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Abstract: The implementation of the conceive, design, implement and operate (CDIO) approach in higher education requires laboratories that effectively support hands-on, experiential learning. Although various laboratory configurations have been documented, a structured and comparative decision support framework remains limited for evaluating which designs best enhance student learning, performance, and satisfaction, particularly for evidence-informed curriculum and infrastructure planning. This study applies fuzzy technique for order preference by similarity to ideal solution (TOPSIS) with bootstrap resampling to systematically aggregate expert judgments in evaluating four laboratory designs using five decision criteria, with weights derived from the assessments of eight domain experts. Uncertainty associated with subjective evaluations is addressed through fuzzy modelling and resampling techniques, extending existing applications of fuzzy multi-criteria decision making in CDIO laboratory assessment. The analysis is bounded by expert-based inputs and the set of evaluated laboratory designs, yet it provides

practical guidance for academic administrators in selecting laboratory configurations that align with desired educational outcomes. Results indicate that virtual laboratories exhibit the highest overall impact.

Keywords: CDIO framework; fuzzy TOPSIS; state university; laboratory designs; virtual laboratory; Philippines.

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1 Introduction

The conceive, design, implement and operate (CDIO) framework is an innovative approach in engineering education aimed at producing graduates who are better prepared for professional practice. CDIO emphasises the mastery of engineering fundamentals within the context of product lifecycles, promoting active learning, problem-solving, and

hands-on experiences through project-based curricula (Lynch et al., 2007; Petrovskaya, 2013). Unlike traditional engineering programs, CDIO prioritises iterative design and implementation cycles, collaboration, and the integration of conceptual knowledge with practical skills. These characteristics require laboratory environments that facilitate experimentation and foster teamwork, communication, critical thinking, and iterative problem-solving (Ngoc Hoang and Anh Do, 2019; Hoffmann and Jorgense, 2011). By linking theory with practice, laboratories become essential for achieving CDIO learning outcomes, enabling students to manipulate materials, energy, and information effectively while developing technical and interpersonal competencies (Crawley 2007; Feisel and Rosa, 2005). Universities implementing CDIO have increasingly focused on integrating practice-oriented modules and design-implement experiences throughout their curricula. Such modules aim to enhance students' engineering competencies and prepare them for real-world problem solving (Petrovskaya, 2013). The development of personal and interpersonal skills, including teamwork and communication, is also emphasised, as these are critical to achieving CDIO learning outcomes (Ngoc Hoang and Anh Do, 2019). Laboratories serve as the primary venues for cultivating these skills, offering students direct engagement with equipment, systems, and experimental procedures. Effective laboratories provide technical training and the opportunity for collaborative learning, fostering communication, coordination, and problem-solving in authentic engineering contexts (Feisel and Rosa, 2005; Guo and Wan, 2022).

The influence of laboratory design on student learning has been well documented. Research indicates that well-designed laboratory spaces promote engagement, facilitate communication, and support experimentation that leads to deeper conceptual understanding (Hinton et al., 2014; Aufschnaiter and Aufschnaiter, 2007). Laboratories that focus on phenomenon-based learning rather than demonstrating theoretical models encourage students to discover and stabilise understanding through experimentation. Project- or discovery-based learning approaches contextualise activities in real-world scenarios, enhancing motivation and supporting the development of practical competencies, problem-solving abilities, and teamwork (Persano Adorno et al., 2023). Laboratory design also impacts student performance and attitudes. Features such as functional layouts, indoor and outdoor spatial organisation, and instructor visibility positively affect achievement. Factors such as time efficiency, excitement, and manageable difficulty influence student engagement and satisfaction (Ariani and Mirdad, 2015; Basey et al., 2008). Student satisfaction is closely linked to laboratory design and is a critical factor in engineering education. Studies show that assigning dedicated laboratory managers and conducting regular student surveys can improve satisfaction significantly (Nikolic et al., 2015). Other influential factors include the quality of laboratory notes, equipment functionality, and available troubleshooting resources, as well as environmental factors such as class size, scheduling, and student-to-instructor ratios (Funnell, 2020). In specialised contexts, such as maritime education, students report overall satisfaction with laboratory facilities but face challenges in equipment operation and time allocation (Caiga et al., 2015). Instruments such as the interactions in undergraduate laboratory classes (IULC) reveal a positive correlation between student-teacher interactions and satisfaction, highlighting the importance of supportive engagement in laboratory settings (Wei et al., 2021).

