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A Neutrosophic Perspective on Enhancing Quality Virtual Simulation Experimental Education of Integrated Circuits: A New Approach

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Abstract: With rapid advancements in technology-related industries, integrated circuits come to be the core of modern electronics (IC). This in turn highlights the indispensable need to figure out advanced techniques for delivering high-quality experimental education in integrated circuits (IC). To that end, this work presents a neutrosophic framework to enhance the quality of education based on the selection of simulation-based tools that best improve the experimental skills of students. Given the inherent challenges of uncertainty, ambiguity, and subjectivity of virtual simulation, we propose to incorporate Interval-Valued Neutrosophic Sets (IVNS) to model uncertainty inherent to virtual simulation scenarios and adapt to encode linguistic variables that can be applied to decision-making in the experimental education of ICs. In our framework, A customized CRITIC (Criteria Importance Through Intercriteria Correlation) method is introduced to give weights for the IVNS representation of each criterion of IC simulation tools. Then, an IVNS-adapted ELECTRE-I (Elimination and Choice Expressing Reality) is presented to make a multi-criteria decision based on weighted representations of the IVNS-represented alternative. A public case study is introduced to experiment with the validity of different simulation tools for improving the experimental education of IC. Both quantitative and qualitative results demonstrate that the proposed methodology can offer a new solution to improve the student experience and optimize resource allocation in IC design courses. The implication of these results lies in enabling educators, researchers, and policymakers to easily elevate the quality of experimental education in integrated circuits.

Keywords: Neutrosophic theory, Integrated circuits, Teaching Quality, Decision making

1. Introduction

The study of Integrated circuits (ICs) has been gaining increased interest because of their important role in most modern electronics, which act as a foundational element in the development of technological solutions across different industries [1]. For years and decades, the process of teaching and training students in the field of ICs has conventionally depended on physical laboratories to offer hands-on experience [2]. Nevertheless, these educational mechanisms encounter many limitations including but not limited to constrained access to lab resources, high costs, and difficulty to cope with rapid technological development [3].

As a remedy, virtual simulations emerged as a transformative educational solution that can provide learners with realistic, collaborative environments to experiment with integrated circuits, enabling flexible, cost-effective, and scalable education [4]. This allows students to simulate the design of circuits, test their functionalities, and investigate performance indicators without performing any physical interactions. Despite these advantages, assessing the quality of experimental education delivered through virtual simulations remains a complex challenge due to the multifaceted nature of educational outcomes and the subjectivity involved in evaluating such methods [5].

As an extension to fuzzy logic, Smarandache [6] proposed neutrosophic sets (NSs) as a theoretical framework for modeling uncertainty in quantitative data with three-folded components: truth ($\mathbb{T}$), falsity ($\mathbb{F}$), and indeterminacy ($\mathbb{I}$). This representation leads to informative characterization by concurrently encoding the uncertainty, inarticulacy, and inconsistencies. With application of neutrosophic theory, we can to develop a robust approach to objectively mediate the quality of experimental education in virtual simulation environments. Later, the interval valued neutrosophic sets (IVNS) [7] were developed to extend the concept of traditional NSs to better address practical scenarios (such as virtual simulations) in which, it is hard to determine the exact value of truth, indeterminacy, and falsity. Instead, IVNS allows representing each of these components in the form of an interval within [0,1] which allows a more flexible way to model uncertainty and imprecision. This allows fulfilling the gap between theoretical adaptability and real-world applicability. Inspired by this, IVNS can help IC educators to better comprehend the points of strengths and weaknesses of virtual educational simulations and recognize areas that can be improved [8], [9].

To handle the gaps in the existing literature, this paper proposed a neutrosophic approach to evaluate teaching quality in university chemistry. The contributions of the proposed approaches can be summarized as follows:

- Our framework gets an insightful weighting of each criterion of simulation tools using the CRITIC (Criteria Importance Through Intercriteria Correlation) method.
- Then, we introduced the IVNS-adapted Elimination and Choice Expressing Reality (IVNS-ELECTRE-I) approach to making a correct decision about the best tools that can result in optimal IC education.

- A quantitative case study is presented, on which proof-of-concept analysis is performed to assess and evaluate the results of the proposed approach, comparing its performance against previous approaches.

The remainder of this paper is formulated as follows. First, we provide a detailed discussion of primary concepts and definitions. Section 3 explains the proposed neutrosophic decision-making approach to the best virtual simulation for improving the experimental education of ICs. Section 4 introduces the results of our approach and discusses them. Section 5 concludes the main findings.

