

# Integrating CDIO and Engineering Design Process in STEM Education: Evidence from High School Implementation

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## ABSTRACT

*This study investigates the integration of the CDIO framework with the Engineering Design Process (EDP) in high school STEM education and its effects on students' problem-solving competence. A quasi-experimental pretest–posttest design was employed, with 49 students participating in a structured STEM intervention based on iterative design cycles. Data were analyzed using the R statistical environment, including paired-samples t-tests, effect size analysis, and Pearson's correlation.*

*The results indicate a significant improvement in overall problem-solving competence ( $t(48) = 2.24, p = .030$ ). However, improvements in specific competency components were not statistically significant, and the correlations among the components were weak. These findings suggest that while the CDIO–EDP framework effectively enhances overall performance, it does not necessarily promote the integrated development of problem-solving sub-skills within a short intervention period.*

*This study contributes a structured instructional framework that combines lifecycle- and process-oriented approaches in STEM education, highlighting the need for sustained and targeted pedagogical support to foster deeper competence development.*

**Keywords:** CDIO; Engineering Design Process; STEM education; problem-solving competence; high school students

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## I. Introduction

In recent years, Science, Technology, Engineering, and Mathematics (STEM) education has been increasingly emphasized as a key approach to preparing students for the demands of the twenty-first century. Beyond disciplinary knowledge, STEM education aims to develop students' problem-solving competence, critical thinking, creativity, and ability to apply knowledge in real-world contexts (OECD, 2018; National Research Council, 2012). However, despite its growing importance, many STEM implementations at the secondary school level remain fragmented and overly focused on theoretical knowledge, lacking structured pedagogical frameworks that effectively connect learning to authentic engineering practices (Bybee, 2014; Moore et al., 2014).

One promising approach to addressing this challenge is the Conceive–Design–Implement–Operate (CDIO) framework, originally developed by the Massachusetts Institute of Technology (Crawley et al., 2007). CDIO conceptualizes engineering education as a complete life cycle process, guiding learners from problem identification to solution implementation and operation. Previous studies have demonstrated that CDIO can enhance experiential learning, interdisciplinary integration, and practical skill development (Crawley et al., 2014; Malmqvist et al., 2015). However, its application in secondary STEM education remains limited and often lacks detailed instructional guidance.

In parallel, the Engineering Design Process (EDP) has been widely recognized as a core pedagogical model in STEM education, offering a structured sequence of steps that supports students' engagement in problem solving and design-based learning (National Research Council, 2012). The EDP promotes iterative thinking, creativity, and evidence-based reasoning, which are essential for developing problem-solving

competence (Kelley & Knowles, 2016). Nevertheless, the EDP alone may not provide a comprehensive framework that connects individual design activities to the broader lifecycle of engineering practice.

Recent studies suggest that integrating CDIO with EDP may provide a more coherent and effective instructional framework by combining structural organization with detailed cognitive processes (Taajamaa et al., 2016; Rouvais et al., 2020). Such integration is expected to support students in transitioning from conceptual understanding to practical implementation, particularly through iterative design cycles in the future. However, empirical evidence on this integrated approach in high school STEM education remains limited, and the relationships between different components of students' competencies, especially between design and implementation skills, are not yet fully understood in the literature.

To address these gaps, this study investigates the implementation of an integrated CDIO–EDP framework in high school STEM education, as shown in Figure 1. This study adopts a hypothesis-driven approach to examine both the effectiveness of the instructional model and the relationships among key competency components.

Accordingly, this study proposes the following hypotheses:

**H1:** The implementation of the CDIO–EDP integrated framework significantly improves students' overall problem-solving competence in STEM learning.

**H2:** The CDIO–EDP framework leads to significant improvements in specific competency components, including problem understanding, idea generation, design, and implementation.

