

Low-Cost Desktop Learning Modules: Effect of Implementation Types on Student's Learning Performance

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DOI: 10.18260/jet.43.1.4

Abstract

Low-Cost Desktop Learning Modules (LCDLMs) are affordable, interactive instructional tools designed to enhance conceptual understanding in engineering education. With the appreciation that engagement of learners in interactive, constructive, active and passive frameworks produces different levels of learning, these modules promote deeper learning by engaging students through hands-on, constructive, or interactive activities. This study investigated the effects of three implementation types—virtual, hands-on, and traditional lecture—on undergraduate engineering students' learning outcomes across three specific LCDLMs: the Hydraulic Loss module, Venturi meter, and Double Pipe heat exchanger. A total of 918 students from fluid mechanics and thermodynamics courses participated. Results from the study revealed that students in the virtual implementation group significantly outperformed those in the hands-on and control groups. Among the module types, the Hydraulic Loss module led to the highest posttest performance. These findings underscore the potential of LCDLMs to optimize active learning strategies and suggest that virtual implementations may offer scalable and effective solutions for integrating technology-enhanced, hands-on learning experiences in engineering curricula.

1. Introduction

In the evolving field of engineering education, enhancing student engagement and learning outcomes through innovative instructional methods is a critical objective (Kaiphanliam et al. 2021). One significant innovation is the use of Low-Cost Desktop Learning Modules (LCDLMs), designed to provide hands-on, practical learning experiences at an affordable cost. These modules bridge the gap between theoretical concepts and real-world applications, allowing students to directly engage with engineering principles (Kaiphanliam et al. 2021). Research highlights that LCDLMs, with their interactive and transparent

components, make abstract concepts more tangible and comprehensible, thereby fostering a deeper understanding and retention of the material (Reynolds et al. 2022). Research describe DLMs as low-cost tools designed to aid student comprehension, with a target cost comparable to a textbook (Khan et al. 2022).

LCDLMs offer pedagogical advantage by facilitating the management of intrinsic cognitive load, which refers to the mental effort required to comprehend complex or unfamiliar information (Sweller, 1988; Paas et al 2003). A hands-on, interactive design such as LCDLM can enhance learning of essential information more effectively. This is particularly beneficial in domains characterized by high content complexity, such as fluid dynamics and heat transfer. Consequently, LCDLMs apply principles that reduce extraneous cognitive load and promote interactive/constructive engagement, addressing limits of lecture-only instruction (Reynolds et al. 2022; Khan et al. 2022; Freeman et al. 2014; Chi and Wylie 2014; Menekse et al., 2013).

Research has argued that low socioeconomic status is the biggest barrier to STEM participation (Taylor & Francis Group 2020). Therefore, an affordable teaching tool like LCDLM would be beneficial for promoting inclusivity and access in engineering. LCDLMs were specifically designed to help engineering students explore fundamental principles in fluid mechanics and heat transfer (Durak 2023; Wong et al. 2024). One of the benefits of LCDLMs is their ability to visually demonstrate complex engineering phenomena, making them easier to understand (Reynolds et al. 2022). These visual tools are particularly effective in clarifying critical engineering concepts, such as delineating system boundaries for calculating heat transfer rates in heat exchangers and assessing fluid velocity in pipes. The broad-reaching potential of LCDLMs greatly enhances educational practices in engineering. LCDLM significantly enhances engineering education by aligning with core principles of constructivist learning theory, which emphasizes the importance of active engagement,

hands-on manipulation, and observation in the construction of knowledge. Berlyne, Piaget and Malcolm (2003) argued that learners build cognitive structures through direct interaction with their environment, especially during problem-solving and experimentation. Similarly, Vygotsky (1978) emphasized the sociocultural context of learning, highlighting how guided participation in hands-on tasks within the learner's zone of proximal development fosters deeper understanding. Therefore, high level students' engagement with selected academic content through visual learning experiences will be associated with positive learning outcome (Watson et al. 2022).

