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The Impact of Implementation Methods and Low-Cost Learning Modules on Engineering Students Engagement and Learning Outcomes

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ABSTRACT

Active, hands-on learning is essential for engineering education, fostering deep engagement and enhancing knowledge retention. This multi-institutional study investigates how different instructional methods—Hands-On, Virtual, and Lecture-only—combined with four distinct Low-Cost Desktop Learning Modules (LCDLMs: Hydraulic Loss, Double Pipe, Shell & Tube, and Venturi Meter) affect student engagement and learning outcomes. Anchored in the ICAP framework (Interactive, Constructive, Active, Passive), the study measured cognitive engagement through direct observations, virtual screen recordings, and self-reported surveys. It assessed learning gains using normalized pre- and post-tests among 2,316 undergraduate engineering students from eight universities. Results indicate that virtual instruction yields significantly higher learning gains, while the Shell & Tube module enhances active engagement through tangible, hands-on experiences. In contrast, the Hydraulic Loss module demonstrates the greatest impact on quantitative knowledge growth. These findings underscore the potential of integrating virtual simulations with physical learning tools to optimize instructional design in engineering education. Implications for future research include refining measurement instruments and exploring the long-term effects of hybrid instructional models.

Keywords: Engineering Education, LCDLMs (Low-Cost Desktop Learning Modules), Virtual Learning, Hands-On Learning, ICAP Framework (Interactive, Constructive, Active, Passive)

INTRODUCTION

Engineering education has long emphasized the importance of interactive, hands-on learning activities to foster deep understanding and practical skill acquisition [2,6,7, 18]. Traditional lecture formats, while still prevalent, often lack the level of engagement and experiential relevance that can be achieved through well-designed, low-cost, and easily deployable teaching tools [1, 3, 5, 6,17, 21]. In particular, Low-Cost Desktop Learning Modules (LCDLMs) have emerged as promising instructional resources, offering accessible, table-top experiments that allow students to visualize and manipulate fundamental concepts in real-time [12, 22, 23]. Prior research posits that these compact, affordable devices can enhance knowledge retention, increase student interest, and provide meaningful connections between theoretical content and practical applications.

Despite a growing body of literature on the value of LCDLMs, there is limited insight into how variations in both the types of modules– namely Hydraulic Loss, Double Pipe, Shell and Tube, and Venturi meter) and the methods used to implement them—namely Hands-On, Virtual, or Lecture-only—might affect student engagement and learning outcomes [4, 16, 21]. Moreover, the rapid shift to online learning during the COVID-19 pandemic has spotlighted the need for flexible instructional strategies that accommodate remote settings without sacrificing educational quality.

In engineering curricula—particularly in fluid mechanics and thermodynamics courses—there has been a longstanding reliance on laboratory-based, hands-on experimentation [17]. However, the recent shift to virtual simulations and digital resources has prompted questions about the relative efficacy of these modalities compared to traditional physical interactions [10, 14]. As in-person classes resumed, it became crucial to evaluate how these different instructional methods impact student engagement and learning outcomes [1, 5].

The present study addresses this need by systematically examining the implementation of four LCDLMs—Hydraulic Loss, Double Pipe, Shell & Tube, and Venturi Meter—across three delivery formats: Hands-On, Virtual, and Lecture-only. Using a large, multi-institutional sample of 2,316 undergraduate engineering students, this research integrates both cognitive and behavioral assessments of learning. Pre- and post-tests are utilized to measure students' knowledge gains, while the ICAP (Interactive, Constructive, Active, Passive) framework offers a structured lens to evaluate the depth of student engagement.

By examining not only whether students learn but also how they engage in the learning process, the study uncovers more robust strategies and conditions that best support conceptual mastery in challenging engineering topics. Drawing from cognitive theories of learning, this study operationalizes both engagement and learning outcomes by linking each LCDLM to specific cognitive processes [2, 7, 9, 14, 15, 18]. For example, the Hydraulic Loss module emphasizes quantitative analysis and conceptual understanding of pressure drop, while the Shell & Tube module fosters procedural learning through tangible, hands-on interaction. The Double Pipe module offers comparative insights into thermal and fluid dynamics, and the Venturi Meter module reinforces quantitative measurement skills through the practical application of Bernoulli's principle.

