A Fuzzy-based Hybrid Approach for Estimating Interdisciplinary Learning Efficiency

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ABSTRACT

Students, industries, and departments focused on civil engineering are engaging in interdisciplinary learning techniques to promote sustainability and meet the urgent requirements of human development. However, only a few studies have discussed the learning efficiency and educational feedback of this trend. Hence, this study surveyed 173 data points from 6 departments that provided interdisciplinary courses based on three-dimensional trapezoidal fuzzy numbers and a Likert scale. The questionnaire factors were modified from the useful and common scales in science, technology, engineering, and mathematics (STEM) education. The existing studies tend to estimate students learning efficiency based on the hybrid approach of data envelopment analysis (DEA) and principal component analysis (PCA). However, the meaning of variables may be changed in the PCA procedures of axis transformation. Hence, a new fuzzy DEA-Mahalanobis distance approach was proposed to solve this problem. Based on the student gains in the sustainability courses, three groups were clustered and compared. Feedback for students was suggested to improve learning strategies. The sensitivity analysis showed that effective teaching practice and learning from other open courses or YouTube are key factors in increasing learning efficiency in sustainability courses for civil engineering students. Therefore, this paper provides a useful and easy approach to improve the learning strategies for civil engineering students in regard to sustainability education.

INDEX TERMS  fuzzy numbers, interdisciplinary learning, sustainability, data envelopment analysis, Mahalanobis distance

I. INTRODUCTION

The advantages of using fuzzy rating scales in the setting of questionnaires, where the extended Cronbach’s alpha is considered to quantify the internal consistency associated with constructs involving fuzzy rating scale-based items, have been verified [1], [2]. Over the decades, fuzzy numbers have been proposed in many educational applications, such as educational grading systems [3], student answer scripts [4], faculty performance evaluations [5], student project evaluations [6], student career selections [7], student perceptions [8], [9], and others [10]. On the other hand, data envelopment analysis (DEA), a nonparametric method used in operations research and economics to estimate production frontiers, has also frequently employed to estimate learning efficiency. DEA is a performance measurement technique that has been used to evaluate the relative efficiency of decision-making units (DMUs) in multiple organizations [11]. A DMU is a distinct unit within an organization. Students from different universities are the DMUs used in this research. The advantages of the DEA method are as follows: (i) it is not necessary to explicitly specify a mathematical form for the production function; (ii) it is capable of handling multiple inputs and outputs; (iii) it is capable of being used with any input-output measurement, although ordinal variables remain tricky; (iv) the sources of inefficiency can be analyzed and quantified for every evaluated unit; and (v) it can identify which DMUs are evaluating themselves against which other DMUs using the dual optimization problem [11]. Furthermore, many studies have discussed DEA applications in education [12]–[15]. These studies have used a Likert scale to estimate
the judgments of participants. More recently, many studies have used fuzzy numbers instead of Likert scales to answer questions related to valuations/opinions/ratings that involve subjectiveness [1], [2]. A relevant advantage of fuzzy numbers is that the suggested format may capture better accuracy, subjectiveness and variability of answers. Consequently, the statistical analysis becomes more interesting [16].

A. LITERATURE REVIEW FOR FUZZY DEA
DEA models with fuzzy numbers (i.e., fuzzy DEA model) can more realistically represent real-world problems than conventional DEA models. Fuzzy numbers allow linguistic data to be used directly within the DEA models [17]. Fuzzy DEA has been used to address the notion of fuzziness in some variables, such as the socioeconomic status of students or test scores. The results have indicated that the estimated measures of performance obtained with the fuzzy DEA approach are highly correlated with those calculated with traditional DEA models [18]. A three-stage fuzzy DEA approach has been proposed based on service quality to evaluate the learning performance evaluation of eight higher education institutes in Iran. The proposed approach increased the accuracy of the performance of educational units based on service quality [19].