2. Fundamentals & Definitions

Definition 1. Given a universal discourse X, the IVNS is configured with three ranged elements: truth ($\mathbb{T}$), falsity ($\mathbb{F}$), and indeterminacy ($\mathbb{I}$) [7]. Each of them has an interval range. $T_N = \left[\mathbb{T}^{L}_{N(x)}, \mathbb{T}^{U}_{N(x)} \subseteq [0,1]\right], I_N(x) = \left[\mathbb{I}^{L}_{N(x)}, \mathbb{I}^{U}_{N(x)} \subseteq [0,1]\right]$, and $F_N(x) = \left[\mathbb{F}^{L}_{N(x)}, \mathbb{F}^{U}_{N(x)} \subseteq [0,1]\right]$. With these ranged components, IVNS can be defined as:

$$N = \left\{\langle x, \left[\mathbb{T}^{L}_{N(x)}, \mathbb{T}^{U}_{N(x)}\right], \left[\mathbb{I}^{L}_{N(x)}, \mathbb{I}^{U}_{N(x)}\right], \left[\mathbb{F}^{L}_{N(x)}, \mathbb{F}^{U}_{N(x)}\right]\rangle \mid x \in X\right\} \tag{1}$$

where

$$0 \leq \mathbb{T}^{L}_{N(x)} + \mathbb{I}^{L}_{N(X)} + \mathbb{F}^{L}_{N(x)} \leq 3.$$

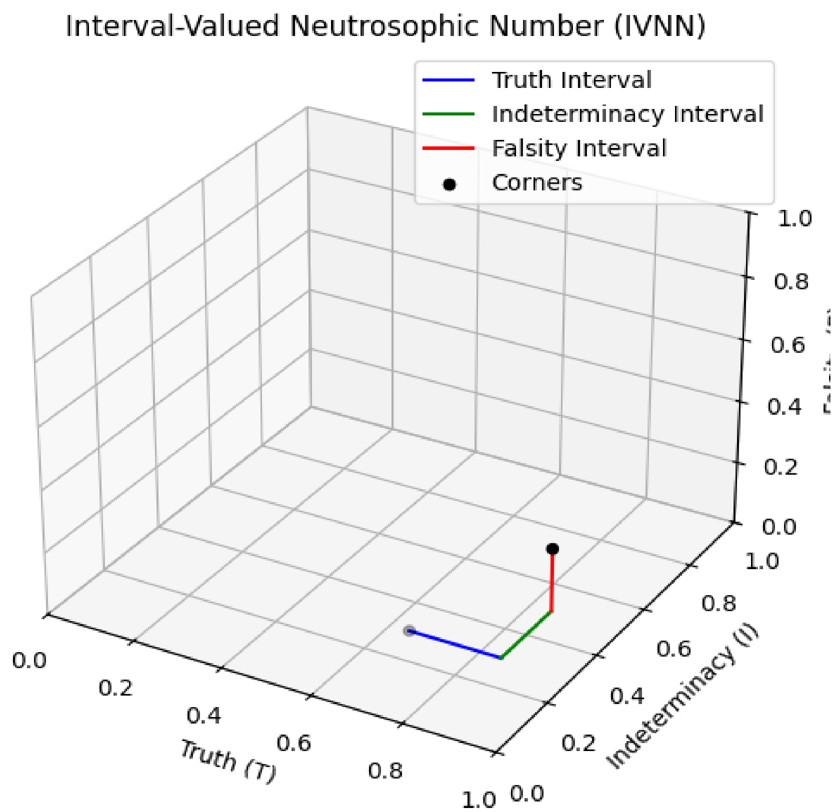


Figure 1. visual representation of IVNS in 3D coordinate system.

Definition 2. Given two IVNs $A = [\mathbb{T}_A^L, \mathbb{T}_A^U], [\mathbb{I}_A^L, \mathbb{I}_A^U], [\mathbb{F}_A^L, \mathbb{F}_A^U]$, and $B = [\mathbb{T}_B^L, \mathbb{T}_B^U], [\mathbb{I}_B^L, \mathbb{I}_B^U], [\mathbb{F}_B^L, \mathbb{F}_B^U]$, there are many mathematical operations that can be applied to them:

- Complement

$$A^c = \langle [\mathbb{T}_A^L, \mathbb{T}_A^U], [1 - \mathbb{I}_A^L, 1 - \mathbb{I}_A^U], [\mathbb{F}_A^L, \mathbb{F}_A^U] \rangle \tag{2}$$

- Addition

$$A \oplus B = \langle [\mathbb{T}_A^L + \mathbb{T}_B^L - \mathbb{T}_A^L \mathbb{T}_B^L, \mathbb{T}_A^U + \mathbb{T}_B^U - \mathbb{T}_A^U \mathbb{T}_B^U], [\mathbb{I}_A^L \mathbb{I}_B^L, \mathbb{I}_A^U \mathbb{I}_B^U], [\mathbb{F}_A^L \mathbb{F}_B^L, \mathbb{F}_A^U \mathbb{F}_B^U] \rangle \tag{3}$$

- Multiplication

$$A \otimes B = \langle [\mathbb{T}_A^L \mathbb{T}_B^L, \mathbb{T}_A^U \mathbb{T}_B^U], [\mathbb{I}_A^L + \mathbb{I}_B^L - \mathbb{I}_A^L \mathbb{I}_B^L, \mathbb{I}_A^U + \mathbb{I}_B^U - \mathbb{I}_A^U \mathbb{I}_B^U], [\mathbb{F}_A^L + \mathbb{F}_B^L - \mathbb{F}_A^L \mathbb{F}_B^L, \mathbb{F}_A^U + \mathbb{F}_B^U - \mathbb{F}_A^U \mathbb{F}_B^U] \rangle \tag{4}$$

