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Technique for Order Performance by Similarity to Ideal Solution (TOPSIS)-entropy Methodology for Inherent Safety Design Decision Making Tool

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Abstract

Inherently Safer Design (ISD) concept has been recognized as a way to achieve safer operation and economically attractive for the process plant. However, the challenges in selecting between ISD alternatives are the need to satisfy conflicting objectives. Therefore, there is the need for a multi-criteria decision-making tool that can make a reliable, coherent and defensible decision. The objective of this paper is to illustrate the use of the TOPSIS-entropy method as a decision-making tool to evaluate the trade-off of ISD alternatives. Entropy method was included in TOPSIS calculation to remove the subjectivity problem during the weight scoring process for attributes. This methodology has been applied to identify the best ISD alternatives for methyl isocyanate storage at West Virginia fertilizer production plant. The results show that the rank obtained for ISD alternatives influenced by the weight value that indicate the priority given to the attributes. The Du Pont method has been identified as the best option when higher priority given to the attributes under external/regulatory pressure and the existing methodology with inventory reduction has been identified as the best option when higher priority given to the attributes under internal/cost pressure. The results obtained using TOPSIS-entropy method are congruent with the results reported in the previous work using Multi Attribute Utility Analysis proves that this method can be used to resolve ISD conflicts effectively. More than that, the capability of TOPSIS to deal with different types of weight estimation techniques gives an added value to this methodology.

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1. Introduction

Inherently safer design (ISD) is the approach to identify the safest design with the elimination of the root causes of hazards based on four main principles: substitution, minimization, moderation and simplification [1], [2]. This concept is believed to minimize potential safety hazards, as well as offer great benefits throughout process lifecycle. For the past twenty years, the research community has been actively developing the tools that can measure inherent safeness of process options. However, due the fact that ISD is not a separate entity from the process, the decision-making process proves as a big challenge because there are several factors

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must be considered while selecting the best options. A study conducted by National Academic of Science (NAS) concluded that one of the primary difficulties in evaluating and choosing between ISD alternatives was the need to satisfy conflicting objectives [3]. This issue can be particularly challenging as the final decision may affect individuals and organizations beyond the company itself. The lack of effective tools that capable of supporting decision making can hinder the implementation of ISD in real work practice. Table 1 summarized the current techniques utilized for multi-criteria decision-making tools that have been used in the inherent safety field. Recently, Multi-attribute Utility Theory (MAUT) was utilized to resolve ISD conflicts and identify the best option of methyl isocyanate (MIC) storage alternatives [4]. The main drawback of the technique is the elicitation process used to determine the score for attributes and weight. Elicitation process is a cognitively demanding task, subject to different biases, and the method of assessment itself will give the influence towards the final result [5]. Therefore, the process of acquiring sufficient high-quality knowledge was a time intensive and expensive activity. Referable to the above limitation, in this paper TOPSIS methodology will be used to resolve ISD conflicts in order to identify the best option. Entropy methodology will be embedded in TOPSIS procedure with the aims to provide alternatives for weight scoring process other than elicitation technique. This methodology has been applied to select MIC storage presented by [4]. The results show that TOPSIS-entropy method can resolve the ISD conflicts effectively in a timely manner.