B. THE LIMITATIONS OF THE FUZZY DEA APPROACH
However, one of the disadvantages of DEA is the limitation of orthogonal attributes. The problem of dependent variables has been considered in many pieces of literature [20], [21]. In particular, traditional DEA and fuzzy DEA are difficult to use in learning with non-orthogonal attributes. In contrast, the multiple attributes utility theory, which focuses on the comparison of DEA, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), the Simple Multi-Attribute Rating Technique (SMART), and others, has been discussed [22]. One of the significant limitations is the independent characteristics of the attributes. In recent research, some papers have discussed the attribute dependency of decision-making problems using the Mahalanobis distance instead of the Euclidean distance. A TOPSIS-Mahalanobis approach has been proposed to incorporate the correlations among the attributes. Meanwhile, the Manhattan distance, Euclidean distance, and the Tchebycheff distance in TOPSIS have been compared and discussed [23]. The TOPSIS-Mahalanobis approach, TOPSIS, and simple additive weight methods have been compared for prioritizing the districts of the Golestan Province with respect to all three susceptibility maps; in addition, the TOPSIS-Mahalanobis approach has been suggested as the better performing ranking method for further environmental managerial actions given its consideration of strong correlations among the criteria. The TOPSIS-Mahalanobis approach framework merits more studies and is applicable to any multicriteria decision-making issue in any branch of science [24]. In summary, these previous articles have shown that the Mahalanobis distance is suitable and useful in utility theory.

C. THE QUESTION OF ESTIMATING EFFICIENCY IN INTERDISCIPLINARY SUSTAINABILITY LEARNING
One of the recent educational questions asked in the field of civil engineering is how construction industry sectors may successfully operate to promote green energy, reduce carbon emissions and face sustainability challenges. Although the implementation of sustainability has proposed a new vision of the construction industry, it concurrently causes many new problems in regard to civil engineering education. The literature regarding interdisciplinarity and its application in education for sustainable development, including practices and barriers, was reviewed to enhance these problems. A case study illustrated the application of the six principles of responsible management education and explained how a sustainability and corporate social responsibility module may encourage students to combine knowledge from all disciplines to advance their understanding and action on sustainable development [25]. The perceptions, status and possible barriers were analyzed for the incorporation of social sciences and humanities in the studies of civil engineering. Their analysis showed differences between individual perceptions, collective reality and legislative frameworks. Even though the survey responses showed a common agreement concerning the inclusion of social sciences and humanities, only a minority of civil engineering departments have introduced social sciences and humanities in their curricula. In addition, accrediting bodies have not yet introduced this practice as a requirement in their criteria. The barriers detected in the incorporation of social sciences and humanities in civil engineering curricula were (i) resistance to change, (ii) external influences on the curricula, (iii) lack of guidelines, and (iv) misconceptions on what social sciences and humanities in relation to civil engineering involve [26]. In summary, courses for sustainability are more important in interdisciplinary education than in civil engineering. In recent literature, interdisciplinary education is shown to be focused on the different fields of higher education. Further, the Interdisciplinary Education Perception Scale (IEPS) has been studied and proposed in several pieces of literature [27]–[29].

The time-variant change in students’ perceptions is one of the important topics in interdisciplinary learning. A cohort of dental students at the University of Manitoba was followed throughout their entire dental education program to explore changes in their perceptions of the learning environment over time. The results indicated that there is a minor positive recalibration of students perceptions in the areas of course relevance and opportunities for outside interests during the first months of year one [30]. Some studies have proposed the education efficiency between input and output based on data envelopment analysis [31] and fuzzy DEA methods [32], [33]. However, only a few studies have discussed interdisciplinary learning, efficiency, changes over time in students perceptions, and feedback on this trend.

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D. THE PURPOSES
This study proposes a fuzzy-based hybrid approach for estimating interdisciplinary learning efficiency in civil engineering students sustainability training. Particularly, three research questions are posed:

i. How can three-dimensional (3D) fuzzy numbers be built to capture time-variant changes in students’ perceptions?

ii. How well does the proposed DEA-Mahalanobis distance approach estimate the efficiency of inputs and outputs with fuzzy numbers in the interdisciplinary learning system?

iii. What is the role of feedback in the students in sustainability courses?

To answer these questions, the methods, results, and discussions are described as follows. In the methods section, the research design, sample questionnaire, data collection and the proposed approach are presented. The data analyses are shown in results section. The comparisons of traditional methods and the proposed approach are shown in the discussion section. The limitations of the proposed approach are also discussed. The conclusion and future work are presented in the conclusion section.