The findings contribute valuable insights into the design and implementation of LCDLMs, particularly during periods of instructional disruption, and lay the groundwork for future inquiries into the long-term benefits of hybrid models that blend both virtual and hands-on learning experiences.

PRESENT STUDY

Although previous studies have explored the effectiveness of individual learning pedagogies, few have systematically compared the impact of different instructional methods on both student engagement and learning outcomes [10]. In this study, we compare three instructional modalities— Hands-On, Virtual, and Lecture-only—across four distinct LCDLMs to determine how each approach influences cognitive engagement and academic performance.

Specifically, the study aims to:

- Evaluate how different instructional methods affect learning outcomes, as measured by pre- and post-test scores.
- Examine the effect of each LCDLM on student engagement by applying the ICAP framework to delineate differences between Interactive, Constructive, Active, and Passive learning states.

By explicitly defining key constructs and operationalizing variables, the present study provides a robust framework for understanding how targeted teaching tools can enhance both engagement and conceptual mastery in engineering education.

METHODS

Participants

This quasi-experimental study involved 2,316 undergraduate engineering students from eight universities. These institutions were selected based on similarities in curricular content and academic standards. Within each institution, students enrolled in fluid mechanics or thermodynamics courses were recruited. Participants were assigned to one of three instructional conditions (Hands-On, Virtual, or Lecture-only) either through random assignment within classes or via pre-existing class sections. To ensure consistency across sites, all testing environments—whether in-person or virtual—were standardized with uniform instructions and monitored conditions.

Materials

Low-Cost Desktop Learning Modules

Four Low-Cost Desktop Learning Modules—Hydraulic Loss, Double Pipe, Shell & Tube, and Venturi Meter—were developed to support student comprehension of fundamental engineering concepts in fluid mechanics and heat transfer. These modules are compact, inexpensive, transparent, and user-friendly, allowing students to gain hands-on experience with process units commonly encountered in industry. Each LCDLM is accompanied by instructional resources (e.g., videos, readings, worksheets, homework assignments) that guide students through the learning process. Past research has shown that incorporating LCDLMs into the classroom effectively enhances both engagement and conceptual understanding [12, 17]. In this study, we implemented four modules, namely, Shell & Tube, Double Pipe, Hydraulic Loss, and Venturi Meter, to explore how each module addresses particular aspects of fluid mechanics and heat transfer concepts. The visual representation of each module is presented in Appendix A.

Measures

Learning Performance

Pre- and post-tests measured students' learning gains using content-specific questions about flow rates, pressure drop, and heat transfer mechanisms. Student engagement was assessed via [2] ICAP framework, classifying engagement into Interactive, Constructive, Active, or Passive dimensions. Engagement data were collected from direct observation in hands-on settings, screen-recorded activity in virtual sessions, and self-reported surveys. In the Hands-on condition, students physically interacted with the experimental kit during in-person instruction, while in the virtual condition, students participated remotely via Zoom. They were not physically handling the modules themselves but instead observed a facilitator manipulate the modules. Analyses included one-way and two-way ANOVAs to examine how instructional method and module type affected pre- to post-test gains. Engagement scores were also compared across conditions to determine how different levels of activity or interaction correlated with learning outcomes. Scores were normalized to facilitate direct comparisons across groups.

Student Engagement

Student engagement was measured using an adapted version of the ICAP framework [2]. This instrument combined data from three sources: direct observations in hands-on settings, screen-recorded activity in virtual sessions, and self-reported surveys. The engagement measure, grounded in validated psychometric instruments, demonstrated strong internal consistency (Cronbach's alpha = 0.85). Engagement scores were composite scores measured as continuous variables reflecting the four dimensions—Interactive, Constructive, Active, and Passive—thereby supporting the use of MANOVA in subsequent analyses.

Procedure

Before the intervention, all participants completed a pre-test to assess baseline knowledge. During class sessions, instructors integrated LCDLM activities following the assigned instructional modality. Instructors received standardized training to ensure consistent implementation across all eight institutions. Following the LCDLM activities, students completed a post-test, an engagement survey, and a demographic questionnaire. All procedures were approved by the Institutional Review Board, and standardized protocols were employed for both in-person and virtual sessions.