Table 1. Summary of multi-criteria decision-making tools

Tools	Descriptions
Integrated Inherent Safety Index (I2SI) [6], [7]	I2SI is an index based a tool with economic evaluation and hazard potential identification for each ISD option. The guideword used in the I2SI methodology is based on the extent of applicability and the ability of five ISD principles to reduce the hazard.
Analytical Hierarchy Process (AHP) [8]–[13]	AHP is a hierarchical structure, decision-making tool based on pairwise comparisons concept. It depends on the experts to derive priority scales. The preferable option indicates by the overall priority called "total weight score".
Mathematical Programming [14]–[18]	Mathematical programming is a mathematical statement of the problems called a "model" involving objective, decision to be made and constraints. Algorithms are required to solve the complex mathematical model in programming. These techniques can search an infinite number of possible solutions within the constraints that can achieve the objective.
Multi-attribute Utility Theory (MAUT) [4]	MAUT was developed to address explicitly the value judgments associated with multiple, competing objectives. Utility function will be used as an indicator on how well one alternative performs on multiple objectives compared to the other alternatives.
Case-Based Reasoning (CBR) [19]	CBR is the method that proposes a solution to a decision-making problem based on the most similar cases from an existing database of cases
Fuzzy Theory [12], [13], [20]–[22]	Fuzzy set theory is the theory that capability to solve a problem that dealing with imprecise and uncertain data. Implementation of fuzzy theory is helpful for combining quantitative data with qualitative information for safety level evaluation

2. Background of Technique for Order Performance by Similarity to Ideal Solution (TOPSIS)

The basic idea of TOPSIS is the ideal alternative will have the shortest distance from the positive ideal solution (PIS) and the farthest from the negative ideal solution (NIS) [23]. Among the advantages of TOPSIS are logically represent the rational of human choice by considering both the best and the worst attributes of alternatives simultaneously, represented by a scalar value, the simplicity on computation and presentation [24]. The number of attributes does not influence the number of steps thus it offers a faster solution [25]. In recent years, TOPSIS has been successfully applied as decision-making tools to different areas including water management [26]–[28], transportation planning [29], human resource [24], mechanical engineering [30], manufacturing engineering [31] and policies development [28]. In the chemical engineering field, this technique has been combined with optimization procedure to identify the best options considering economic and environment factor [32]

2.1. TOSIS Methodology

In this section, the step of TOPSIS methodology will be presented as a series of consecutive steps as below [23]. All symbols has been defined in nomenclature section:

Step 1: Calculate the normalized decision matrix. The normalized value r_{ij} of the i_{th} alternative with respect to the j_{th} attribute is calculated as:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}} \quad j = 1,2,3,\ldots,J, i = 1,2,3,\ldots,n \tag{1}$$

Step 2: Calculate the weighted normalized decision matrix. The weighted normalized value

$$v_{ij} = w_j \times r_{ij} \quad j = 1,2,3,\ldots,J, i = 1,2,3,\ldots,n \tag{2}$$

Where w_j is the weight of the j_{th} attribute and $\sum_{i=1}^{J} w_j = 1$
Step 3: Determine the ideal and negative ideal solution:

$$A^+ = \{v_1^+,\ldots,v_J^+\} = \{(\max(or \min) v_{ij} | j \in J)\} \quad j = 1,2,3,\ldots,J, i = 1,2,3,\ldots,n \tag{3}$$

$$A^- = \{v_1^-,\ldots,v_J^-\} = \{(\min(or \min) v_{ij} | j \in J)\} \quad j = 1,2,3,\ldots,J, i = 1,2,3,\ldots,n \tag{4}$$

Step 4: Calculate the separation measures, using the n-dimension Euclidean distance. The separation of each alternative form the ideal solution is given as:

$$D_i^+ = \sqrt{\sum_{j=1}^{J} \left(v_{ij} - v_j^+\right)^2} \quad j = 1,2,3,\ldots,J \tag{5}$$

$$D_i^- = \sqrt{\sum_{j=1}^{J} \left(v_{ij} - v_j^-\right)^2} \quad j = 1,2,3,\ldots,J \tag{6}$$

Step 5: Calculate the relative closeness to the ideal solution. The relative closeness of A_i with respect to A^+ is defined as:

$$C_i^+ = \frac{D_i^-}{D_i^+ + D_i^-} \text{ where } 0 < C_i^+ < 1 \quad i = 1,2,3,\ldots,n \tag{7}$$

It is clear that $C_i^+ = 1$ if $A_i = A^+$ and $C_i^+ = 0$ if $A_i = A^-$, therefore a preferable option is the one that poses the value closer to 1.
Step 6: Rank the preference order based on the descending order of C_i^+