II. METHODS
A. RESEARCH DESIGN
Here, the advantages of fuzzy numbers, DEA, and Mahalanobis distance are introduced. In summary, fuzzy numbers have higher internal consistency in general cases. DEA is a useful and common method for estimating the relative efficiency of DMUs. The Mahalanobis distance can transfer the data dimension to erase the data dependency. However, few studies have integrated the three methods and studied the interdisciplinary learning efficiency problem. To extend the application of the fuzzy DEA method and the efficiency estimation question of sustainability education in civil engineering, a fuzzy-based hybrid approach based on three-dimensional fuzzy numbers, DEA, and the Mahalanobis distance is proposed.

B. SAMPLES
Based on 2020 course maps compiled by the Ministry of Education in Taiwan R.O.C., only 6 departments (civil or construction engineering departments) were shown to offer sustainability courses, including green energy, sustainable development, or sustainable material. Students enrolled in these schools or those who graduated within 3 years from these 6 departments were thus selected.

C. QUESTIONNAIRE AND DATA COLLECTION
Data were collected from February 2021 to May 2021. The questionnaire was modified from the measurement of interdisciplinary competence for engineers [34], namely, the National Survey of Student Engagement [35], and IEPS [28]. All 23 questions were classified into input and output parts. The 10 items for inputs used fuzzy numbers, and the other 13 items for outputs used a traditional Likert scale (crisp numbers).

D. ETHICAL CONSIDERATIONS
All information analyzed was data obtained from the open survey website. Ethical approval for this study was obtained from the Human Research Ethics Council (HREC code: 110-331).

E. THE PROPOSED APPROACH
A flowchart of the proposed approach is illustrated in Figure 1.

Definition 1. Following [36], [37], the definition of real fuzzy number $\tilde{A}$ as any fuzzy subset of the real line $\mathbb{R}$ with membership function $f_\tilde{A}$ possesses the following properties:

i. $\tilde{A}$ is a continuous mapping from $\mathbb{R}$ to the closed interval $[0, 1]$;

ii. $A(x, t) = 0$, for all $x \in (-\infty, a]$ at different $t$;

iii. $A$ is strictly increasing on $[a, b]$;

iv. $A(x, t) = 1$, for all $x \in [b, c]$ at different $t$;

v. $A$ is strictly decreasing on $[c, d]$;

vi. $A(x, t) = 0$, for all $x \in [d, \infty)$ at different $t$; and

vii. $A$ is linear on $[p, q]$,

where $a, b, c, d, p$ and $q$ are real (crisp) numbers.

The membership function $f_\tilde{A}$ of trapezoidal fuzzy numbers is defined as Equation 1:

$$f_\tilde{A}(x, t) = \begin{cases} \frac{c-x}{b-a}, & \text{if } a \leq x \leq b \\ 1, & \text{if } b \leq x \leq c \\ \frac{d-x}{d-c}, & \text{if } c \leq x \leq d \\ 0, & \text{otherwise} \end{cases}$$

(1)

An example of 3D trapezoidal fuzzy numbers is shown in Figure 2. The perception, time, and membership degree are shown in the diagram.

A survey was carried out to represent students perceptions, as shown in Table 1. The fuzzy numbers of the questionnaires were surveyed based on suggestions from the literature [1], [9]. The graphic explanation is shown as Figure 3. For example, Question 1 is I am not late and do not leave early in the course.

If the participant believes that the membership function is as seen in Figure 3, then the participant replies to numbers (40,50,70,80).

After an explanation of the formalization and meaning of fuzzy sets in the questionnaire on the website, the participants were requested to reply by using fuzzy numbers on a $[0,100]$-scale. In stage 1 and stage 2, the participants finished the middle and final tests of the interdisciplinary course. The learning effect continued between stage 1 and stage 2. Thus, the data from stage 1 and 2 are dependent. The feedback from most participants in this learning period is positive. This is the reason for the increased participant perception during the three months. For example, Figure 2 shows that a participants perceptions of a question were (40,50,70,80) at stage 1 and (50,60,70,80) in state 2.