Advances in technology have enabled virtual and hybrid laboratories, offering alternatives to traditional on-site laboratories. The successful adoption of these digitally enabled learning environments depends not only on technical feasibility but also on user

acceptance, perceived usefulness, and institutional readiness to adopt new technologies in educational contexts (Casquejo et al., 2020). Additionally, digital learning environments, including interactive simulations and educational games, have been shown to improve students' engagement and strengthen foundational academic skills, demonstrating the potential of technology-enhanced learning tools in higher education (Go et al., 2022). Virtual laboratories provide interactive, media-rich simulations that allow flexible experimentation without constraints of physical space or schedule (Jaya, 2013; Li et al., 2011). Features such as pre-tests, tutorials, and simulations support both cognitive and psychomotor skill development (Zheng et al., 2017). Hybrid laboratories combine remote and hands-on components, maintaining some elements of physical experimentation while leveraging online platforms to expand accessibility and flexibility (Rodriguez et al., 2023; Enneking et al., 2019). Despite these benefits, these modalities face challenges such as technical issues, limited interaction, and persistent digital divides that affect learning outcomes, equity, and student motivation (Sitzmann et al., 2010; Mesuwini and Mokoena, 2024; Caparas and Yango, 2023). Addressing these challenges requires provision of hardware and software, technological literacy training, pre-learning motivation strategies, and ongoing instructor support (Wang et al., 2022). The diversity of laboratory formats in CDIO implementation, from traditional to virtual and hybrid, highlights the need for systematic evaluation. Although school administrators are interested in alternative designs due to their potential to enhance student learning, no analytical framework currently exists to objectively assess these alternatives. Laboratory design evaluation can be framed as a multi-criteria decision-making (MCDM) problem, where each design is assessed across multiple, often conflicting criteria to identify the optimal solution (Majumder and Saha, 2016). MCDM methods such as decision making trial and evaluation laboratory (DEMATEL), best-worst method (BWM), technique for order preference by similarity to ideal solution (TOPSIS), multiple-stakeholder target-oriented robust optimisation (MS-TORO) approach, interpretive structural modelling (ISM), and data envelopment analysis (DEA), among others, have been widely applied in consumer buying behaviour, air traffic management, warehouse location analysis, microbusiness success, performance efficiency evaluation, educational technology analysis contexts for ranking and selecting alternatives based on multiple criteria (Castro et al., 2025; Bongo and Sy, 2024; Bongo and Seva, 2023; Himang et al., 2023; Medalla et al., 2021; Bongo and Del Pilar, 2021; Del Pilar et al., 2019; Ocampo et al., 2020; Bongo and Ocampo, 2018, 2016; Abing et al., 2018; Bongo et al., 2018).

These methods allow decision-makers to integrate technical information, stakeholder values, and performance measures into a coherent evaluation process.

Fuzzy set theory enhances MCDM by handling vagueness and uncertainty inherent in expert judgments. Introduced by Zadeh (1965), fuzzy set theory allows partial membership, providing a mathematical framework to represent imprecise or linguistic concepts. It has been successfully applied in fields such as medicine and engineering to formalise uncertain information (Massad et al., 2008; Xu and Zhou, 2011). In laboratory design evaluation, linguistic assessments of criteria and alternatives, such as perceived complexity, engagement, or satisfaction, can be effectively modelled using fuzzy numbers. Fuzzy TOPSIS extends the traditional TOPSIS method to handle such fuzziness, normalising ratings and weights, aggregating expert judgments, and ranking alternatives quantitatively (Chu and Lin, 2009; Wang and Elhag, 2006). Compared to other MCDM approaches, fuzzy TOPSIS is particularly suitable for evaluating laboratory

designs because it accommodates multiple criteria, integrates group expert opinions, and produces a clear ranking under uncertain or subjective evaluations.

This study addresses the question of which laboratory designs most effectively support student learning, performance, and satisfaction in a state university implementing the CDIO framework in technology and engineering education. To answer this pedagogical question under conditions of expert judgment and uncertainty, we employ fuzzy TOPSIS with bootstrap resampling to evaluate four alternative laboratory designs. The approach contributes theoretically by demonstrating the applicability of fuzzy MCDM to CDIO-aligned laboratory evaluation and practically by providing administrators and curriculum designers with evidence-informed guidance for selecting laboratory configurations that maximise educational outcomes. The novelty lies in integrating fuzzy TOPSIS with bootstrap resampling to systematically assess multiple laboratory modalities across both pedagogical and technical criteria, an approach not previously reported in the literature. Bootstrap resampling generates multiple simulated datasets from expert ratings, allowing robust evaluation of ranking stability under uncertainty. A comprehensive search of Scopus, Web of Science, and IEEE Xplore confirmed that this methodological framework is original, offering a replicable and robust tool for informed decision making in technology and engineering laboratory design.

2 Methodology

2.1 Case study background

The CDIO framework has demonstrated significant advantages in technology and engineering education through successful adoption by leading universities worldwide. To leverage these benefits, Cebu Technological University in the Philippines is preparing for full implementation of CDIO by developing dedicated workspaces and laboratories that support both teaching and learning activities. This study focuses on undergraduate technology and engineering programs, with laboratories such as electronics, control systems, and applied technology labs that vary in their feasibility for virtual, on-site, or hybrid delivery. The specific laboratory types were selected to balance pedagogical relevance with practical implementation considerations, acknowledging that some experiments, such as electronics simulations, are well-suited for online platforms, whereas others requiring physical interaction are better addressed in on-site or hybrid settings.

2.2 Laboratory types and delivery modes

Specifically, the laboratories evaluated in this study encompass a combination of physical experiments and software-based simulations, reflecting the range of practical and virtual learning experiences in undergraduate technology and engineering programs. Virtual laboratories primarily involve software simulations of experiments, allowing students to interact with lab equipment and observe experimental outcomes through a browser-based interface. Online presence laboratories provide a combination of remote access to physical lab equipment and guided online instruction, enabling students to control certain apparatus virtually while observing live data. On-site presence laboratories are traditional physical labs where students perform experiments directly under instructor supervision.