LCDLMs reflect these principles by enabling students to physically manipulate components, observe system responses, and engage in exploratory learning activities that promote conceptual change and mental model development. LCDLMs models are further supported by the ICAP framework, which highlights how LCDLMs facilitate student engagement and deeper understanding (Taylor & Francis Group 2020; Durak 2023; Wong et al. 2024).

The ICAP framework categorizes learning activities into four distinct types: Interactive (I), Constructive (C), Active (A), and Passive (P). Accordingly, Durak (2023) noted that learning activities that necessitate more intensive engagement, such as interactive and constructive activities, are more effective for learning compared to those that involve lesser degrees of engagement, such as active and passive activities. Specifically, the framework posits that interactive engagement facilitates superior cognitive involvement compared to constructive engagement, which in turn is more beneficial than active engagement. Active engagement, while more involved than passive engagement, still ranks lower in promoting cognitive engagement than either interactive or constructive engagement. Recognizing the importance of hands-on learning, educators created small-scale, cost-effective versions of industrial equipment to offer practical learning experiences (Kaiphanliam et al. 2021; Berlyne, Piaget and Malcolm. 2003; Menekse et al., 2013).

Spatial reasoning ability plays a critical role in engineering education, enabling students to visualize, manipulate, and interpret complex systems and structures (Zhou et al. 2024). Research has demonstrated that spatial abilities are strong predictors of success in STEM fields—often above and beyond other cognitive skills—particularly in relation to engagement in STEM activities and the pursuit of advanced education in these domains (Wai, Lubinski and Benbow 2009; Zhou et al. 2024). In engineering specifically, students with higher spatial visualization skills tend to perform better in tasks involving

three-dimensional comprehension, mental rotation, and the application of abstract principles to physical systems. LCDLMs are well-positioned to support the development of spatial skills by offering students direct, hands-on experiences with physical models that reflect core engineering concepts. These modules encourage learners to observe real-time system responses, manipulate components, and mentally translate between theoretical representations and mechanical behaviors. Such active engagement fosters the refinement of spatial reasoning abilities through iterative visual, tactile, and cognitive interaction (Khan et al. 2022). In this way, LCDLMs not only enhance conceptual understanding but also nurture a set of cognitive skills that are foundational for long-term success in engineering and STEM pathways.

Active learning literature shows that interactive methods generally outperform traditional lectures (Freeman et al. 2014; Watson et al. 2022), though effectiveness depends on contextual factors such as instructor proficiency and student prior knowledge. Simple module design like hydraulic loss often yields larger gains, while more complex designs, such as the Venturi meter, tend to produce smaller effects. Structured implementation and instructor preparation can further enhance outcomes (Deslauriers, Schelew and Wieman 2011), and LCDLMs may particularly benefit students with lower prior knowledge (Watson et al. 2022).

Research on the effectiveness of LCDLMs in engineering education has produced mixed results. In prior work, the hands-on hydraulic loss module significantly outperformed its virtual counterpart, whereas the double pipe module showed minimal differences between formats (Reynolds et al. 2022), likely due to the more visual nature of the hydraulic loss phenomena and stronger alignment of its assessments with observable concepts. For the Venturi meter LCDLM, measured values closely matched theoretical predictions, confirming its accuracy for instructional use. Comparisons of hands-on and virtual implementations revealed no significant differences in learning gains, indicating that virtual delivery can be as effective as in-person instruction (Van Wie et al. 2022). While previous studies have compared individual LCDLMs—such as hydraulic loss, double pipe, and old versus new versions of the shell-and-tube and Venturi—most have done so in isolation or in combinations of only two modules (Hunsu, Adesope and Van Wie 2017, Reynolds et al. 2022). Few have directly compared three or all four modules on learning performance within the same study. Such comprehensive comparisons are valuable not only for identifying relative effectiveness across modules but also for generating consistent datasets

that can inform future systematic reviews or meta-analyses on LCDLM implementation in engineering education.