Definition 2. The $\alpha$-cut of fuzzy number $\tilde{A}$ is defined as:

$$\tilde{A}^{\alpha} = \{ x | f_\tilde{A}(x, t) \geq \alpha \} ,$$

(2)
The arithmetic of the defined fuzzy number can then be expressed as:

\[ \tilde{A} \oplus \tilde{B} = (a_1 + a_2, b_1 + b_2, c_1 + c_2, d_1 + d_2), \]  

\[ (\tilde{A} \times \tilde{B}) = (a[L_1, L_2], b, c, d[R_1, R_2]), \]  

where \( a = a_1 \cdot a_2, b = b_1 \cdot b_2, c = c_1 \cdot c_2, d = d_1 \cdot d_2, L_1 = (b_1 - a_1) \cdot (b_2 - a_2), L_2 = a_2 \cdot (b_1 - a_1) + a_1 \cdot (b_2 - a_2), R_1 = (d_1 - c_1) \cdot (d_2 - c_2),\) and \( L_2 = -(d_2 \cdot (d_1 - c_1) + d_1 \cdot (d_2 - c_2)).\)

The centroid of the trapezoidal fuzzy number \( \tilde{A} = (a, b, c, d) \) is:

\[ CT_{\tilde{A}} = \frac{c^2 + d^2 + cd - a^2 - b^2 - ab}{3(c + d - a - b)}. \]  

Based on the defuzzification procedure of \( CT \), the 3D trapezoidal fuzzy numbers were transferred to crisp numbers.

The correlation coefficients for the 5 parameters are shown in Table 2. The results showed that the correlations in SE and CE, SE and IS, and SE and IO were significant. Based on Table 2, some variables were correlated, and the axes were not orthogonal. This result means that efficiency measurements are difficult to use in traditional DEA.

To solve the attribute dependency problem, the Mahalanobis distance was used to rebuild the datasets following [23] and [24]. Furthermore, the application of the Mahalanobis distance was explained, discussed, and compared with the Euclidean distance [38]. The Mahalanobis distance between two series is defined as:

\[ d = ((x_A - x_B)^T \times C^{-1} \times (x_A - x_B))^{0.5}, \]  

where \( x_A \) and \( x_B \) are a pair of series, and \( C \) is the sample covariance matrix. The covariance matrix \( C \) is a measure of how much \( x_A \) and \( x_B \) variables move together in the same direction.

To select the suitable model in the education case, the Banker Charnes Cooper (BCC) model [39] was used to distinguish between technical and scale inefficiencies by (i) estimating pure technical efficiency at the given scale of operation and (ii) identifying whether the possibilities of increasing, decreasing or constant returns to scale are present for further exploitation. In the study case, the DMUs are students. The resources of the DMUs are different. Using the BCC model, the scale efficiency is far from 1. Thus, the author believes that using the BCC model is suitable for the CCR model. The steps for using the BCC model are as follows: assume that there are \( n \) DMUs (DMU\( j; j = 1, 2, \ldots, n \)), which consume \( m \) inputs \( (x_i; i = 1, 2, \ldots, m) \) to produce \( s \) outputs \( (y_r; r = 1, 2, \ldots, s) \). The BCC input-oriented model evaluates the efficiency of DMUs, under consideration, by
solving the following linear program:

\[
\begin{align*}
\text{Max} & \quad \sum_{s}^{r=1} u_r y_{rj} - u_0 \\
\text{s.t.} & \quad \sum_{m}^{i=1} w_i x_{io} = 1 \\
& \quad \sum_{s}^{r=1} u_r y_{rj} - u_0 - \\
& \quad \sum_{m}^{i=1} w_i x_{ij} \leq 0, \quad j = 1,2,\ldots,n \\
& \quad u_0, \quad \text{free} \\
& \quad w_i \geq \varepsilon, \quad i = 1,2,\ldots,m \\
& \quad u_r \geq \varepsilon, \quad r = 1,2,\ldots,s,
\end{align*}
\]  

where \( x_{ij} \) and \( y_{rj} \) are the inputs and outputs of the \( j \)th DMU, and \( w_i \) and \( u_r \) are the input and output weights (also referred to as multipliers). \( x_{io} \) and \( y_{ro} \) are the inputs and outputs of DMUs.

