cost Factors. The criteria assume the following: Performance and Risk Factors are evaluated based on carbon steel. Generation of Airborne Radioactivity is limited to radioactive aerosols generated during metal cutting. Construction Cost includes both initial and operation costs. The determined alternatives are Thermal Cutting (Laser, Plasma arc, and Flame), Mechanical Cutting (Diamond saw), and Electrical Cutting (Arc saw).

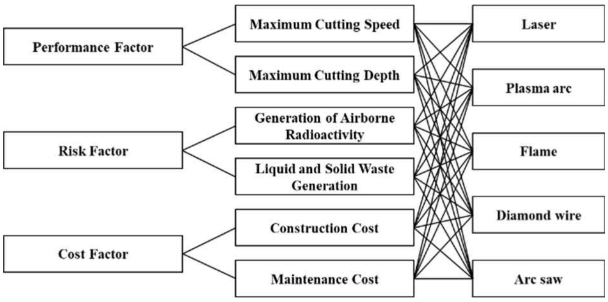

Fig. 2. Hierarchical structure of decision problem

2.2 Phase 2: Fuzzy operation and TOPSIS

In this phase, the aggregated data is transformed into triangular fuzzy numbers (TFN), and alternatives are evaluated for each attribute. The equations used for evaluation are referenced in Figure 1.

Step 1: Five Saaty's linguistic scales are distinguished for pairwise comparisons and evaluation of alternatives, as shown in Table 1.

Step 2: Pairwise comparisons among alternatives are conducted based on the results of previous research, resulting in the derivation of a fuzzy decision matrix (1) and criteria weights (2), as shown in equations (1,2).

Step 3: Normalization is carried out using equations (4, 5) for the TOPSIS method. Benefit criteria and cost criteria are classified for each of the six attributes, and normalization is performed accordingly.

Step 4: A weighted normalized fuzzy decision matrix is derived using equation (6), incorporating the weights.

Table I: Saaty's scale versus Fuzzy scale

Saaty's scale	**Linguistic Variables**	**Definition**	**Fuzzy Scale**	
			TFS	**Reciprocal TFS**
1	EqI	Equally Important	(1,1,1)	(1/1,1/1,1/1)
3	MI	Moderately Important	(2,3,4)	(1/4,1/3,1/2)
5	SI	Strongly Important	(4,5,6)	(1/6,1/5,1/4)
7	VI	Very Strongly Important	(6,7,8)	(1/8,1/7,1/6)
9	ExI	Extremely important	(9,9,9)	(1/9,1/9,1/9)
2, 4, 6, 8	Intermediate values between the two adjacent judgment			

2.3 Phase 3: Fuzzy TOPSIS to rank the alternatives for the problem

This phase involves calculating distances from TOPSIS results and ranking alternatives based on the closeness coefficient.

Step 5: The distance, d^* and d^-, of each alternative from the fuzzy positive (benefit)-ideal solution (FPIS, A^*) and fuzzy negative (cost)-ideal solution (FNIS, A^-) are calculated using equations (7-11). The distance calculation method employs the Euclidean equation (11).

Step 6: Utilizing the calculated d^* and d^-, the closeness coefficient(CC_i) is computed using equation (12). Rank alternatives based on CC_i results.

3. Result

The performance of alternatives for carbon steel was evaluated, as shown in Figure 3. To calculate the performance of alternatives, the Triangular Fuzzy numbers for each alternative were defuzzified to calculate the BNP (Best Nonfuzzy Performance). The BNP value for each alternative's Triangular Fuzzy number (A, B, C) within a criterion is calculated as follows:

$$(13)\quad BNP_{ij} = [(C_{ij} - A_{ij}) - (B_{ij} - A_{ij})]/3$$

In the Performance Factor, for P1: Maximum Cutting Speed and P2: Maximum Cutting Depth, Arc saw technology and Flame technology respectively exhibit the highest efficiency. In the Risk Factor, for R1: Generation of Airborne Radioactivity, Diamond wire technology is the most efficient. For R2: Liquid and Solid Waste Generation, except for Arc saw, minimal generation was observed across alternatives. In the Cost Factor, for C1: Construction Cost, Laser technology is the most expensive. For C2: Maintenance Cost, Diamond wire technology is the most expensive.