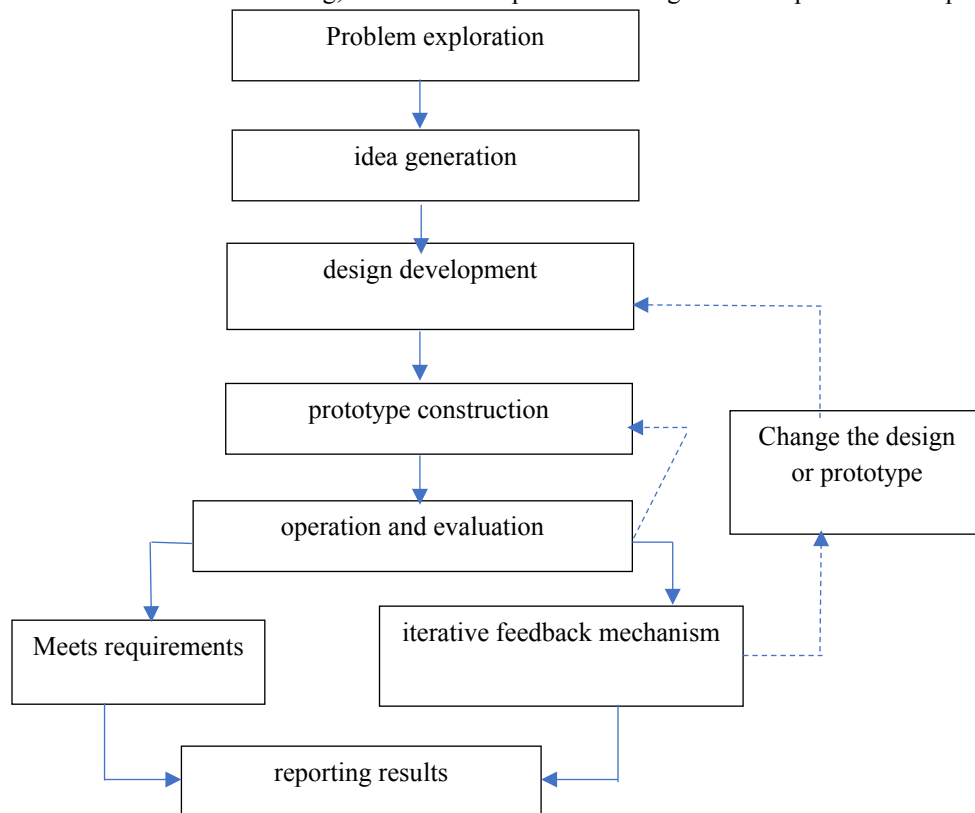
**H3:** There is a significant positive relationship between students' design and implementation skills within the CDIO–EDP framework.

By testing these hypotheses, this study aims to contribute to STEM education research both theoretically and empirically. Theoretically, it provides a structured integration of CDIO and EDP as a multilevel instructional framework. Empirically, it provides evidence of how this framework supports the development of problem-solving competence in high school students, thereby informing the design of more effective STEM learning environments.

## II. Theoretical Framework

### 2.1. The CDIO–EDP Integrated Framework

To provide a comprehensive foundation for STEM instruction, this study adopts an integrated framework that combines the CDIO (Conceive–Design–Implement–Operate) model with the Engineering Design Process (EDP). This integration is conceptualized as a multilevel instructional model in which CDIO provides the overall structure of learning, whereas EDP specifies the cognitive and procedural steps within each



**Figure 1.** The CDIO model in STEM education.

phase.

As illustrated in **Figure 1**, the proposed framework represents STEM learning as a *cyclical and iterative process* in which students progress through a sequence of interconnected stages: problem exploration, idea generation, design development, prototyping, and evaluation. Unlike linear instructional models, this framework emphasizes continuous refinement through feedback loops, reflecting authentic engineering practices.

## **2.2. Interpretation of the CDIO–EDP Process (Figure 1)**

In **Figure 1**, the learning process begins with *problem exploration*, corresponding to the conceive phase of CDIO and the problem identification stage in the EDP. At this stage, students analyze real-world contexts and define the problem to be solved, which forms the foundation for the subsequent design activities.

This is followed by idea generation, where students propose potential solutions based on scientific knowledge and creative thinking. This stage reflects the transition from problem understanding to conceptual design.

The next stage, *design development*, represents the core of engineering thinking. Students translate abstract ideas into structured designs, including diagrams, materials, and explanations of the underlying principles. This stage aligns with both the *Design* phase of CDIO and the ideation–modeling processes of the EDP.

Subsequently, the students engage in *prototype construction*, corresponding to the *Implement* phase. Theoretical designs are transformed into tangible products through hands-on activities. This stage is critical for bridging conceptual knowledge and practical applications.

The process continues with *operation and evaluation*, which aligns with the *Operate* phase of CDIO and the testing–evaluation stage of EDP. Students assess the performance of their prototypes based on predefined criteria such as functionality, efficiency, and feasibility.

A key feature of the framework, as shown in Figure 1, is its *iterative feedback mechanism*. If the product does not meet the required criteria, students are guided to revise the design or prototype. This iterative loop reflects the core principle of engineering design, in which failure is treated as a learning opportunity rather than an endpoint (Kolodner et al., 2003).

Once the solution satisfies the requirements, students proceed to *report results*, which supports reflection, communication, and knowledge consolidation.

## **2.3. Iteration as a Core Mechanism of Learning**

The iterative loops shown in Figure 1 play a central role in this theoretical framework. These loops operationalize the concept of learning through design cycles, wherein students continuously refine their understanding and solutions based on feedback.

This aligns with: Engineering design principles (iteration and optimization) ; Experiential learning theory (Kolb, 1984); Constructivist learning theory, where knowledge is built through active engagement

Through iteration, students develop not only technical skills but also metacognitive abilities, such as monitoring, evaluating, and adjusting their strategies.