2.2. Entropy Method for Assessing Weight

There are several methods for assessing weight for decision-making process such eigenvector method, weighted least square method, entropy method, and linear programming technique for multidimensional analysis of preference (LINMAP) [23]. However, entropy and LINMAP method are more suitable to be used when the data of the decision matrix is known. According to [30], entropy method offers faster solution compared with LINMAP. The entropy method is especially valuable to examine disparities between sets of information. According to this principle, if the same values obtain for certain attributes for different alternatives, the attributes need to eliminate. The entropy formulation is shown in Eq. (8)

$$E_j = -k \sum_{i=1}^{n} p_{ij} \ln p_{ij} \quad j = 1,2,3,\ldots,J, i = 1,2,3,\ldots,n \tag{8}$$

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}} \quad j = 1,2,3,\ldots,J, i = 1,2,3,\ldots,n \tag{9}$$

$$k = 1/\ln n \tag{10}$$

Where p_{ij} is a discrete probability distribution of the i^{th} alternative with respect to the j^{th} attribute. Constant k used to ensure that $0 \le e_j \le 1$. Degree of divergence, d_j can be calculated as:

$$d_j = 1 - E_j \quad j = 1,2,3,\ldots,J \tag{11}$$

Final relative weights for j^{th} attribute can be obtained by simple additive normalization:

$$w_j = \frac{d_j}{\sum_{j=1}^{J} d_j} \quad j = 1,2,3,\ldots,J \tag{12}$$

3. Results & Discussion

3.1. Case Study : Selection of MIC storage alternatives

In this section, TOPSIS-entropy methodology will be applied to evaluate four ISD alternatives of the MIC storage tank in consequence of the near miss accident happened at fertilizer production plant at West Virginia in 2008. Four alternatives considered are the existing Union Carbide Corporation (UCC) process for MIC production, 80% reduction of store inventory using existing UCC process, Du Pont process and non-MIC process. The details of alternatives can be found in [3]. The scoring for fifteen attributes for four alternatives by [4] was presented in Table 2. The scoring was given considering all the benefits and the trade-off of alternatives. In this case study, each attribute was evaluated on an integral scale from 1 (the worst) to 10 (the best). Alternative 2 offers a safer design compared to the original one (Alternative 1) via minimization principles. In this case, the consequence of toxic release will be reduced with the reduction of intermediate MIC storage from 90 000 kg to 18 000 kg. However, these changes will increase the frequency of shutdowns due to the lack of MIC required by the operation. This modification can leds to the higher accidents potential because higher risk carried by startup and shutdown compared to the normal operation. In Alternative 3, safer option was provided via minimization principles where MIC was produced at the gaseous phases, thus eliminates the necessity of large on-site storage. However, in order to fulfill process requirement, that requires high purity MIC, the additional unit operation for purification and operation are compulsory. More than that, the concern regarding the toxic waste stream and registration approval time make this alternative less attractive. Alternative 4 offers a safer alternative via elimination principle with the process without MIC. However, this process produces a lower yield and involve corrosive materials [4].

Table 2. Scoring for MIC storage alternatives [4]

Attributes	Alternative 1 Existing UCC	Alternative 2 Reduced inventory	Alternative 3 DuPont method	Alternative 4 Non-MIC method
External/ regulatory pressure				
Risk for harm to surrounding communities	1	3	7	10
Community acceptance	1	3	7	10
Risk for worker injury due to MIC exposure	1	5	8	10
Risk for worker injury due to non-MIC process safety incident	8	10	5	1
Wastewater disposal requirements	10	10	5	1
Length of time for regulatory approval	10	9	1	2
Internal/cost pressure				
Product purity	10	9	1	3
Cost and availability of chemical feedstock	10	5	1	8
Capital costs	10	8	4	1
Equipment O&M costs	10	9	5	1
Costs of safety equipment	1	3	10	5
Process corrosivity	10	10	4	1
Process yield	10	9	3	1
Availability of in-house expertise	10	9	1	5