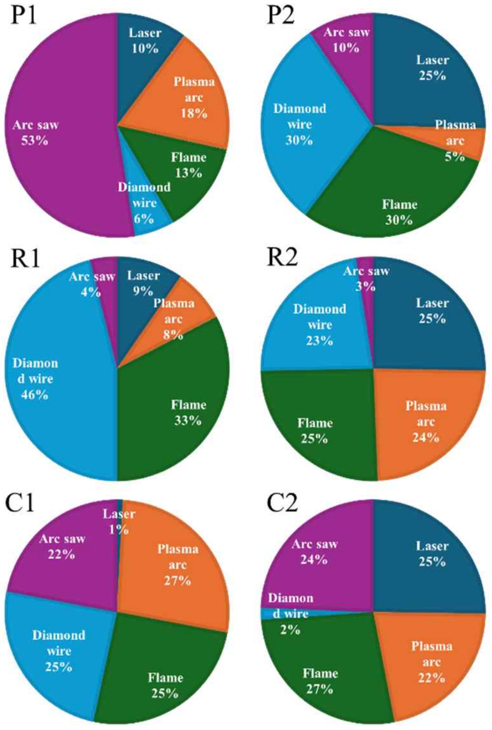

Fig. 3. Importance degree of evaluation factor.

The calculated weights for each attribute are shown in Table II. The Cost factor has been determined to have the highest weight. This result corresponds with the conclusion reached by G.R. Lee, 2022, who proposed cost to be the most important factor. Additionally, among the sub-attributes, Construction Cost was determined to have the highest weight.

Table II: The important degrees of criteria

Symbol	Factors	weights
P	**Performance Factor**	**0.34**
P1	Maximum Cutting Speed	0.17
P2	Maximum Cutting Depth	0.17
R	**Risk Factor**	**0.28**
R1	Generation of Airborne Radioactivity	0.14
R2	Liquid and Solid Waste Generation	0.14
C	**Cost Factors**	**0.38**
C1	Construction Cost	0.27
C3	Maintenance Cost	0.11

The ranking of alternatives obtained through distance calculation from the weighted fuzzy decision matrix is shown in Table III. A higher value of CC_i indicates a better alternative. Consequently, Flame > Diamond wire > Laser > Plasma arc > Arc saw were evaluated as the most optimal cutting technologies.

Table III: Computation of d_i^*, d_i^- and CC_i

Alternative	d_i*	d_i^-	CC_i	Ranking
Laser	3.816	2.170	0.363	3
Plasma arc	4.108	1.896	0.316	4
Flame	2.872	3.247	0.531	1
Diamond wire	3.673	2.326	0.388	2
Arc saw	4.682	1.450	0.237	5

4. Conclusions

This study evaluated the preferences for cutting technologies for introducing a metal radioactive waste melting facility. Building upon previous research, a MDCM model was constructed to assess six criteria and five alternatives based on cutting methods. Using five linguistic scales (EqI, MI, SI, VI, and ExI) represented by triangular fuzzy numbers, decision criteria and alternatives were evaluated through fuzzy set theory. Furthermore, using the TOPSIS methodology, CCi was derived to determine the priority of alternatives. When evaluated comprehensively based on six attributes, Flame cutting was identified as the most efficient. Flame cutting demonstrates the best performance in Maximum Cutting Depth, Liquid and Solid Waste Generation, and Maintenance Cost.

Through the fuzzy set theory evaluation method, subjective opinions were minimized to select optimal cutting technologies. However, the results have limitations concerning carbon steel. For example, if the cutting target changes to stainless steel, the cutting performance may vary. And criteria may be further refined depending on factors such as the shape of the cutting material and conditions in the melting facility. Therefore, additional research considering cutting conditions and costs for each cutting technology could lead to a more practical analysis.

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