Definition 3. Given two IVNS $A = [\mathbb{T}_A^L, \mathbb{T}_A^U], [\mathbb{I}_A^L, \mathbb{I}_A^U], [\mathbb{F}_A^L, \mathbb{F}_A^U]$, and $b = [\mathbb{T}_B^L, \mathbb{T}_B^U], [\mathbb{I}_B^L, \mathbb{I}_B^U], [\mathbb{F}_B^L, \mathbb{F}_B^U]$, the following relations apply as follows:

$$a \subseteq b \text{ if and only if } \mathbb{T}_A^L \le \mathbb{T}_B^L, \mathbb{T}_A^U \le \mathbb{T}_B^U; \mathbb{I}_A^L \ge \mathbb{I}_B^L, \mathbb{I}_A^U \ge \mathbb{I}_B^U; \mathbb{F}_A^L \ge \mathbb{F}_B^L, \mathbb{F}_A^U \ge \mathbb{F}_B^U \tag{5}$$

$$A = b \text{ if and only if } A \subseteq b \text{ and } b \subseteq A. \tag{6}$$

Definition 4. The weighted averaging operator for IVNS is defined to aggregate a number of IVNS weighted by the weight vector $Y = (y_1, \dots, y_j, \dots, y_n))$ and $\sum_{j=1}^n y_j = 1$.

$$WA_{IVNNs}(x_1, \dots, x_j, \dots, x_n) = \sum\nolimits_{j=1}^n y_j x_j = \left\langle \left[1 - \prod\nolimits_{j=1}^n \left(1 - \mathbb{T}_j^L\right)^{y_j}, 1 - \prod\nolimits_{j=1}^n \left(1 - \mathbb{T}_j^U\right)^{y_j}\right] \left[\prod\nolimits_{j=1}^n \left(\mathbb{I}_j^L\right)^{y_j}, \prod\nolimits_{j=1}^n \left(\mathbb{I}_j^U\right)^{y_j}\right], \left[\prod\nolimits_{j=1}^n \left(\mathbb{F}_j^L\right)^{y_j}, \prod\nolimits_{j=1}^n \left(\mathbb{F}_j^U\right)^{y_j}\right] \right\rangle \tag{7}$$

Definition 5. Given an IVNS $A = [\mathbb{T}_A^L, \mathbb{T}_A^U], [\mathbb{I}_A^L, \mathbb{I}_A^U], [\mathbb{F}_A^L, \mathbb{F}_A^U]$, the deneutrosophication can be computed as follows:

$$\mathfrak{D}(A) = \left(\frac{(\mathbb{T}_A^L + \mathbb{T}_A^U)}{2} + \left(1 - \frac{(\mathbb{I}_A^L + \mathbb{I}_A^U)}{2}\right)\left(\mathbb{I}_A^U\right) - \left(\frac{(\mathbb{F}_A^L + \mathbb{F}_A^U)}{2}\right)\left(1 - \mathbb{F}_A^U\right) \right) \tag{8}$$

3. Research Approach

In this section, we provide a detailed description of the IVNS-based decision-making framework that integrates a customized CRITIC method with the IVNS-ELECTRE-I approach. IVNS are intelligently used to model uncertainty, vagueness, and imprecision in IC features. This integration enables achieving robust and elastic decision-making that enables addressing complex, multi-criteria problems in uncertain environments.

3.1. Criteria Importance Through Intercriteria Correlation (CRITIC)

In this section, we start to objectively calculate the weight of each criterion criteria according to two key facets namely contrast intensity (which is estimated based on standard deviation) and the interaction among criteria [10]. By analyzing the versatility among criteria, the CRITIC was designed to allocate high weights for criteria that exhibit less correlation with others, which ensures that the weights represent the significance as well as the exclusivity of each criterion. We decide to apply this method to avoid subjectivity in the process of determination of weight and is predominantly valuable when the decision matrix encompasses various or contradictory information. This is achieved as follows:

First, we establish the initial decision matrix based on deneutrosophication of IVNS matrix, X.

$$X = \left(\mathfrak{D}_{ij}(\mathcal{M})\right)_{m\times n} \tag{9}$$

Second, a normalization matrix, NN, is computed as follows:

$$NN = \left(NN_{ij}\right)_{m\times n} \tag{10}$$

The building of NN_{ij} is conditioned based on the following expression:

$$NN_{ij} = \begin{cases} \dfrac{X_{ij} - minX_j}{maxX_j - minX_j} & j > 0 \\ \dfrac{maxX_j - X_{ij}}{maxX_j - minX_j} & j < 0 \end{cases} \tag{11}$$