Previous experience with large-scale production	10	4	1	6

In this work, the weights has been computed using an entropy methodology (Eq. 8 to Eq. 12) as shown in Figure 1(a). The highest weight obtained is 0.0890 for attributes length of time for regulatory approval and the lowest weight obtained by three attributes which are the risk for worker injury due to MIC exposure, the risk for worker injury due to non-MIC process safety incident and the cost and availability of chemical feedstock with the values 0.0574 respectively. By using entropy method, the weight for attributes were estimated based on the divergence between the data which is justified to undertake the weighting process independently of subjective preferences of the decision maker. As been highlighted by [27], the rationality behind this concept is that each scenario is objectively described by its performance scores, and that scores represent the source of information emitted to the decision maker. Therefore, it is possible to recognize the relative weights of criteria by quantifying the intrinsic information emitted by each criterion through related scores given by the assessor. Total weight obtained for external/ regulatory pressures is lower compared to internal/cost pressures with the values are 0.4079 and 0.5921 respectively that result in the total weight is 1. This value indicates that more priority was given to the attributes related to internal/cost pressures (business factors) during the decision-making process. As can be seen in Table 1, attributes under internal/cost pressure are obviously part of business decision which is important to the company. In particular, the attributes considered under this category related to the investments by company, including the cost of the chemicals, labour and energy requirements, and new capital expenditures, as well as the quality of the product and revenues expected from its production. Other than that, consideration of in-house expertise and experiences also important, when unavailable, consultations from outside are required that can led to the additional cost. The rank was calculated using TOPSIS methodology (Eq. 1 to Eq. 7) using the weights obtained as presented in Figure 1(a). Considering both factors (separation from NIS and separation from PIS) the relative closeness to the ideal solution was calculated using Eq. (7) as shown in Figure 2. As mentioned in the methodology section, the most preferable option is the one that poses the value closer to 1, thus the results show that reduced inventory (Alternative 2) was deemed as best options when more priority given to internal/cost pressure. When more priority is given to internal cost pressure, the safety benefits offer by the other two alternatives (Alternative 3 and Alternative 4) outweighed by their negative impact such as corrosion problem, lower yield, product purity, etc. The rank obtained in descending order of preference are reduced inventory>existing UCC> non-MIC method>Du Pont method.

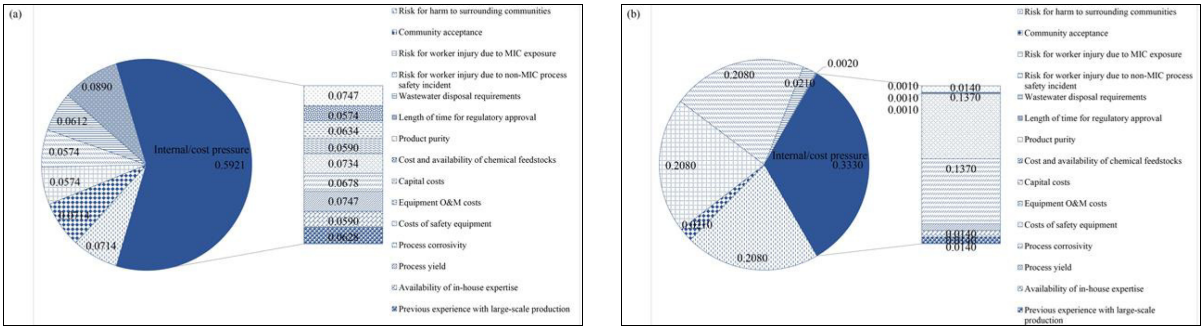

Fig. 1. (a) weight values via entropy; (b) weight values for sensitivity analysis