## **2.4. Link to Problem-Solving Competence**

The CDIO–EDP framework illustrated in Figure 1 provides a structured pathway for developing students' problem-solving competencies. Each stage contributes to a specific dimension of competence: Problem exploration → Problem understanding; Idea generation → Solution generation; Design development → Planning and modeling; Prototype construction → Implementation skills; Evaluation and iteration → Reflection and improvement

Importantly, the framework highlights the strong connection between design and implementation skills, as students must translate conceptual solutions into practical outcomes and refine them through iterative testing.

## **2.5. Conceptual Model of the Study**

Based on Figure 1, this study conceptualizes STEM learning as a process in which the CDIO–EDP instructional process drives the development of students' problem-solving competence, with particular emphasis on iterative transitions between design and implementation phases.

# **III. Method**

## **3.1. Research Design**

This study employed a quasi-experimental pretest–posttest design to examine the effects of the CDIO–EDP instructional framework on students' problem-solving competencies. The intervention was

implemented through STEM learning activities structured according to iterative design cycles, including problem exploration, idea generation, design development, prototyping, and evaluation (Figure 1).

**3.2. Participants**

The participants consisted of 49 high school students from intact classes in a natural classroom setting in Indonesia. The sample size corresponds to the number of valid paired observations included in the statistical analysis ( $df = 48$ ). All participants completed both the pre- and post-test assessments under the same instructional conditions.

**3.3. Instructional Intervention**

The intervention was designed based on the integrated CDIO–EDP framework, which combines the CDIO phases (Conceive–Design–Implement–Operate) with the iterative processes of the Engineering Design Process.

Students engaged in a sequence of learning activities, including: Problem identification and exploration; Idea generation and solution planning; Design development and explanation ; prototype construction; Testing, evaluation, and iterative refinement

A key feature of the intervention was the use of iterative feedback loops, which allowed students to revise and improve their solutions based on evaluation results. This approach aimed to simulate authentic engineering practices and support active, inquiry-based learning in the classroom.

**3.4. Instruments**

Students’ problem-solving competence was assessed using a performance-based rubric aligned with the CDIO–EDP Framework. The rubric included three main components: Problem Understanding (PU), Solution Planning and Idea Generation (SPI), and Implementation and Evaluation (EI).

Scores were collected for both the pre- and post-tests, and composite scores were calculated to represent overall problem-solving competence.

**3.5. Data Analysis**

All data were analyzed using **R statistical software**. The analysis included:

- Descriptive statistics to summarize performance
- Paired-samples *t*-tests to examine pre–post differences (H1, H2)
- Effect size calculations (Cohen’s *d*) to evaluate the magnitude of change
- Pearson correlation analysis to examine relationships among competency components (H3)

Only complete paired observations were included in this analysis. Statistical significance was set at  $p < .05$ .

**IV. Results**

**H1:** To examine the overall effect of the CDIO–EDP instructional framework on students’ problem-solving competence, a paired-samples *t*-test was conducted comparing pre- and post-test total scores. Table 1

**Table 1.** Paired *t*-test for Total Score

t	df	p-value	Mean Difference	95% CI
2.24	48	0.030	0.56	[0.06, 1.07]

The results indicated a statistically significant improvement in overall problem-solving performance ( $t(48) = 2.24, p = .030$ ). The mean difference between the post- and pre-test scores was 0.56, with a 95% confidence interval ranging from 0.06 to 1.07.

These findings demonstrate that students’ overall problem-solving competence improved significantly following the intervention. Therefore, H1 was supported, suggesting that the CDIO–EDP framework positively impacted students’ overall learning outcomes.

**H2.** To further investigate the impact of the intervention on specific components of problem-solving competence, paired-samples *t*-tests and effect size analyses were conducted for each sub-dimension. Table 2

**Table 2.** Effects on Competency Components

Component	t	p-value	Cohen's d	Interpretation
SPI	0.14	0.891	0.03	Negligible
EI	1.28	0.205	0.29	Small

The results revealed that the improvement in solution planning (SPI) was not statistically significant,  $t(48) = 0.14, p = .891$ , with a negligible effect size ( $d = 0.03$ ). Similarly, the improvement in implementation and evaluation skills (EI) was not statistically significant,  $t(48) = 1.28, p = .205$ , although a small effect size ( $d = 0.29$ ) was observed.

These findings indicate that while slight improvements were observed in individual competency components, the magnitude of change was limited and did not reach statistical significance. Therefore, H2 was not supported, suggesting that the intervention did not produce consistent improvements across all subdimensions of problem-solving competence.