Third, we calculate the standard deviation for each criterion, S_j. This can be expressed as follows:

$$S_j = \sqrt{\frac{\sum_{i=1}^{m}\left(NN_{ij} - \overline{NN}_j\right)^2}{n-1}} \tag{12}$$

Fourth, we drive the correlation coefficient between every possible pair of criteria. This can be expressed as follows:

$$r_{bj} = \frac{\sum_{b,j=1}^{n}(NN_{ib} - \overline{NN}_b)\left(NN_{ij} - \overline{NN}_j\right)}{\sqrt{\sum_{b=1}^{n}(NN_{ib} - \overline{NN}_b)^2 \sum_{j=1}^{n}\left(NN_{ij} - \overline{NN}_j\right)^2}} \tag{13}$$

Fifth, we compute the contradictory distinctive between every possible pair of criteria, A_j.

$$Q_j \leftarrow \sum_{b=1}^{n}\left(1 - r_{bj}\right) \tag{14}$$

Sixth, we compute the amount of information controlled in $j - th$ criterion, C_j.

$$C_j \leftarrow S_j\, Q_j \tag{15}$$

Finally, we compute the weight of the $j - th$ criterion, w_j.

$$w_j \leftarrow \frac{C_j}{\sum_{j=1}^{n} C_j} \tag{16}$$

3.2. IVNS-ELECTRE-I

Herein, we discuss the methodological steps for building IVNS-ELECTRE-I to select the best virtual simulation alternatives. Given a group of simulation alternatives $A = \{a_1, a_2, \dots, a_m\}$, and a group of the evaluation criteria, $A = \{a_1, a_2, \dots, a_n\}$, for academic stockholders. The implementation of IVNS-ELECTRE-I follow this sequence of steps:

Step 1, we take the IVNS values of the alternatives w.r.t different criteria as characterized by a weighted decision matrix, in which weights are obtained by the CRITIC method in Equations (16). The weighting procedure can be implemented in many ways.

$$Y = (z_{ij}) = (z_{ij}^1, z_{ij}^2, z_{ij}^3, \dots, z_{ij}^m), \quad (17)$$
$$z_{ij} = w_j \cdot x_{ij}.$$

In step 2, we calculate fuzzy concordance sets as follows:

$$\mathcal{F}_{pq} = \{1 \le j \le s: v_{pj} \ge v_{qj}, p \ne q; p, q \leftarrow 1,2,3 \cdots n\}$$
$$v_{ij} = z_{ij}^1 + z_{ij}^2 + z_{ij}^3 + \cdots + z_{ij}^m. \quad (18)$$

Step 3, we calculate concordance indices according to the following:

$$\mathscr{f}_{pq} = \sum\nolimits_{j \in F_{pq}} w_j \; for\ all\ p, and\ q \quad (19)$$

Step 4, we compute the concordance matrix, $\boldsymbol{\mathcal{F}}$, according to the following:

$$\mathcal{F} = \begin{pmatrix} - & \mathscr{f}_{12} & \mathscr{f}_{13} & \cdots & \mathscr{f}_{1n} \\ \mathscr{f}_{21} & - & f_{23} & \cdots & \mathscr{f}_{2n} \\ \mathscr{f}_{31} & \mathscr{f}_{32} & - & \cdots & \mathscr{f}_{3n} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ \mathscr{f}_{n1} & \mathscr{f}_{n2} & \mathscr{f}_{n3} & \cdots & - \end{pmatrix}. \quad (20)$$

Step 5, we calculate discordance indices, $\mathcal{G}_{pq}$, according to the following:

$$\mathscr{g}_{pq} = \frac{max_{j \in \mathcal{G}_{pq}} \sqrt{\frac{1}{m}[(z_{pj}^1 - z_{qj}^1)^2 + (z_{pj}^2 - z_{qj}^2)^2 + \cdots + (z_{pj}^m - z_{qj}^m)^2]}}{max_j \sqrt{\frac{1}{m}[(z_{pj}^1 - z_{qj}^1)^2 + (z_{pj}^2 - z_{qj}^2)^2 + \cdots + (z_{pj}^m - z_{qj}^m)^2]}} \quad (21)$$

Step 6, we calculate discordance matrix, $\boldsymbol{\mathcal{G}}$, according to the following:

$$\mathcal{G} = \begin{pmatrix} - & \mathscr{g}_{12} & \mathscr{g}_{13} & \cdots & \mathscr{g}_{1n} \\ \mathscr{g}_{21} & - & \mathscr{g}_{23} & \cdots & \mathscr{g}_{2n} \\ \mathscr{g}_{31} & \mathscr{g}_{32} & - & \cdots & \mathscr{g}_{3n} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ \mathscr{g}_{n1} & \mathscr{g}_{n2} & \mathscr{g}_{n3} & \cdots & - \end{pmatrix}. \quad (22)$$