Data Analysis

Learning performance data were analyzed using ANCOVA to assess the impact of instructional modality on post-test scores while controlling for pre-test performance. Engagement data—measured as continuous variables—were analyzed using one-way MANOVA to evaluate differences across the four LCDLM types. Prior to analysis, assumptions regarding normality, homogeneity of variances, and data integrity were verified.

RESULTS

Before analysis, data entry was verified and checked for missing values, outliers, and normality [20]. All variables met acceptable criteria for skewness and kurtosis [20].

Descriptive Statistics

Table 1 summarizes the descriptive statistics for the four engagement dimensions—Interactive, Constructive, Active, and Passive—and the normalized Knowledge Growth percentages for each LCDLM type. (Note: Engagement scores are presented as raw values reflecting observed engagement behaviors, whereas Knowledge Growth values are expressed as normalized percentage improvements from pre- to post-test scores. Pre- and post-test scores were normalized by dividing the number of correct responses by the total number of items (e.g., a score of 0.5 indicates 50% correct). This resulted in all knowledge scores being reported on a 0–1 scale. Normalization allowed for direct comparison across participants and conditions and supported the use of ANOVA for statistical analysis.

Table 1. Descriptive Statistics for Engagement and Knowledge Growth by LCDLM Type

	Hands-on		**Virtual**		**Lecture only**	
	Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*
Pretest	0.50	0.22	0.50	0.29	0.50	0.29
Posttest	0.64	0.23	0.74	0.27	0.63	0.24

Note: For Knowledge Growth, the two values per module represent an average improvement in conceptual understanding. SD = Standard Deviation.

Learning Outcomes (ANCOVA Analysis)

To address Research Question 1, an analysis of covariance (ANCOVA) was conducted to examine the effect of instructional modality on post-test scores, controlling for pre-test performance. The results revealed a statistically significant effect of instructional modality on post-test scores, $F(2, 2312) = 15.65$, $p < .001$. Post-hoc comparisons using Tukey's HSD test indicated that the Virtual group ($M = 0.74$, $SD = 0.27$) scored significantly higher than both the Hands-On ($M = 0.64$, $SD = 0.23$) and Lecture-only ($M = 0.63$, $SD = 0.24$) groups (see Table 2). These normalized post-test scores are based on a scale where values less than one indicate relative performance against a predefined benchmark.

Table 2.

	Double Pipe		**Hydraulic Loss**		**Shell & Tube**		**Venturi**	
	Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Interactive	15.78	3.01	15.50	3.10	15.79	3.00	15.55	3.10
Constructive	15.54	3.08	15.19	3.21	15.49	3.01	15.23	3.01
Active	14.45	3.14	14.07	3.08	14.75	2.97	14.14	3.08
Passive	10.07	4.05	9.81	3.81	9.51	3.98	9.75	3.85
Knowledge Growth	7.74%	22.8%	25.79%	36.91%	6.38%	19.83%	9.32%	23.79%

Note. SD = Standard Deviation.

Engagement Outcomes (MANOVA Analysis)

To address Research Question 2, a one-way multivariate analysis of variance (MANOVA) was conducted on the four engagement dimensions (Interactive, Constructive, Active, Passive) with LCDLM type as the independent variable. The analysis revealed a statistically significant overall effect of LCDLM type on engagement, $F(12, 5781) = 2.00$, $p < .05$, *Wilk's lambda* = .99, partial $\eta^2 = 0.04$. Specifically, there was a significant effect on Active engagement scores, $F(3, 2188) = 4.36$, $p < .01$, partial $\eta^2 = 0.06$, with the Shell & Tube module producing significantly higher Active engagement scores compared to the Hydraulic Loss module. No significant differences were observed for the Interactive, Constructive, or Passive dimensions (all $p > .05$). It is important to note that the engagement measures are continuous variables, which justifies the application of MANOVA.

Table 3.