2. Implementation Types

Research indicates that hands-on learning significantly enhances student engagement, comprehension, and conceptual understanding. Particularly through LCDLMs, hands-on approaches reinforce theoretical knowledge by allowing students to directly interact with learning materials and experiment in meaningful ways (Kaiphanliam et al. 2021; Reynolds et al. 2022). These methods also increase student motivation. However, they can be resource-intensive and less scalable due to the need for physical presence and specialized materials, which may be limited in certain instructional contexts (Reynolds et al. 2022).

In contrast, virtual tools—such as videos and simulations—offer scalable, flexible learning opportunities, especially useful when in-person instruction is not feasible, as during the COVID-19 pandemic (Merchant et al. 2014; Van Wie et al. 2022). Studies on virtual learning environments more broadly have found that students using video-based or simulation-based demonstrations can achieve learning gains comparable to those using physical setups (Van Wie et al. 2022; Hunsu, Adesope and Van Wie 2017). Well-designed virtual settings can, in some contexts, match or even exceed the learning outcomes of physical formats by providing structured, distraction-free spaces where learners can proceed at their own pace, revisit content, and concentrate on essential concepts without the logistical constraints of physical setups (Sweeney et al. 2022). Broader research on virtual instruction also highlights its capacity to expand access to complex or abstract phenomena that are difficult to replicate in physical settings (Li and Liang 2024) and can boost motivation for learners with limited hands-on experience (Mahendra and Killis 2025).

Traditional lecture-based methods remain widely used, offering a consistent structure and serving as a useful baseline for comparing the effectiveness of innovative strategies. However, recent studies comparing hands-on and virtual methods suggest that transitioning to virtual formats does not compromise learning outcomes. Comparable improvements in student performance have been observed in both delivery modes (Hunsu, Adesope and Van Wie 2017), underscoring the need for continued research to determine the optimal conditions for each type of implementation.

The purpose of this study is to examine the effectiveness of three Low-Cost Desktop Learning Module (LCDLM) implementation types—virtual, hands-on, and traditional lecture—on undergradu-

ate engineering students' academic outcomes. Although prior research has demonstrated the pedagogical value of LCDLMs in fostering engagement and conceptual understanding (Kaiphanliam et al. 2021; Reynolds et al. 2022), limited evidence exists on how different implementation types influence their effectiveness in engineering contexts. This study extends the literature by validating the conditions under which these approaches can be optimally employed to enhance student learning. Data were collected from participants across Fall and Spring 2022, increasing the generalizability of findings within a single academic year. While the study does not assess long-term retention or transfer, it addresses a critical gap by providing empirical insights into the immediate effects of different implementation types. Specifically, it investigates how both implementation type and LCDLM design affect student learning, guided by the following research questions:

RQ1: What is the effect of LCDLM implementation types on undergraduate engineering students' learning performance?

RQ2: To what extent do different LCDLMs influence undergraduate engineering students' learning performance?

3. Methodology

3.1. Participants

Participants consisted of 918 (Female 31.4%; Male; 62.0%; Non-binary 1.5%; Prefer not to answer 1.3%) postsecondary undergraduate engineering students enrolled in heat transfer and fluid mechanics courses across 8 different schools in the United States. The majority of students reported being of white ethnicity (Native American 0.6%; Asian 9.8%; Black/African American 7.7%; Hispanic 4.4%; International 1.7%; White 73.6%; Mixed 1.1%; Prefer not to answer 1.1%) and in their junior year of college (Freshman 0.2%; Sophomore 13.9%; Junior 64.8%; Senior 20%; Graduate (Masters) 0.3%; Graduate (PhDs) 0.6%; Prefer not to answer 0.1%). Participants were primarily undergraduates (96%) enrolled in engineering courses related to fluid mechanics and thermodynamics between the semesters of Fall 2021 and Spring 2022. Student recruitment was conducted in-class by instructors, who, along with their teaching assistants, received specific training prior to the study's implementation. Student participation in the study was voluntary. Assignment to instructional mode (LCDLM or control) was not randomized but was determined by whether their instructor opted to implement the LCDLMs or continue with standard instruction. This study was approved by Washington State University's Institutional Review

Board. Instructors received standardized training, with materials—including video demonstrations, PowerPoint slides, and detailed instructions—shared via OneDrive. To protect participant confidentiality, all identifying information was removed, and pseudonymous codes were assigned to each student. This study was approved by Washington State University's Institutional Review Board.