Step 7, we calculate the levels of concordance and discordance according to the following:

$$\bar{f} = \frac{1}{n(n-1)} \sum_{\substack{p=1 \\ p \neq q}}^{n} \sum_{\substack{q=1 \\ q \neq p}}^{n} f_{pq}\,,$$
$$\bar{g} = \frac{1}{n(n-1)} \sum_{\substack{p=1 \\ p \neq q}}^{n} \sum_{\substack{q=1 \\ q \neq p}}^{n} g_{pq}\,. \tag{23}$$

Step 8, we build the dominance matrices based on concordance and discordance levels as formulated below:

$$H = \begin{pmatrix} - & h_{12} & h_{13} & \dots & h_{1n} \\ h_{21} & - & h_{23} & \dots & h_{2n} \\ h_{31} & h_{32} & - & \dots & h_{3n} \\ \vdots & \vdots & \vdots & \dots & \vdots \\ h_{n1} & h_{n2} & h_{n3} & \dots & - \end{pmatrix}, where\ h_{pq} = \begin{cases} 1, & f_{pq} \geq \bar{f}, \\ 0, & f_{pq} < \bar{f}. \end{cases} \tag{24}$$

$$L = \begin{pmatrix} - & l_{12} & l_{13} & \dots & l_{1n} \\ l_{21} & - & l_{23} & \dots & l_{2n} \\ l_{31} & l_{32} & - & \dots & l_{3n} \\ \vdots & \vdots & \vdots & \dots & \vdots \\ l_{n1} & l_{n2} & l_{n3} & \dots & - \end{pmatrix}, where\ l_{pq} = \begin{cases} 1, & g_{pq} < \bar{g}, \\ 0, & g_{pq} \geq \bar{g}. \end{cases} \tag{25}$$

Step 9, based on the multiplication of the above dominance matrices, we drive a new matrix, M, representing the aggregation of dominance.

$$M = \begin{pmatrix} - & m_{12} & m_{13} & \dots & m_{1n} \\ m_{21} & - & m_{23} & \dots & m_{2n} \\ m_{31} & m_{32} & - & \dots & m_{3n} \\ \vdots & \vdots & \vdots & \dots & \vdots \\ m_{n1} & m_{n2} & m_{n3} & \dots & - \end{pmatrix}. \tag{26}$$

Step 10, the alternatives are ranked according to outrank values of matrix M.

4. Results and Discussions

This section introduces a quantitative case study for our work based on a new university trying to implement virtual simulation to improve experimental teaching of IC design and testing. The decision maker reported that there are many qualitative and quantitative criteria to consider to be able to determine the effectiveness of this virtual education. For each criterion, fuzzy linguistic terms (such as "Very Low," "Low," "Moderate," "High," and "Very High”) are used to express and characterize subjective decisions for each assessment criterion. These terms can be later mapped into IVNS. In Table 1, we provide different criteria, related descriptions, and linguistic terms.

Table 1. Summary of criteria in terms of name, description, and linguistic terms.

Criterion	ID	Description	Linguistic terms	Type

Ease of Use	C1	Simplicity of user interface and learning curve.	Difficult, Somewhat Difficult, Moderate, Easy, Very Easy	Cost
Realism Simulations	C2	Degree to which the platform replicates real IC behavior.	Poor, Fair, Good, Very Good, Excellent.	Benefit
Educational features	C3	Degree to which the students can benefit from the platform.	Nonexistent, Limited, Moderate, Extensive, Highly Comprehensive.	Benefit
Cost-Efficiency	C4	The value for money.	Very Expensive, Expensive, Moderate, Affordable, Very Affordable.	Cost
Hardware integration support	C5	The ability to integrate with hardware circuits.	Not Supported, Partially Supported, Moderately Supported, Well Supported, Fully Supported.	Benefit

The decision-maker investigation for simulation tools leads to four distinct alternatives as shown in Table 2.

Table 2. Summary of main educational IC simulation platforms

Simulator	ID	Source
LTspice	Alt1	https://www.analog.com/en/resources/design-tools-and-calculators/ltspice-simulator.html
Proteus	Alt2	https://www.labcenter.com/
PSpice	Alt3	https://www.cadence.com/en_US/home/tools/pcb-design-and-analysis/analog-mixed-signal-simulation/pspice.html
Tina-TI	Alt4	https://www.cadence.com/en_US/home/tools/pcb-design-and-analysis/analog-mixed-signal-simulation/pspice.html
NI Multisim	Alt5	https://www.ni.com/en/support/downloads/software-products/download.multisim.html#452133
SPICE	Alt6	https://publichealth.buffalo.edu/cat/kt4tt/best-practices/need-to-knowledge-ntk-model/ntk-commercial-devices/master-list-of-tools/electrical-electronic-engineering/spice--simulation-program-with-integrated-circuit-emphasis--.html

Using the linguistic variables and criteria mentioned above, we build IVNS-based decision matrix as shown in Table 3.