Hybrid laboratories integrate both physical and virtual components, allowing portions of the experiment to be conducted on-site while others are simulated or controlled remotely, providing flexibility and continuity in learning.

2.3 Selection of criteria and alternatives

The decision criteria and laboratory design alternatives, shown in Tables 1 and 2, were developed through literature review and consultation with domain experts. The five criteria namely student activity, student performance, student satisfaction, vulnerability to technical issues, and digital divide among students, capture different dimensions that influence laboratory effectiveness, including outcomes, perceptions, constraints, and risks. It can be noted that these are different types of criteria; but these were intentionally selected to reflect the real-world complexity of CDIO laboratory evaluation. Expert input was used to validate and refine the criteria to ensure they are relevant and comprehensive.

Table 1 Decision criteria considered for the laboratory design

| <i>Criteria</i> | <i>Description</i> |
|-----------------------------------|--|
| Student activity | Student activities and learning outcomes are influenced by well-designed spaces which promote communication and affective dimensions of learning (Seery et al., 2019). |
| Student performance | Well-designed school environments, including functional views and indoor/outdoor spaces, positively affect student achievement (Ariani and Mirdad, 2015). |
| Student satisfaction | Key factors that influence student satisfaction in laboratory designs include the quality of laboratory notes, equipment, and resources for troubleshooting (Nikolic et al., 2015). |
| Vulnerability to technical issues | Technical issues such as connectivity issues can impair learning and increase attrition rates, particularly among less motivated students (Sitzmann et al., 2010). |
| Digital divide among students | Bridging the digital divide involves more than just giving equipment; it also demands enhancing technological literacy, emphasising learning processes, and encouraging parental involvement as 'media mentors' (Wang et al., 2022). |

Table 2 Alternative laboratory designs

| <i>Alternatives</i> | <i>Description</i> |
|-------------------------------|---|
| Virtual laboratories | These laboratories involve interactive, dynamic, and animated simulations that improve students' skills without the constraints of time and place (Jaya, 2013). |
| Online presence laboratories | This type of laboratory is created as a live stream with live interactions from students at home (Zhang et al., 2025). |
| On-site presence laboratories | The on-site presence laboratory allows students to undertake virtual and real activities on their own experience themes including safety, machinery, and handling (Zhang et al., 2025). |
| Hybrid laboratories | These laboratories combine remote and hands-on elements which offers flexibility and accessibility in digital electronics education (Rodriguez et al., 2023). |

The four laboratory alternatives (i.e., virtual laboratories, online presence laboratories, on-site presence laboratories, and hybrid laboratories), were selected to represent the range of feasible delivery modes in higher education. Their descriptions were drawn from prior studies and best practices (Jaya, 2013; Rodriguez et al., 2023) and confirmed by experts to align with the university context and CDIO objectives. For this case study, the four alternatives were evaluated against the five criteria using expert assessments on a linguistic scale from very high impact to no impact (see Table 3). While the criteria mix different types of factors, fuzzy TOPSIS with bootstrap resampling accounts for their relative importance under uncertainty, providing a systematic way to rank the alternatives.

Table 3 Linguistic evaluation converted to fuzzy numbers of alternatives with respect to each decision criterion

| <i>Linguistic scale</i> | <i>Code</i> | <i>Fuzzy number</i> | <i>Description</i> |
|-------------------------|-------------|---------------------|--|
| Very huge impact (VHI) | VHI | (0.7, 0.9, 1.0) | An alternative has a very huge impact to a criterion |
| Huge impact (HI) | HI | (0.5, 0.7, 0.9) | An alternative has a huge impact to a criterion |
| Fair impact (FI) | FI | (0.3, 0.5, 0.7) | An alternative has a fair impact to a criterion |
| Slight impact (SI) | SI | (0.1, 0.3, 0.5) | An alternative has a slight impact to a criterion |
| No impact (NI) | NI | (0.0, 0.1, 0.3) | An alternative has no impact to a criterion. |

Table 4 Expert details

| <i>Experts</i> | <i>Gender</i> | <i>Rank</i> | <i>Number of years in service</i> |
|----------------|---------------|---------------------|-----------------------------------|
| Expert 1 | Male | Professor | 25 |
| Expert 2 | Male | Professor | 16 |
| Expert 3 | Male | Professor | 5 |
| Expert 4 | Male | Associate professor | 25 |
| Expert 5 | Male | Instructor | 7 |
| Expert 6 | Female | Professor | 3 |
| Expert 7 | Male | Professor | 25 |
| Expert 8 | Male | Associate professor | 16 |

2.4 Expert panel

Eight domain experts from Cebu Technological University participated in the study (see Table 4). The experts have an average of 15.25 years of professional experience, with academic ranks ranging from Instructor to Professor. The selection of these experts follows fuzzy TOPSIS guidelines that prioritise diversity of perspectives and informed judgment over large sample sizes. As fuzzy TOPSIS is an expert-driven multi-criteria decision-making approach, participants were chosen based on their demonstrated expertise in technology and laboratory instruction rather than statistical representativeness of a broader population. This approach is consistent with recent applications of fuzzy TOPSIS, which typically engage at least three field experts to

ensure robustness and reliability of the results (Nguyen et al., 2025; Pinto et al., 2025; Aishwarya et al., 2025; Sudjono et al., 2025; Liu et al., 2025).