3.2. LCDLM Implementation Descriptions

To help teach and demonstrate abstract engineering concepts, learning modules and materials for four LCDLMs were created and used: double pipe, hydraulic loss, shell & tube, and Venturi meter. The hydraulic loss, double pipe, and Venturi LCDLMs are low-cost, small-scale devices fabricated using injection molding, robotically assisted adhesive application, and 3D printing. The hydraulic loss module features a constant-diameter pipe with four stand-pipe manometers for observing head loss. The double pipe heat exchanger has a transparent annular shell for visualizing fluid flow patterns. The Venturi meter, made from ABS and PETG, enables observation of velocity and pressure changes. Battery-operated pumps circulate colored water, and students collect measurements to calculate each module's key engineering parameters.

However, only three modules were included in this study - double pipe, hydraulic loss, and Venturi meter. The Shell & Tube Module for Virtual and Control groups were unavailable for virtual and traditional conditions; therefore, Shell & Tube Module was removed from this study. Professors and teaching assistants at the participating universities were provided training videos and materials on the LCDLMs by the research team. Three modes of instruction for the LCDLMs were available to the participants throughout the academic session. Students engaged with LCDLM content through one of three modes:

(1) traditional lecture (control), (2) hands-on use of a physical LCDLM, or (3) virtual instruction using videos and simulations. Instructors selected the implementation mode for their course, and integration into the curriculum was aligned with relevant topics such as fluid mechanics or heat transfer. While the core content was consistent, the depth and timing of implementation varied slightly across instructors and institutions based on instructional preferences and logistical factors (see Figures 1.1 to 1.3).

3.3. Measures

3.3.1 Learning Performance

The pre- and posttests were developed by the research team in collaboration with experienced engineering faculty and aligned with the specific learning objectives of each LCDLM module. The number of pre and posttest items ranges from six to nine questions. The test items have been refined and used across multiple course offerings over the past three years, supporting their content validity and practical utility in assessing key engineering concepts such as fluid mechanics and heat transfer. Expert instructors with over a decade of teaching and research experience reviewed the items to ensure relevance and alignment with instructional content. While formal construct validation was not conducted, internal consistency reliability was acceptable (Cronbach's $\alpha = 0.74$). The tests included conceptual multiple-choice, true/false, and open-ended questions.

3.4. Procedure

During two academic semesters, faculty at participating universities implemented LCDLMs as instructional tools to facilitate student learning in fluid mechanics and heat transfer. All participants received a minimum of 50 minutes of weekly instruction, delivered through one of three modes: traditional lecture, hands-on, or virtual instruction. Instructors in

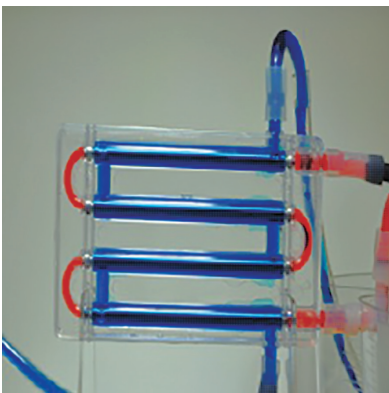


Figure 1.1. Example of double pipe.

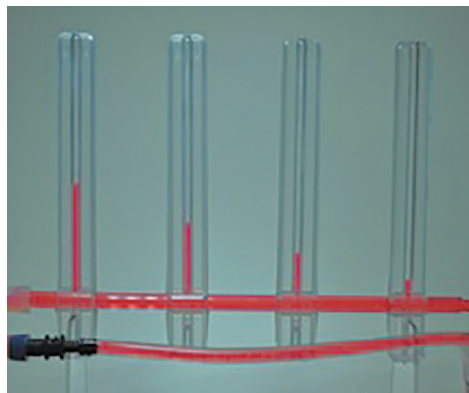


Figure 1.2. Example of hydraulic loss.