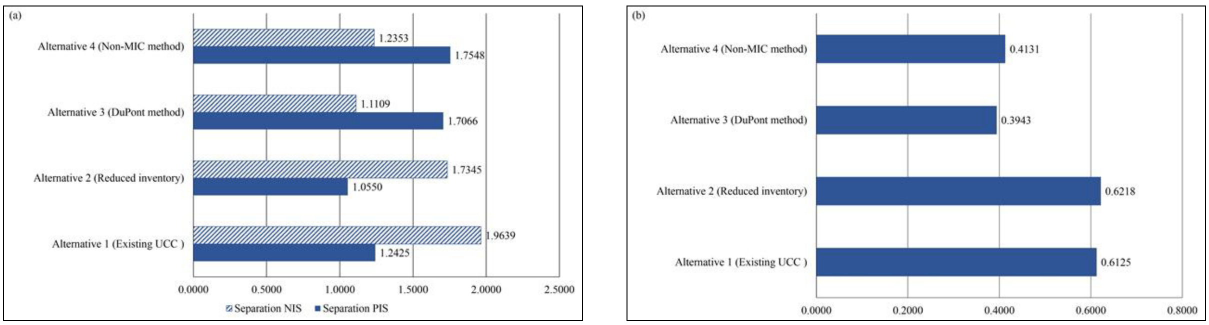

Fig. 2. (a) PIS and NIS value obtained using weight via entropy method; (b) relative closeness value obtained using weight via entropy methodology

Although in this paper, the entropy was embedded with TOPSIS procedure with the objective to removes the problems related to the dependencies of experts judgment, the authors want to stress, we do not refute the power of knowledge transfer via elicitation method. The insight that can be achieved during the elicitation process can be as valuable as what is obtained during processing of elicited values, become the key ingredient in decision analysis process. More than that, with a proper documentation the preservation of organizational knowledge can be ensured for new recruits. In the condition, where there is a needed to analyzes the benefit of choice towards the different competing stakeholders, sensitivity analysis with weights score via elicitation method still can be used with TOPSIS methodology. In order to show the impact of sensitivity analysis the weight values obtained using elicitation method from [4] have been used (Figure 1(b)). The weights has been varied to see the influence of external/regulatory pressure Total external/regulatory pressure weight is 0.668 and total internal/cost pressure weight is 0.333, imply that higher priority given to the external/regulatory factor. Three attributes involving different types of risk obtained the highest priority under external/regulatory body factor where the values are 0.2080 respectively. As can be seen based on the scores given in Table 2, higher risk to surrounding community will led to the lower community acceptance. According to [3], community acceptance plays crucial roles in determining the success of the project. Community perception and understanding of risk and safety are important, thus the relationship between company and surrounding community need to be maintained in order to allow for open discussion about risks and responses. The poor relationship between company and community can result in the failures/delays of the project which will give a negative impact towards business. Approvals from the regulatory body also need to be considered because the approval process can be lengthy and could result in significant loss of production. This can led to the possibility of permanent customer loss, when the customers need to switch to the other alternatives. Different rank obtained by prioritizing external/regulatory factor, which Alternative 3 (Du Pont) deemed as the best option (Figure 3). The benefits bring by this option via risk reduction and high potential of community acceptance overweight the negative impact that comes mainly from internal/cost pressure, such as product purity, cost and availability of chemical feedstock and lack of in-house expertise and experiences. The rankings obtained in descending order of preference are Du Pont>reduced inventory>non-MIC method>existing UCC method. Both results obtained in Figure 2 and Figure 3 are in agreement with the results obtained in the previous study by [4].