Following the fuzzy TOPSIS approach, the steps executed to proceed with the analysis of laboratory designs according to decision criteria are described in the succeeding sections:

Step 1 Develop a decision matrix comprised of the evaluation of alternatives

Recall that there are five decision criteria (e.g., labelled as criterion 1 through 5) and four alternatives (e.g., labelled as alternative 1 through 4) under evaluation. The alternatives are evaluated in terms of various decision criteria using the linguistic scales shown in Table 3. As an illustration of this evaluation process, a sample linguistic evaluation is presented in Table 5. It can be seen that, for instance, alternative 2 has a fair impact with respect to criterion 1 with a rating code of FI. The rest of the table elements are interpreted in the same manner. Then, the details in Table 5 is converted into fuzzy numbers, for example, SI is converted to (0.1, 0.3, 0.5), as seen in Table 6. Note that there are eight experts tapped in this study; therefore, the individual decision matrices of each expert are aggregated by taking the arithmetic mean of their responses. The aggregated fuzzy decision matrix is shown in Table 7.

Table 5 Sample linguistic evaluation of alternatives with respect to each decision criterion

| | <i>Criterion 1</i> | <i>Criterion 2</i> | <i>Criterion 3</i> | <i>Criterion 4</i> | <i>Criterion 5</i> |
|---------------|--------------------|--------------------|--------------------|--------------------|--------------------|
| Alternative 1 | SI | SI | FI | VHI | FI |
| Alternative 2 | FI | SI | SI | VHI | FI |
| Alternative 3 | VHI | VHI | HI | HI | SI |
| Alternative 4 | FI | FI | FI | SI | SI |

Notes: Criteria 1 – student activity, criteria 2 – student performance, criteria 3 – student satisfaction, criteria 4 – vulnerability to technical issues, and criteria 5 – digital divide among students. Alternative 1 – virtual laboratories, alternative 2 – online presence laboratories, alternative 3 – on-site presence laboratories, and alternative 4 – hybrid presence laboratories.

Table 6 Linguistic evaluation converted to fuzzy numbers of alternatives with respect to each decision criterion

| | <i>Criterion 1</i> | <i>Criterion 2</i> | <i>Criterion 3</i> | <i>Criterion 4</i> | <i>Criterion 5</i> |
|---------------|--------------------|--------------------|--------------------|--------------------|--------------------|
| Alternative 1 | (0.1, 0.3, 0.5) | (0.1, 0.3, 0.5) | (0.3, 0.5, 0.7) | (0.7, 0.9, 1.0) | (0.3, 0.5, 0.7) |
| Alternative 2 | (0.3, 0.5, 0.7) | (0.1, 0.3, 0.5) | (0.1, 0.3, 0.5) | (0.7, 0.9, 1.0) | (0.3, 0.5, 0.7) |
| Alternative 3 | (0.7, 0.9, 1.0) | (0.7, 0.9, 1.0) | (0.5, 0.7, 0.9) | (0.5, 0.7, 0.9) | (0.1, 0.3, 0.5) |
| Alternative 4 | (0.3, 0.5, 0.7) | (0.3, 0.5, 0.7) | (0.3, 0.5, 0.7) | (0.1, 0.3, 0.5) | (0.1, 0.3, 0.5) |

Notes: Criteria 1 – student activity, criteria 2 – student performance, criteria 3 – student satisfaction, criteria 4 – vulnerability to technical issues, and criteria 5 – digital divide among students. Alternative 1 – virtual laboratories, alternative 2 – online presence laboratories, alternative 3 – on-site presence laboratories, and alternative 4 – hybrid presence laboratories.

Table 7 Aggregated fuzzy decision matrix of experts

| | <i>Criterion 1</i> | <i>Criterion 2</i> | <i>Criterion 3</i> | <i>Criterion 4</i> | <i>Criterion 5</i> |
|---------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| Alternative 1 | (0.213, 0.375, 0.575) | (0.213, 0.375, 0.575) | (0.175, 0.350, 0.550) | (0.175, 0.350, 0.550) | (0.150, 0.300, 0.500) |
| Alternative 2 | (0.175, 0.350, 0.550) | (0.163, 0.325, 0.525) | (0.175, 0.350, 0.550) | (0.163, 0.325, 0.525) | (0.125, 0.275, 0.475) |
| Alternative 3 | (0.025, 0.150, 0.350) | (0.025, 0.150, 0.350) | (0.038, 0.175, 0.375) | (0.163, 0.325, 0.525) | (0.138, 0.275, 0.475) |
| Alternative 4 | (0.088, 0.250, 0.450) | (0.075, 0.225, 0.425) | (0.088, 0.250, 0.450) | (0.200, 0.375, 0.575) | (0.113, 0.275, 0.475) |

Notes: Criteria 1 – student activity, criteria 2 – student performance, criteria 3 – student satisfaction, criteria 4 – vulnerability to technical issues, and criteria 5 – digital divide among students. Alternative 1 – virtual laboratories, alternative 2 – online presence laboratories, alternative 3 – on-site presence laboratories, and alternative 4 – hybrid presence laboratories.