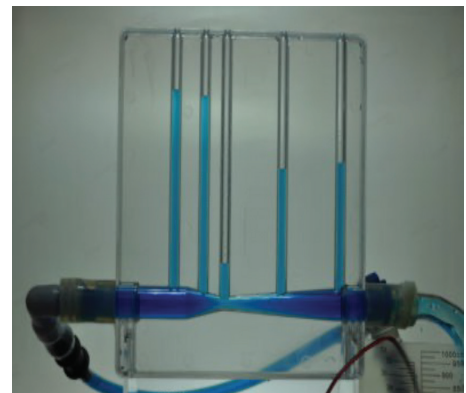


Figure 1.3. Example of Venturi meter.

the virtual condition used a combination of Zoom and YouTube for synchronous instruction, conducting live sessions and sharing pre-recorded demonstrations to enhance flexibility and accessibility. As modules were implemented, students were informed of the opportunity to participate in our study and were provided consent forms if they decided to participate. Students who consented were also given a demographic survey via Qualtrics. Before engaging in a LCDLM activity, students completed a pretest related to the topic. After the LCDLM activity, they were given the corresponding posttest. Data were collected from both in-person and online settings. The pre-test and post-test were both administered via Qualtrics. The pre-test was administered before students started working on the LCDLMs and the post-test was administered after completion of LCDLM learning activities.

3.5. Data Analysis

A one-way Analysis of Covariance was conducted to examine the effect of LCDLM implementation type (virtual, hands-on, or traditional lecture) on students' posttest performance, controlling for pretest scores. All ANCOVA assumptions—normality, homogeneity of variances, linearity, and homogeneity of regression slopes—were tested and met. Instructional mode was not randomized but determined by whether instructors adopted LCDLMs or continued with standard instruction. To minimize bias, student module use was guided and monitored. The Shell & Tube module was implemented exclusively within the hands-on LCDLM condition; therefore, it was

excluded from the analysis due to concerns about threats to internal validity and lack of comparability across implementation types. Additionally, missing data associated with Shell & Tube module, which was only implemented in the hands-on condition, were handled in accordance with best practices for addressing structurally missing data (Allison 2009).

4. Results

4.1. Preliminary Analysis

Prior to data analysis, the accuracy of data entry, missing values, outliers, and distribution normality were assessed. Skewness values ranged from -1.03 to 0.76 and kurtosis from -1.05 to 0.12 for implementation type, LCDLMs, pretest, and posttest scores—indicating acceptable univariate normality [25]. To determine whether students began the study with comparable levels of prior knowledge, a one-way analysis of variance (ANOVA) was conducted. The independent variable was LCDLM implementation type, and the dependent variable was the pretest score. Results revealed a significant difference in pretest performance across groups, $F(2, 850) = 24.74$, $p < .001$. Students in the Venturi group ($M = 0.55$, $SD = 0.02$) outperformed those in the Double Pipe group ($M = 0.51$, $SD = 0.01$) and the Hydraulic Loss group ($M = 0.43$, $SD = 0.01$). Because these differences indicate unequal starting points, pretest score was included as a covariate in subsequent analyses to statistically control for prior knowledge and strengthening the internal validity (See Table 1.1 and Figure 1.4 for descriptive statistics).