Table

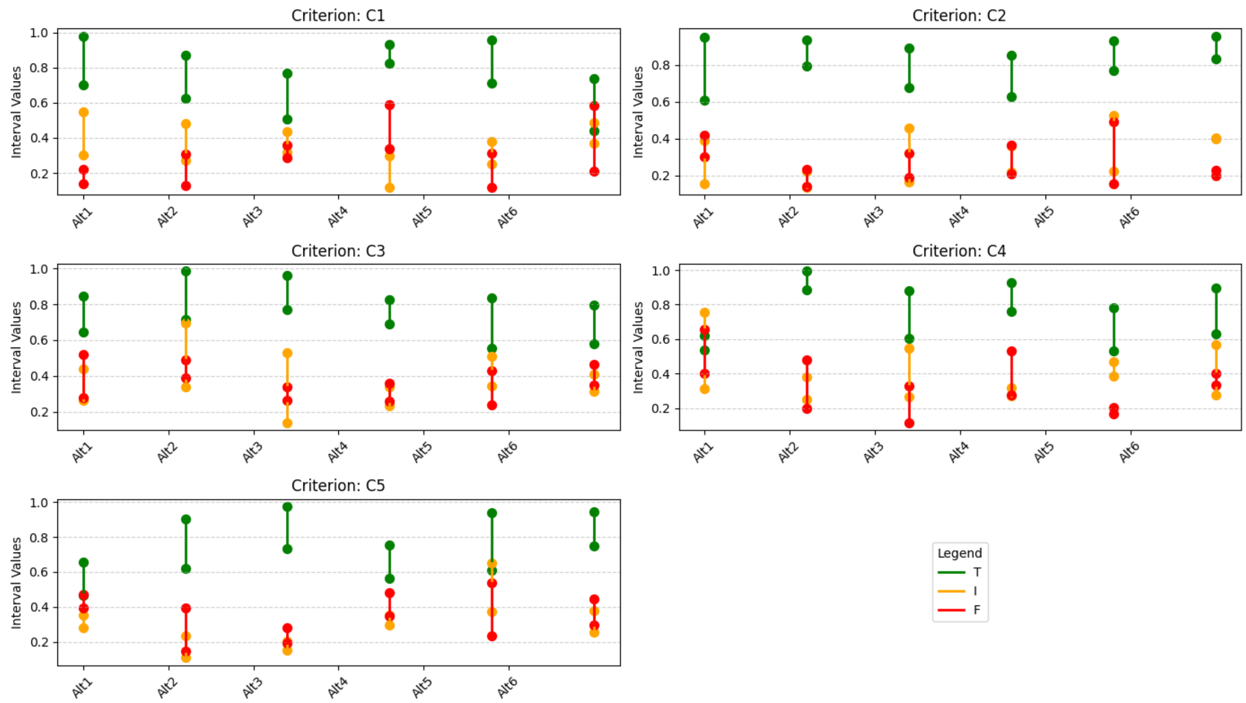


Figure 2. Visualization of IVN components for different alternatives with respect to each criterion.

3. IVNS-based decision matrix.

Criteria / Alternative	C1	C2	C3	C4	C5
Alt1	<[0.7005, 0.9799], [0.302, 0.5471], [0.1409, 0.2194]>	<[0.6068, 0.9488], [0.1558, 0.3894], [0.2996, 0.4197]>	<[0.6471, 0.8459], [0.2634, 0.4383], [0.2821, 0.5221]>	<[0.5396, 0.6196], [0.3112, 0.7575], [0.3997, 0.6581]>	<[0.4651, 0.6566], [0.2805, 0.3523], [0.3932, 0.4719]>
Alt2	<[0.6253, 0.8706], [0.2724, 0.4818], [0.1277, 0.3081]>	<[0.7909, 0.937], [0.1344, 0.2202], [0.1414, 0.2326]>	<[0.7141, 0.983], [0.3384, 0.6968], [0.3902, 0.488]>	<[0.8844, 0.9928], [0.2504, 0.3818], [0.1973, 0.4802]>	<[0.623, 0.9005], [0.1101, 0.2356], [0.1466, 0.3919]>
Alt3	<[0.5065, 0.7682], [0.3155, 0.4341], [0.2863, 0.3568]>	<[0.6761, 0.8892], [0.1656, 0.4542], [0.1896, 0.3209]>	<[0.7679, 0.9618], [0.1415, 0.5318], [0.2672, 0.3406]>	<[0.6061, 0.8784], [0.2668, 0.5466], [0.1172, 0.3312]>	<[0.7311, 0.9745], [0.1545, 0.2031], [0.1933, 0.2822]>
Alt4	<[0.8229, 0.9329], [0.1183, 0.2962], [0.3401, 0.59]>	<[0.6263, 0.8531], [0.2158, 0.3597], [0.2072, 0.3659]>	<[0.6898, 0.8269], [0.237, 0.3403], [0.2587, 0.3605]>	<[0.7617, 0.9264], [0.2722, 0.3198], [0.2791, 0.5303]>	<[0.5632, 0.7563], [0.2973, 0.3534], [0.3465, 0.4842]>
Alt5	<[0.7134, 0.9568], [0.2515, 0.3803], [0.1201, 0.3124]>	<[0.7701, 0.9311], [0.2234, 0.5247], [0.1563, 0.4903]>	<[0.5551, 0.8372], [0.3438, 0.5111], [0.239, 0.4281]>	<[0.5298, 0.7795], [0.3851, 0.4715], [0.1669, 0.2018]>	<[0.6119, 0.9377], [0.3722, 0.6511], [0.2354, 0.54]>
Alt6	<[0.4433, 0.7357], [0.3718, 0.4867], [0.2116, 0.5825]>	<[0.8307, 0.9555], [0.3994, 0.4052], [0.1981, 0.2251]>	<[0.5814, 0.7971], [0.3148, 0.4102], [0.3499, 0.4649]>	<[0.6292, 0.895], [0.2783, 0.5697], [0.3316, 0.4038]>	<[0.749, 0.9417], [0.2582, 0.381], [0.2961, 0.4443]>