Step 2 Compute for the normalised decision matrix

In this step, the positive and negative ideal solutions in equations (1) and (2) are used to compute for the normalised decision matrix (see Table 8).

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*} \right); c_j^* = \max_i c_{ij}; \text{positive ideal solution} \tag{1}$$

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}} \right); a_j^- = \min_i a_{ij}; \text{negative ideal solution} \tag{2}$$

Table 8 Normalised fuzzy decision matrix

| | <i>Criterion 1</i> | <i>Criterion 2</i> | <i>Criterion 3</i> | <i>Criterion 4</i> | <i>Criterion 5</i> |
|---------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| Alternative 1 | (0.370, 0.652, 1.000) | (0.370, 0.652, 1.000) | (0.318, 0.636, 1.000) | (0.304, 0.609, 0.957) | (0.300, 0.600, 1.000) |
| Alternative 2 | (0.304, 0.609, 0.957) | (0.283, 0.565, 0.913) | (0.318, 0.636, 1.000) | (0.283, 0.565, 0.913) | (0.250, 0.550, 0.950) |
| Alternative 3 | (0.043, 0.261, 0.609) | (0.043, 0.261, 0.609) | (0.069, 0.318, 0.682) | (0.283, 0.565, 0.913) | (0.276, 0.550, 0.950) |
| Alternative 4 | (0.153, 0.435, 0.783) | (0.130, 0.391, 0.739) | (0.160, 0.455, 0.818) | (0.348, 0.652, 1.000) | (0.226, 0.550, 0.950) |

Notes: Criteria 1 – student activity, criteria 2 – student performance, criteria 3 – student satisfaction, criteria 4 – vulnerability to technical issues, and criteria 5 – digital divide among students. Alternative 1 – virtual laboratories, alternative 2 – online presence laboratories, alternative 3 – on-site presence laboratories, and alternative 4 – hybrid presence laboratories.

Step 3 Calculate the weighted normalised decision matrix

Taking into account the weights of each criterion, the weighted normalised decision matrix is computed by as a product of the weight of each criterion and the normalised fuzzy decision matrix. The following expression in equation (3) is used to compute for

this matrix, where \tilde{w}_{ij} represents weight of criterion c_j . The weighted normalised decision matrix is shown in Table 9.

$$\tilde{v}_{ij} = \tilde{r}_{ij} \cdot \tilde{w}_{ij} \tag{3}$$

Step 4 Solve for the fuzzy positive ideal solution (FPIS, A^) and the fuzzy negative ideal solution (FNIS, A^-) vectors*

To compute for the FPIS and FNIS of alternatives, equations (4) and (5) are used, where \tilde{v}_i^* is the max value of i for all the alternatives and \tilde{v}_i^- is the min value of i for all the alternatives. B and C represent the positive and negative ideal solutions, respectively. Table 10 shows the fuzzy positive and negative ideal solutions.

$$A^* = \{\tilde{v}_1^*, \tilde{v}_2^*, \dots, \tilde{v}_n^*\} = \left\{ \left(\max_j v_{ij} \mid i \in B \right), \left(\min_j v_{ij} \mid i \in C \right) \right\} \tag{4}$$

$$A^- = \{\tilde{v}_1^-, \tilde{v}_2^-, \dots, \tilde{v}_n^-\} = \left\{ \left(\min_j v_{ij} \mid i \in B \right), \left(\max_j v_{ij} \mid i \in C \right) \right\} \tag{5}$$

Table 9 Normalised fuzzy decision matrix

| | Criterion 1 | Criterion 2 | Criterion 3 | Criterion 4 | Criterion 5 |
|---------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| Alternative 1 | (0.074, 0.130, 0.200) | (0.074, 0.130, 0.200) | (0.064, 0.127, 0.200) | (0.061, 0.122, 0.191) | (0.060, 0.120, 0.200) |
| Alternative 2 | (0.061, 0.122, 0.191) | (0.057, 0.113, 0.183) | (0.064, 0.127, 0.200) | (0.057, 0.113, 0.183) | (0.050, 0.110, 0.190) |
| Alternative 3 | (0.009, 0.052, 0.122) | (0.009, 0.052, 0.122) | (0.014, 0.064, 0.136) | (0.057, 0.113, 0.183) | (0.055, 0.110, 0.190) |
| Alternative 4 | (0.031, 0.087, 0.157) | (0.026, 0.078, 0.148) | (0.032, 0.091, 0.164) | (0.070, 0.130, 0.200) | (0.045, 0.110, 0.190) |

Notes: Criteria 1 – student activity, criteria 2 – student performance, criteria 3 – student satisfaction, criteria 4 – vulnerability to technical issues, and criteria 5 – digital divide among students. Alternative 1 – virtual laboratories, alternative 2 – online presence laboratories, alternative 3 – on-site presence laboratories, and alternative 4 – hybrid presence laboratories.