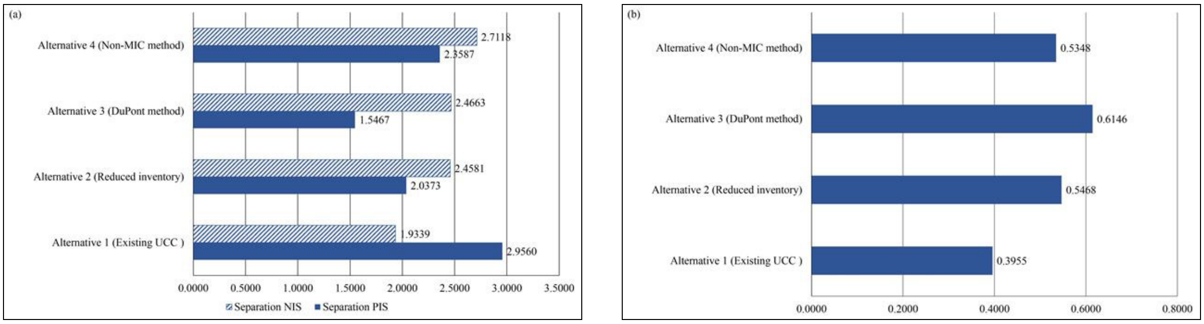

Fig. 3. (a) PIS and NIS value (higher priority to external/regulatory factor); (b) relative closeness value (higher priority to external/regulatory factor)

It is worthy to note that the main finding through this study is TOPSIS-entropy methodology can be valuable to assist the decision-making process for the industrial practitioner that working under time and cost constraints. One of the benefits is TOPSIS methodology offers a faster solution due to the fact that the number of attributes does not influence the number of steps. Other benefits obtained via the flexibility of TOPSIS to deal with a different type of weight scoring process. When the experts are unavailable or the weight values are arguable or the limited times are provided, entropy method will be valuable for weight estimations. However, if there is a requirement to evaluate the impact of choice towards different competing stakeholders, sensitivity analysis with weight scores via elicitation method can be useful.

4. Conclusion

Although ISD approach has been proven as safest and economically attractive for process plants, different conflicting objectives that need to be satisfied, result in ambiguity for ISD selection. Therefore, there is the need for a multi-criteria decision tool that can make a reliable, coherent and defensible decision. In this paper, the capability of TOPSIS to deal with a large number of attributes in timely manners has been demonstrated. The results show that, the rank obtained for ISD alternatives is highly depended on the weight value which indicate the priorities given to the attributes. The rank obtained from the most to the least preferable when higher priority given to the attributes under internal/cost pressure are reduced inventory>existing UCC> non-MIC method>Du Pont method.

Different rank obtained when higher priority given to the attributes under external/regulatory pressure, which are Du Pont>reduced inventory>non-MIC method>existing UCC method. The results obtained in this work are in agreement with the results from the previous study using MAUT proves that this methodology can be used to identify the best ISD option. More than that, the capability of TOPSIS to deal with different types of weight estimation techniques gives an added value to this methodology. Entropy method can be used in TOPSIS methodology to removes the problems related to the subjective judgment. However, if there is a requirement to evaluate the impact of choice towards different competing stakeholders, sensitivity analysis with weight scores via elicitation method still can be used with TOPSIS methodology. Thus, it is proven that TOPSIS-entropy has indeed been an effective tool for resolving the trade-off of ISD alternatives.

Nomenclature

A^+	Positive ideal solution (PIS)
A^-	Negative ideal solution (NIS)
C_i^+	Relative closeness to the ideal solution of the i^{th} alternative
D_i^+	Separation measure from PIS
D_i^-	Separation measure from NIS
d_j	Degree of divergence of the j^{th} attribute
E_j	Entropy of the j^{th} attribute
i	Number of alternative
j	Number of attribute
J	Total number of alternatives
n	Total number of alternatives
p_{ij}	Discrete probability distribution of the i^{th} alternative with respect to the j^{th} attribute
r_{ij}	Normalized value of the i^{th} alternative with respect to the j^{th} attribute
v_{ij}	Weighted normalized value of the i^{th} alternative with respect to the j^{th} attribute
w_j	Weighted value the j^{th} attribute
x_{ij}	Attributes value of the i^{th} alternative with respect to the j^{th} attribute

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