Next, we perform deneutrosophication of the decision matrix and apply the CRITIC method to obtain the quantitative weights of each criterion as displayed in Table 4.

Table 4. CRITIC weights for different criteria based on deneutrosophication of IVNS-based decision matrix.

Criteria / Alternative	C1	C2	C3	C4	C5
Alt1	1.014404	0.852345	0.838859	0.751499	0.573253
Alt2	0.897298	0.901605	0.959867	1.023631	0.792896
Alt3	0.701928	0.922753	1.017228	0.916603	0.848929
Alt4	0.922042	0.814195	0.802433	0.879102	0.683934
Alt5	0.94657	1.01425	0.798023	0.777058	0.914423
Alt6	0.701516	0.971319	0.732753	0.871024	0.898862
CRITIC weights	0.1907	0.1443	0.2477	0.2608	0.1562

The concordance matrix, as displayed in Table 5, provides a hot summary of levels of agreement between the alternatives. Each of the tabulated values represents the degree to which one alternative is concordant with another according to the weighted standing of the criteria.

Table 5. Concordance Matrix

	Alt1	Alt2	Alt3	Alt4	Alt5	Alt6
Alt1	0.0000	0.7976	0.8080	0.3740	1.0000	0.9544
Alt2	0.3432	0.0000	0.1681	0.0725	0.3562	0.3106
Alt3	0.9159	0.5726	0.0000	0.6452	0.7171	0.1464
Alt4	0.2707	0.4615	0.6296	0.0000	0.6756	0.6300
Alt5	0.1988	0.7227	0.6425	0.2991	0.0000	0.2754
Alt6	0.9171	0.6657	0.8338	0.6464	0.7183	0.0000

In Table 6, we provide a discordance matrix, representing the degree of divergence between alternatives. This can be regarded as a complementary matrix for the concordance matrix, in which we can identify the areas in which noteworthy differences occur between alternatives.

Table 6. Discordance Matrix

	Alt1	Alt2	Alt3	Alt4	Alt5	Alt6
Alt1	0.0000	1.0000	0.6569	0.3431	1.0000	0.6569
Alt2	0.2941	0.0000	0.2941	0.5392	0.4902	0.4804

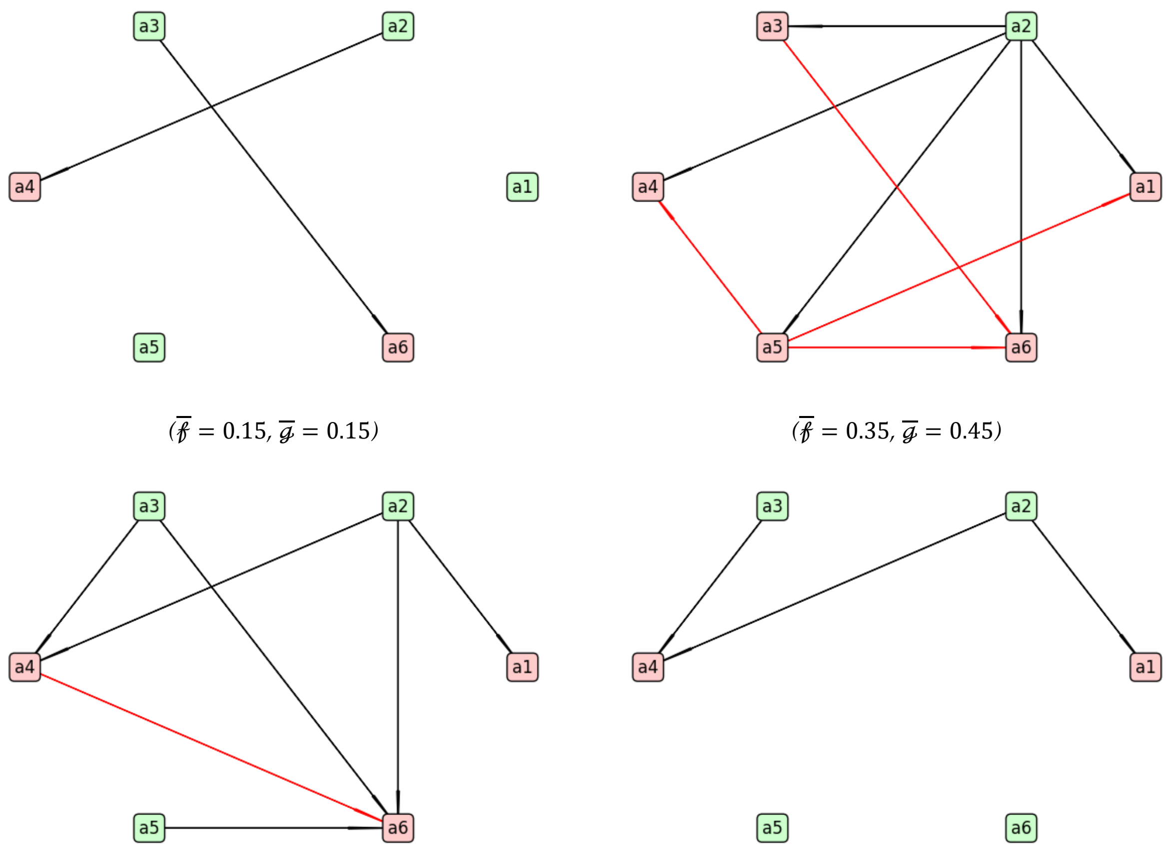
Alt3	0.4216	0.3431	0.0000	0.6667	0.6176	0.4706
Alt4	0.4902	0.8039	0.4902	0.0000	0.8039	0.6765
Alt5	0.4118	0.1275	0.0980	0.4118	0.0000	0.4608
Alt6	0.6176	0.4902	0.3922	0.9608	0.9118	0.0000