Table 10 Fuzzy positive and negative ideal solutions

| | Positive ideal solution | Negative ideal solution |
|-------------|-------------------------|-------------------------|
| Criterion 1 | (0.074, 0.130, 0.200) | (0.009, 0.052, 0.122) |
| Criterion 2 | (0.074, 0.130, 0.200) | (0.009, 0.052, 0.122) |
| Criterion 3 | (0.064, 0.127, 0.200) | (0.014, 0.064, 0.136) |
| Criterion 4 | (0.070, 0.130, 0.200) | (0.057, 0.113, 0.183) |
| Criterion 5 | (0.060, 0.120, 0.200) | (0.045, 0.110, 0.190) |

Notes: Criteria 1 – student activity, criteria 2 – student performance, criteria 3 – student satisfaction, criteria 4 – vulnerability to technical issues, and criteria 5 – digital divide among students.

Step 5 Compute for the distances between each alternative and the fuzzy positive ideal solution A^ and between each alternative and the fuzzy negative ideal solution A^-*

In order to compute for the distances between the alternatives and the ideal solutions, equations (6) and (7) are used, where d is the distance between two fuzzy numbers [equation (8)], when given two triangular fuzzy numbers (a_1, b_1, c_1) and (a_2, b_2, c_2) , distance between the two can be calculated as follows. Note that $d(\tilde{v}_{ij}, \tilde{v}_j^*)$ and $d(\tilde{v}_{ij}, \tilde{v}_j^-)$ are crisp numbers:

$$S_i^* = \sum_{j=1}^n d(\tilde{v}_{ij}, v_j^*) \quad i = 1, 2, \dots, m \tag{6}$$

$$S_i^- = \sum_{j=1}^n d(\tilde{v}_{ij}, \tilde{v}_j^-) \quad i = 1, 2, \dots, m \tag{7}$$

$$d_v(\tilde{M}_1, \tilde{M}_2) = \sqrt{\frac{1}{3} [(a_1 - a_2)^2 + (b_1 - b_2)^2 + (c_1 - c_2)^2]} \tag{8}$$

Step 6 Solve for the closeness coefficient and ranking of the alternatives

To solve for the closeness coefficient of each alternative, equation (9) is used. The best alternative is closest to the FPIS and farthest to the FNIS. The closeness coefficient of each alternative and the ranking order of it are shown in Table 11.

$$CC_i = \frac{S_i^-}{S_i^+ + S_i^-}$$

Table 11 Closeness coefficient and ranking of alternatives

| | d_i^+ | d_i^- | CC_i | Rank |
|---------------|---------|---------|--------|------|
| Alternative 1 | 0.009 | 0.227 | 0.963 | 1 |
| Alternative 2 | 0.054 | 0.183 | 0.773 | 2 |
| Alternative 3 | 0.232 | 0.006 | 0.024 | 4 |
| Alternative 4 | 0.141 | 0.095 | 0.403 | 3 |

Notes: Alternative 1 – virtual laboratories, alternative 2 – online presence laboratories, alternative 3 – on-site presence laboratories, and alternative 4 – hybrid presence laboratories.

3 Empirical evidence from laboratory design assessment

The implementation of CDIO framework in technology and engineering education calls for significant redesigns of laboratory facilities and practices in order to fully maximise the capabilities of both the students and faculty alike. Universities, such as the one under investigation in this paper, are developing new laboratory setups to enhance students’ practical skills in technology and other engineering fields. With such in mind, these redesigned laboratories aim to integrate knowledge impartment with capability cultivation, promoting coordinated growth in students’ knowledge, abilities, and

qualities. In fact, some universities are exploring mobile and personalised laboratory experiences, allowing students to conduct experiments at their convenience using low-cost evaluation boards. These laboratory experiences are attached to various types such as virtual, online presence, on-site presence, and hybrid. Due to the huge investment associated to the preparation of CDIO implementation, specifically the logistics needed for laboratory redesign, universities must be able to prioritise accordingly so as to maximise the resources available. In order to do this, this paper employed fuzzy TOPSIS to evaluate alternative laboratory designs in a state university in Philippines.

It is notable that the results identified virtual laboratories as the design with the highest overall suitability, followed by online presence laboratories, hybrid presence laboratories, and on-site presence laboratories. Virtual laboratories were observed to have the greatest impact across multiple decision criteria, including student engagement, performance, satisfaction, susceptibility to technical issues, and equity in digital access. It should be noted that the prominence of virtual laboratories in the rankings is influenced not only by pedagogical considerations but also by broader organisational factors, such as perceived feasibility, implementation support, and institutional familiarity with digitally enabled systems. These conditions are consistent with the wider technology adoption literature, which emphasises that successful implementation depends on critical organisational factors rather than technical capability alone (Bongo et al., 2020). This outcome reflects context-specific tendencies and should not be interpreted as absolute superiority. Since the pandemic in 2021, the university and students have adopted fully virtual learning, including laboratory classes. Fully virtual laboratories provide interactive, dynamic, and animated simulations that enable students to develop technological and engineering skills without being physically co-located. Additionally, these laboratories can operate synchronously (i.e., simultaneously) or asynchronously (i.e., at the students' convenience), offering flexibility in scheduling. Post-pandemic, many universities in the Philippines have retained hybrid arrangements, with some classes conducted virtually, which may have influenced expert preference for virtual laboratories due to the logistical convenience for students, faculty, and laboratory managers alike. Previous literature also highlights that open or flexible laboratory models have been integrated into CDIO education reform, promoting innovative talent development and skill acquisition (Wu, 2012). Such adaptations in laboratory design and management have been associated with positive student feedback and enhanced educational outcomes (Guo and Wan, 2022; Wu, 2012).