III. RESULTS
The 173 surveyed records were analyzed using the proposed model. For the internal consistency reliability, the total Cronbach's alpha value was 0.872. The value of that first eigenvalue of the survey data was 8.8. The suggestion threshold in more than 30 datasets for the Cronbach's alpha value was 6.0 [40]. The Cronbach’s alpha values of the input (fuzzy numbers) and output (crisp numbers) items were 0.91 and 0.76, respectively. The difference in the Cronbach’s alpha values in the two parts also showed the advantages of using fuzzy rating scales for reliability. The details of the alpha if items deleted values are shown in Table 1.

The questionnaire was modified from [28], [34], [35] and certified by 3 associate professors. These three associate professors work in the civil engineering field, and they have majored and teach in the fields of engineering management and remote sensing, which are also interdisciplinary research topics in civil engineering. The experts used a 4-1 scale for the content validity index, and the averages of 23 questions were over 3. The interdisciplinary learning questionnaire were modified from references and estimated based on expert validity. The validity was found to be sufficient to establish the reliability. The questionnaire can be checked on GitHub (https://github.com/ziping-chiang/questionnaire). The output factors (student engagement and college engagement) and input factors (interdisciplinary skills, reflective behavior, and incentive outcomes) of the DMUs were analyzed based on the BCC model, output-oriented, and variable return to scale (VRS) approaches. The results are shown in Table 3.

Based on the Mahalanobis distance, the matrix of the original 5 factors can be transferred to a new matrix. The results of the DEA-Mahalanobis analysis are shown in Table 4. The values and standard deviation of the mean for technical efficiency from constant returns to scale are 0.432 and 0.262, respectively. According to the BCC model, technical efficiency was classified as technical efficiency from variable return to scale and scale efficiency. The values of the mean for the two parts are 0.668 and 0.626. These results showed that the efficiencies of DMUs have a greater possibility of improvement.

By accumulating the outputs (IS, RB, and IO) and inputs (SE and CE) of DMUs, a scatter diagram of efficiency, output, and input was created, as shown in Figure 4.

IV. DISCUSSION
The descriptive analysis of the surveyed data, calculated results, and diagram are shown. The discussions of the three study purposes are as follows.

A. THE SITUATION OF INTERDISCIPLINARY EDUCATION FOR SUSTAINABILITY AND CIVIL ENGINEERING FIELDS
By comparison with [41], the students were less accustomed to having discussions with the faculty. The problem of using mobile phones in the course affects the students engagement, which has also reported previously [42]. Notably, “effective teaching practices (SE8=46.79)” and learning from other open courses or YouTube (SE6=46.71) may be the key items. In interdisciplinary courses on sustainability and civil engineering, case studies help students understand the kernel concept of sustainable development for industry and social requirements. Active self-learning based on case studies also allows students to achieve a positive cycle of learning. Self-discipline and adherence to classroom norms, such as arriving in class on time and not using mobile phones, can improve learning efficiency as well. However, based on the
analysis of the questionnaire content, the effect of self-disciplined learning is good among peers and other personnel. Furthermore, students can learn and improve greatly by studying with a professional. It is important and necessary for students to understand other fields of knowledge and technology to solve civil engineering problems. It is also valuable to ask students about their understanding of different fields or approaches to solve civil engineering problems and explore different solutions. Moreover, students are willing to apply cross-field learning and practical applications, as they think both are helpful.
B. THE COMPARISON OF THE PROPOSED APPROACH AND THE DEA WITH PCA METHOD

Principal component analysis (PCA) is a common statistical tool used to compute the principal components and perform a change of basis on data. PCA is used to reduce dimensionality by projecting each data point only on the first few principal components to obtain lower-dimensional data while preserving as much of the data's variation as possible. Several pieces of literature have discussed the combination or integration of DEA and PCA. The usage of PCA as a means of weighing inputs and outputs parsimoniously has been discussed. The basic model and its modifications have been proposed [43]. Furthermore, the hybrid approaches of DEA and PCA have been used in supplier selection, performance estimation, and score ranking problems [44]–[49].