MANOVA Results for ICAP Scores as Dependent Variables

Multivariate Tests						
	value	***F***	***df1***	***df2***	***p***	***Partial Eta Squared***
LCDLMs	Wilks' Lambda	2.00	12	5781.26	<.05	.004
Univariate Tests						
	Dependent Variable	**Sum of Squares**	***df***	**Mean Square**	***F***	***p***
LCDLMs	Interactive	36.45	3	12.15	1.30	.273
	Constructive	57.13	3	19.04	1.95	.119
	Active	124.38	3	41.46	4.36	< .01
	Passive	75.69	3	25.23	1.64	.178
Residuals	Interactive	20456.86	2188	9.35		
	Constructive	21357.19	2188	9.76		
	Active	20791.29	2188	9.50		
	Passive	33632.52	2188	15.37		

DISCUSSION & CONCLUSION

The present study investigated two key research questions: (1) how different instructional methods (Hands-On, Virtual, and Lecture-only) affect student learning outcomes, and (2) how distinct Low-Cost Desktop Learning Modules (LCDLMs) influence student engagement as measured by the ICAP framework. The findings reveal that virtual instructional methods produced significantly higher post-test scores than both hands-on and lecture-only approaches. One possible explanation is that virtual environments may provide more flexible learning opportunities and foster autonomous engagement, which can enhance conceptual understanding. While the present study did not directly measure content revisitation or repeatability, these factors have been suggested in prior literature as potential advantages of virtual learning [13, 19].

In contrast, the engagement profiles varied by LCDLM type. Notably, the Shell & Tube module elicited higher Active engagement scores, underscoring the value of physical interaction in promoting deeper cognitive processing. This finding aligns with the ICAP framework [2], which posits that hands-on activities enhance active participation and facilitate robust learning experiences. Meanwhile, the Hydraulic Loss module was associated with the greatest knowledge growth, suggesting that modules emphasizing quantitative analysis can be particularly effective when integrated into virtual settings.

While the study's multi-institutional design and standardized testing protocols enhance the generalizability of these findings, the aggregation of participants from eight institutions necessitates caution regarding curricular consistency and grouping assumptions. Future research should further validate the measurement instruments across diverse educational contexts and examine potential moderating factors related to participant heterogeneity.

This study provides important insights into the differential impacts of instructional modalities and LCDLM types on student engagement and learning outcomes in engineering education. By integrating the ICAP framework with cognitive theories of learning, our findings highlight that virtual environments can significantly enhance academic performance, while hands-on modules remain essential for fostering active engagement. The results suggest that a thoughtful combination of virtual and physical teaching tools can bridge the gap between theoretical understanding and practical application.

Future research is encouraged to explore the long-term effects of hybrid instructional models and to refine the measurement of engagement and learning outcomes. Such efforts will enable educators to tailor instructional strategies more effectively, ultimately advancing pedagogical practices in engineering education. Overall, the integration of both virtual and hands-on modalities emerges as a promising approach to optimize student outcomes in increasingly dynamic academic settings.

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APPENDIX

Appendix A. Low-Cost Desktop Learning Modules (LCDLMs)

Figure 1.

Hydraulic-loss setup

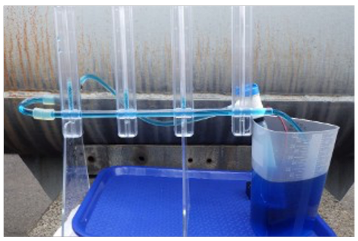

Figure 2.
Venturi setup

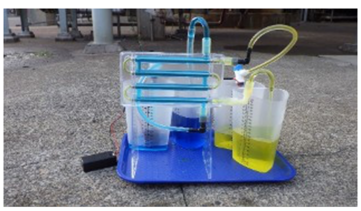

Figure 3.

Double-pipe heat exchanger setup

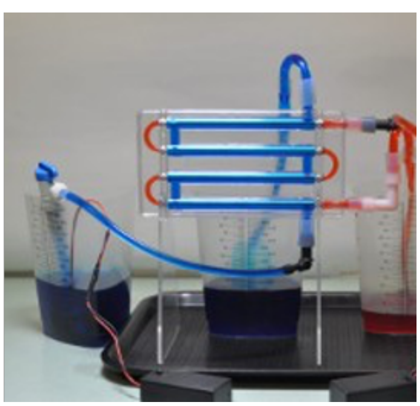

Figure 4.
Shell-and-tube heat exchanger setup