Another interesting result generated from the fuzzy TOPSIS approach revealed that online presence and hybrid presence laboratories are seen to have a significant impact to the decision criteria considered. It can be understood that online presence and hybrid presence laboratories both takes advantage of the live streaming capability of holding laboratory classes and ensuring that remote and hands-on elements are present, especially for technology and engineering education programs. Furthermore, this result resonates with that of previous works in the literature which highlights the capability of using online presence and hybrid presence laboratories. For one, these hybrid labs aim to leverage the advantages of both approaches, offering realism, scalability, and cost-effectiveness (Rodríguez-Gil et al., 2017). Aside from that, collaborative online laboratories, where groups of users work together in virtual communities, have also been explored to enhance learning experiences (Gravier and Callaghan, 2012). These innovations in online laboratory models have been seen to improve accessibility,

usability, and educational effectiveness while overcoming technical challenges associated with traditional remote and virtual labs.

Finally, on-site presence laboratories garnered the last rank among the other laboratory designs presented in this paper. Note that on-site presence laboratories work similar to virtual laboratories which provide digital twins of experiments, allowing students to practice before working with real equipment. With remote laboratories in place, this technique enables off-campus access to on-campus systems, expanding educational reach. Although this is perceived to be beneficial in terms of enhanced accessibility and resource optimisation, the advantages of on-site laboratories are limited in contexts where virtual and hybrid solutions predominate, and accessibility challenges remain.

Overall, school administrators of universities can recommend several key aspects of laboratory design to enhance science education in the midst of CDIO implementation. Based on the key findings generated in this paper, inclusive design practices should be implemented, such as making materials accessible in various formats and even using assistive technologies to accommodate students with disabilities. Laboratory experiences should be carefully examined to ensure they contribute effectively to science learning and develop scientific process skills be that especially in virtual laboratories. Furthermore, school administrators should focus on aligning laboratory activities with curriculum standards, developing higher-level cognitive skills, and training students in scientific methods. Then, school administrators must also be open to adopting laboratory designs that is best suited to facilitate the construction of knowledge by linking observed facts to existing knowledge. It is also important to emphasise that the mean closeness coefficients of the laboratory alternatives differ by less than 0.003. Consequently, while fuzzy TOPSIS provides a ranking, these differences are numerically minor and should be interpreted as relative expert preferences rather than definitive outcomes. The rankings reflect tendencies under the specific context and weighting scheme rather than absolute superiority. It is, therefore, encouraged to consider these rankings alongside other contextual factors, such as institutional resources, pedagogical goals, and student needs, when making decisions about laboratory design.

3.1 Fuzzy TOPSIS robustness analysis using bootstrap resampling approach

To evaluate the robustness of the fuzzy TOPSIS rankings for laboratory alternatives, MATLAB-based bootstrap resampling was employed. This non-parametric technique generates multiple simulated datasets by randomly sampling the original fuzzy decision matrix with replacement, allowing assessment of the stability of expert judgments across all criteria rather than validating the correctness of the rankings. In this study, 1,000 bootstrap iterations were performed. During each iteration, the fuzzy TOPSIS methodology was applied to compute the closeness coefficients of all alternatives with respect to the fuzzy positive and negative ideal solutions. The consistency of the rankings was then measured by determining the proportion of iterations in which each alternative achieved the top rank, providing a quantitative indication of the reliability and stability of the decision outcomes under uncertainty.

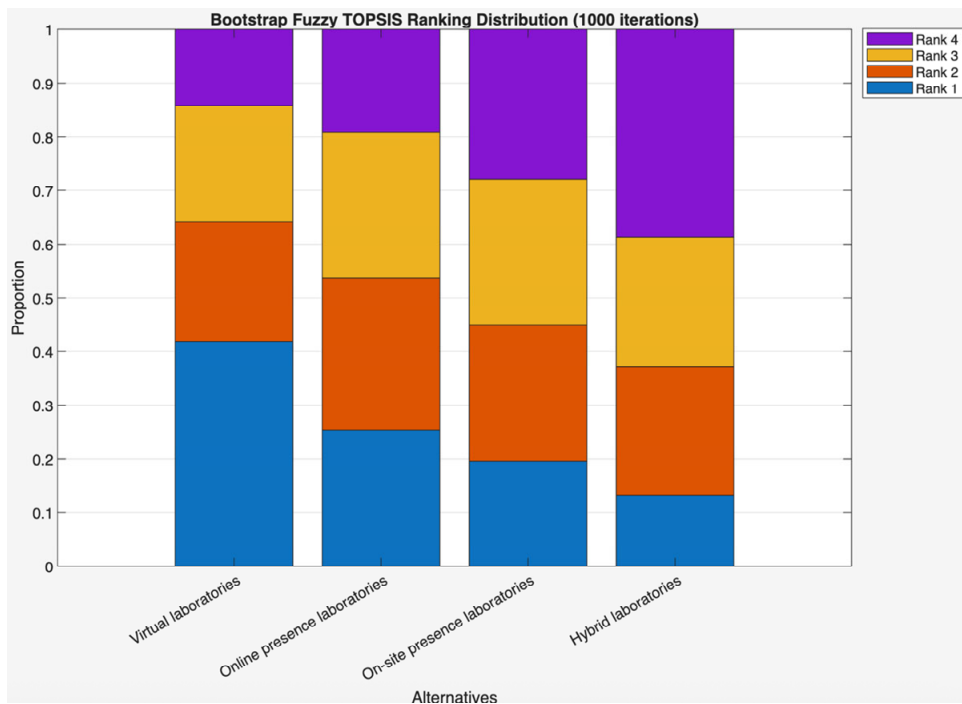
In Table 12 and Figure 1, the bootstrap analysis shows that virtual laboratories ranked first in 41.9% of the 1,000 iterations, followed by online presence laboratories at 22.3% and on-site presence laboratories at 21.6%. Hybrid laboratories ranked first least frequently, appearing in 14.2% of iterations. These results indicate that while virtual