The theory and applications of the Mahalanobis distance have been discussed in many works in the literature [23], [24], [38]. However, only a few articles have discussed the hybrid approaches of the DEA and Mahalanobis distance. Therefore, the proposed approach focused on this problem. The comparison of the DEA with nonorthogonal variables, DEA with PCA, and the proposed approach is described as follows. For example, an original dataset for inputs and output has three nonorthogonal variables $X_1$, $X_2$, and $Y_1$. The problem is hard to solve by traditional DEA. Based on the DEA with PCA, the original coordinate axes $X_1$ and $X_2$ are transferred to $P_1$ and $P_2$. However, the meanings of variables ($P_1$ and $P_2$) are different from $X_1$ and $X_2$. According to the proposed approach, the nonorthogonal coordinate axis is transferred to orthogonal $X_1$ and $X_2$. In explaining the variables, the proposed approach is clearer than DEA with the PCA method.

C. EFFICIENCY ANALYSIS FEEDBACK TO THE STUDENTS

The primary aim of the efficiency and performance analysis of education was student feedback. The grade group number was set as 3 for subjective judgment. These three groups indicate high, normal, and low output grades. By the k-means clustering method, the two thresholds can be calculated as 1.32 and 0.78. The sizes of three groups are 66, 42, and 65. The results showed that the differences in the input mean and efficiency among groups 1 to 3 were significant ($p$ value=2.02e-4 and 0.0055). This result may show that the interest and desire of active learning are important for interdisciplinary learning in sustainability courses. Figure 5 shows the diagram of the inputs and VRS efficiency among different groups. The DMUs can be divided into strong efficiency ($efficiency \geq 0.78$), middle efficiency ($0.78 > efficiency \geq 0.45$), and low efficiency ($efficiency < 0.45$). The grade group number was set as 3 for subjective judgment. These three groups indicated high, normal, and low output grades. By the k-means clustering method, the two thresholds could be calculated as 0.78 and 0.45. The sizes of three
groups were 39, 67, and 67. A slack variable is a variable added to an inequality constraint to transform it into an equality constraint. The introduction of a slack variable replaces an inequality constraint with an equality constraint and a non-negativity constraint on the slack variable. Slack variable analysis can help DMUs increase their student efficiency. Based on slack variable analysis, student engagement is the key factor. The suggestions are as follows:

i. Conducting effective teaching practices by participating in sustainable activities;
ii. Learning from other open courses or YouTube;
iii. Discussing with faculty frequently; and
iv. Trying to learn with peers.

D. THE LIMITATIONS OF THE PROPOSED APPROACH

Based on the discussion of methodology and the data analysis of the case study, the limitations of the proposed approach can be shown as follows:

i. If the correlation coefficients of inputs and outputs in DEA are not significant, the usage of the Mahalanobis distance approach is not necessary;
ii. As seen by comparing with the DEA-Mahalanobis and DEA-PCA approaches, the results are similar. However, the meanings of the variables in the two approaches are different;
iii. Although the Cronbach’s alpha coefficient in the case study is suitable in 173 data sets, more survey data sets mean clearer information; and
iv. The 3D trapezoidal fuzzy numbers were built in two stages. However, it is difficult to introduce more stages.

V. CONCLUSIONS AND FUTURE WORK

Interdisciplinary learning in sustainability for civil engineering is important for human development and industry requirements. The students input and output factors were defined by modifying the useful and common scales in STEM education. Then, 173 data points from 6 departments were found to issue interdisciplinary courses were surveyed. Descriptive analysis was used to explain the current status. The 3D trapezoidal fuzzy numbers were used in the 10-item questionnaire for the engagements of students and schools. The difference in the Cronbach’s alpha values of the two parts also showed the advantages of using fuzzy rating scales for reliability. Many studies have estimated students efficiency based on fuzzy DEA or DEA with the PCA method. However, the variables may be changed by the procedures of the axis transformation in PCA. Hence, a new fuzzy DEA-Mahalanobis distance approach was proposed to solve this problem. The limitations of the proposed approach in methodology and case study data have been described. Moreover, the advantages of the method have been discussed, and an improved learning strategy in interdisciplinary learning has been suggested to increase students efficiency. In the future, it will be interesting to estimate the efficiency for different research fields in the time dimension. Also in future work, the extension and applications of the proposed approach can be developed continually.

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