The dominance matrix, shown in Table 7, integrates the information from the concordance and discordance matrices to determine the dominance relationships among alternatives. Each entry reflects whether one alternative outranks another based on the combined evaluation of concordance and discordance thresholds.

Table 7. Dominance Matrix

	Alt1	Alt2	Alt3	Alt4	Alt5	Alt6
Alt1	0.0	0.0	0.0	0.0	0.0	0.0
Alt2	1.0	0.0	0.0	1.0	0.0	0.0
Alt3	0.0	0.0	0.0	1.0	0.0	0.0
Alt4	0.0	0.0	0.0	0.0	0.0	0.0
Alt5	0.0	0.0	0.0	0.0	0.0	0.0
Alt6	0.0	0.0	0.0	0.0	0.0	0.0

In Figure 3, we provide a graphical representation of the dominance interactions among the alternatives according to the results of the decision-making process. As shown, the comparative strengths of each alternative are represented by directed edges between nodes. Also, sensitivity analysis is performed to figure shows the effect of changing the thresholding parameters $(\overline{f}, \overline{g})$ on the total dominance. It could be noted that these parameters require careful choice to better determine the final dominance matrix. In Table 8, we provide a comparative analysis results, in which compare the ranking results obtained using the IVNS-ELECTRE-I method and Combinative Distance-Based Assessment(CODAS) reported in [11]. The tabulated results explain the differences in the ranking of different simulation tools for IC design education. When it comes to the IVNS-ELECTRE-I method, Alt2 is ranked the highest, followed by Alt3 and Alt5, while the rankings in CODAS place Alt3 first, followed by Alt5 and Alt6. Notably, the alternative Alt6 in the IVNS-ELECTRE-I method ranks higher than in CODAS, where it is positioned in the lower tiers. On the other hand, Alt1 appears lower in the IVNS-ELECTRE-I method compared to CODAS, reflecting the differing methodologies used to assess the alternatives. Alt4 consistently holds the last rank in both methods.



$(\overline{f} = 0.15, \overline{g} = 0.15)$ $(\overline{f} = 0.35, \overline{g} = 0.45)$

$(\overline{f} = 0.65, \overline{g} = 0.65)$ $(\overline{f} = 0.8, \overline{g} = 0.8)$

Figure 3. visualization of the dominance relationships between different alternatives

Table 8. Comparative analysis

Rank	IVNS-ELECTRE-I	[11]
1	Alt2	Alt3
2	Alt3	Alt5
3	Alt5	Alt6
4	Alt6	Alt1
5	Alt1	Alt2
6	Alt4	Alt4

5. Conclusions

In this paper, we presented a neutrosophic decision-making framework that integrates IVNS to model uncertainty in the virtual simulation of experimental education of ICs. Our framework integrates customized CRITIC weighting to get objective insights about the importance of each alternative. Then, we drive an IVNS-ELECTRE-I approach to make multi-criteria decisions about uncertain and imprecise settings of learning tools. Our framework exploited the flexibility of IVNS to model truth, indeterminacy, and falsity degrees, which reflect a richer representation of uncertainty compared to traditional techniques. The results of a numerical case study demonstrate the effectiveness of the framework through detailed computations of concordance, discordance, and dominance matrices.

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