laboratories is the most frequently preferred alternative, the rankings are not strongly decisive, as the other alternatives frequently dominate in a substantial portion of iterations. The mean closeness coefficients are close across all alternatives, ranging from 0.514 to 0.517, suggesting that overall performance across criteria is similar. Thus, although virtual laboratories shows slightly higher stability, the alternatives remain competitive, and selection should consider context-specific priorities and operational constraints rather than relying solely on the rankings.

Table 12 Bootstrap fuzzy TOPSIS results for laboratory alternatives

| <i>Virtual laboratories</i> | <i>Proportion ranked first</i> | <i>Mean closeness coefficient</i> |
|-------------------------------|--------------------------------|-----------------------------------|
| Virtual laboratories | 0.419 | 0.517 |
| Online presence laboratories | 0.223 | 0.515 |
| On-site presence laboratories | 0.216 | 0.514 |
| Hybrid laboratories | 0.142 | 0.514 |

Figure 1 Bootstrap-based fuzzy TOPSIS assessment of laboratory alternatives in a CDIO framework (see online version for colours)



4 Concluding remarks

This paper was formulated to assess alternative laboratory designs under various decision criteria in the implementation of the CDIO framework in technology and engineering education. To achieve this goal, a fuzzy TOPSIS approach integrated with bootstrap

resampling was applied to a real-life case study in a state university in the Philippines. Four alternatives, namely virtual laboratories, online presence laboratories, on-site presence laboratories, and hybrid laboratories, were evaluated according to five decision criteria: student activity, student performance, student satisfaction, vulnerability to technical issues, and digital divide among students. A key finding of the analysis indicates that virtual laboratories have the most significant overall impact across the evaluated criteria. Although this result may appear counterintuitive due to potential technical issues and digital divide concerns, the benefits of virtual laboratories, particularly their ease of implementation and flexibility, likely contribute to this outcome. The widespread adoption of full virtual classes during the COVID-19 pandemic has also increased institutional familiarity with virtual laboratory capabilities, which may have influenced expert preferences in this context.

The practical implications suggest that school administrators need to address concerns regarding awareness, procurement, and resource allocation for virtual laboratories, especially in institutions with limited financial capacity. Despite these challenges, student satisfaction with virtual laboratories remains generally high, with approval rates exceeding 75 percent for content, design, and interactivity. While virtual laboratories provide substantial benefits, they are best implemented as a complement to hands-on laboratory experiences, given persistent concerns such as cognitive overload and assessment challenges.

The primary contribution of this study lies in demonstrating the application of fuzzy TOPSIS combined with bootstrap resampling to evaluate CDIO-aligned laboratory designs, providing a structured approach to rank alternatives and assess ranking stability over 1,000 iterations. This does not represent methodological novelty per se, but highlights the utility of the approach in supporting evidence-informed decision-making under uncertainty. It is acknowledged that the results may reflect contextual factors, such as institutional bias toward virtual delivery during the COVID-19 pandemic. Empirical validation using student outcome data, such as grades or retention, was not included and is recommended for future research to corroborate the fuzzy TOPSIS findings. Furthermore, while aggregated expert ratings minimised disagreement, future studies could apply formal measures of inter-rater reliability to strengthen the robustness of results. Consideration of infrastructure costs and long-term pedagogical effects should also be incorporated in subsequent analyses to provide a more comprehensive evaluation of laboratory alternatives.

As a final note, a key limitation of this study is its focus on a single university, a single national context, and a single expert panel, which inherently limits the generalisability of the findings. The results should therefore be interpreted as a context-specific illustration of applying fuzzy TOPSIS with bootstrap resampling to evaluate CDIO-aligned laboratory designs. Nonetheless, the methodological framework is replicable and adaptable, providing a structured approach that other institutions, contexts, and expert panels can adopt to support evidence-informed laboratory design decisions. Future research could expand this approach across multiple universities, diverse national settings, and larger expert panels to strengthen external validity and broaden applicability.

Declarations

All authors declare that they have no conflicts of interest.

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