**H3.** To explore the relationships among different components of problem-solving competence, Pearson correlation analysis was conducted using post-test scores. Table 3

**Table 3.** Correlation Matrix

	PU	SPI	EI
PU	1.00	0.06	0.20
SPI	0.06	1.00	-0.07
EI	0.20	-0.07	1.00

The results showed weak and non-significant correlations among the components. Specifically, the correlation between problem understanding (PU) and solution planning (SPI) was negligible ( $r = .06$ ), and the correlation between SPI and implementation and evaluation skills (EI) was also negligible ( $r = -.07$ ). A slightly higher but still weak relationship was found between PU and EI ( $r = .20$ ).

Overall, the results suggest that the components of problem-solving competence function relatively independently in this context, with no statistically significant relationships identified among them. Therefore, H3 is not supported.

## V. Discussion

This study investigated the effects of the CDIO–EDP instructional framework on students’ problem-solving competence, with particular attention to overall performance, specific competency components, and the relationships between these components. The findings provide several important insights into the effectiveness and limitations of the intervention.

First, the results support H1, indicating that the CDIO–EDP framework significantly improved students’ overall problem-solving competence. This finding is consistent with prior research suggesting that design-based and engineering-oriented instructional models enhance students’ ability to engage with complex authentic problems. The structured sequence of CDIO–EDP, ranging from problem identification to iterative refinement, appears to provide a coherent learning pathway that supports the integration of knowledge and action. From a constructivist perspective, this improvement can be attributed to the active engagement of learners in meaningful problem contexts in which knowledge is constructed through iterative design and evaluation processes.

However, the findings for H2 reveal a more nuanced view. Although slight improvements were observed in specific competency components, such as solution planning (SPI) and implementation and evaluation skills (EI), these changes were not significant. This suggests that while the CDIO–EDP framework enhances overall performance, its impact on individual sub-skills may require a longer duration or more targeted instructional support to be fully realized. One possible explanation is that the different components of problem-solving competence develop at different rates. For example, planning and evaluation skills often involve higher-order metacognitive processes, which are known to require sustained practice and explicit scaffolding. Therefore, the relatively short intervention period may not have been sufficient to produce measurable gains in these areas.

The results for H3 further reinforce this conclusion. The absence of significant correlations among the competency components suggests that these skills function relatively independently in this context. This lack of integration indicates that students may not have developed a coherent internal structure linking problem understanding, planning, and implementation. In other words, while students improved their overall performance, this improvement did not translate into a well-organized system of interrelated competency. This finding aligns with research on novice learners, which shows that the early stages of skill development are often characterized by fragmented knowledge structures rather than integrated expertise.

Taken together, these findings highlight an important theoretical implication: instructional effectiveness at the performance level does not necessarily imply structural competence development. The CDIO–EDP framework appears to function effectively as a performance-enhancing model that enables students to complete problem-solving tasks more successfully. However, the development of deeper and more integrated competencies may require additional instructional elements, such as explicit metacognitive guidance, longer learning cycles, or opportunities for reflective practice.

From a pedagogical perspective, the results suggest that educators should not assume uniform development across all dimensions of problem-solving competence. Instead, targeted support may be needed to strengthen specific components, particularly those related to planning, evaluation, and implementation. Integrating reflective activities, formative feedback, and iterative design cycles can help students better connect the different stages of the problem-solving process.

Finally, the findings underscore the importance of considering both outcome- and process-based measures when evaluating instructional interventions. While overall performance gains are important, they may mask the underlying limitations of how competencies are structured and integrated. Therefore, future research

should adopt longitudinal designs to examine how these relationships evolve over time and identify the conditions under which integrated competence development can be achieved.

## VI. Conclusion

This study provides empirical evidence that integrating the CDIO framework with the Engineering Design Process (EDP) contributes to improving students' overall problem-solving competence in STEM education. The findings demonstrate that the CDIO–EDP framework serves as an effective instructional approach for enhancing students' performance in solving complex design-based problems.

However, the results also indicate that improvements at the overall performance level do not necessarily translate into significant gains across individual competency components or into coherent relationships among these components. This suggests that the development of problem-solving competence is a gradual, multidimensional process that requires sustained instructional support.

Overall, this study highlights the potential of the CDIO–EDP framework as a performance-enhancing model, while also emphasizing the need for longer-term and more targeted pedagogical strategies to foster deeper and more integrated competence development in STEM learning.

**This study is limited** by its relatively small sample size and the use of intact classes, which may affect the generalizability of the findings. Additionally, the short duration of the intervention may not have been sufficient to capture the development of specific competency components and their interrelationships. Future research should employ larger samples and longitudinal designs to examine the evolution of integrated problem-solving competence.

**Artificial Intelligence (AI) Disclosure:** Artificial Intelligence (AI) Disclosure: ChatGPT (OpenAI, 2025) was used solely to assist with language-related tasks, including paraphrasing, grammar, wording, and clarity during the revision process.

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