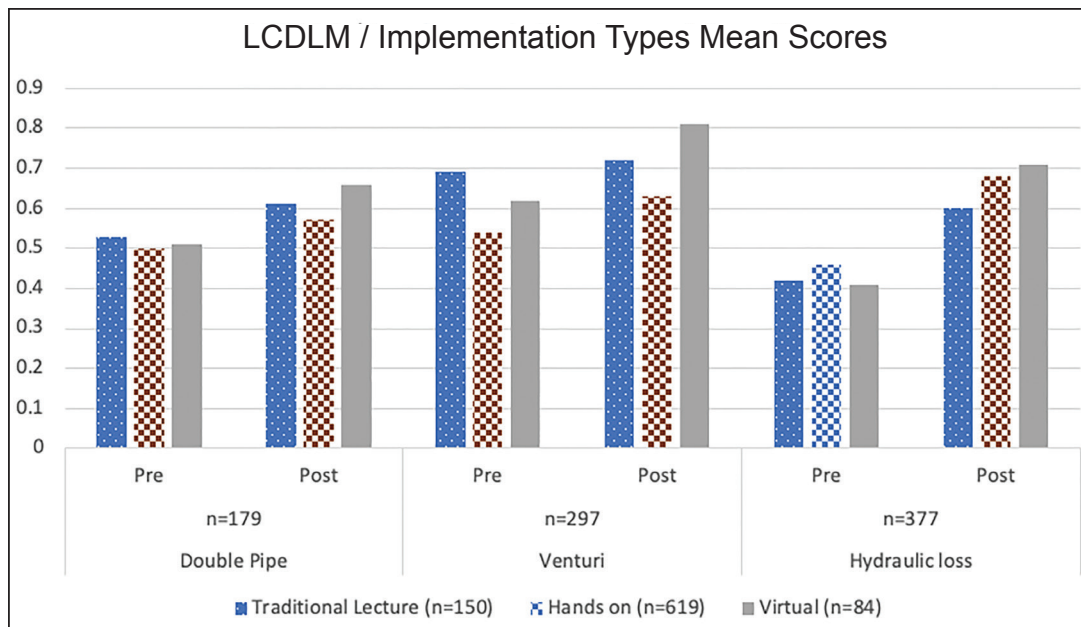


Figure 1.4. LCDLM Implementation Types Descriptive Statistics Bar Chart.

Table 1.1 LCDLM implementation types descriptive statistics

LCDLM	Double Pipe (<i>n</i> = 179)		Venturi (<i>n</i> = 297)		Hydraulic Loss (<i>n</i> = 377)	
Implementation	Pre	Post	Pre	Post	Pre	Post
Traditional Lecture (Control) (<i>n</i> = 150)	<i>M</i> = 0.53 <i>SD</i> = 0.16	<i>M</i> = 0.61 <i>SD</i> = 0.24	<i>M</i> = 0.69 <i>SD</i> = 0.13	<i>M</i> = 0.72 <i>SD</i> = 0.14	<i>M</i> = 0.42 <i>SD</i> = 0.28	<i>M</i> = 0.60 <i>SD</i> = 0.33
Hands-On (<i>n</i> = 619)	<i>M</i> = 0.50 <i>SD</i> = 0.18	<i>M</i> = 0.57 <i>SD</i> = 0.21	<i>M</i> = 0.54 <i>SD</i> = 0.18	<i>M</i> = 0.63 <i>SD</i> = 0.20	<i>M</i> = 0.46 <i>SD</i> = 0.32	<i>M</i> = 0.68 <i>SD</i> = 0.29
Virtual (<i>n</i> = 84)	<i>M</i> = 0.51 <i>SD</i> = 0.36	<i>M</i> = 0.66 <i>SD</i> = 0.19	<i>M</i> = 0.62 <i>SD</i> = 0.16	<i>M</i> = 0.81 <i>SD</i> = 0.14	<i>M</i> = 0.41 <i>SD</i> = 0.28	<i>M</i> = 0.71 <i>SD</i> = 0.30

4.2. LCDLM implementation types and learning performance.

To address the first research question regarding the effect of LCDLM implementation types on learning performance, a one-way analysis of covariance (ANCOVA) was conducted. The analysis examined differences in learning performance across implementation types—Virtual, Hands-on, and Control—while statistically controlling for prior knowledge (pretest scores). Results revealed a significant effect of implementation type on learning performance (posttest scores), $F(2, 914) = 6.33$, $p < .002$, partial eta squared = .014. Post-hoc comparisons using the Tukey HSD test indicated mean scores for the Virtual group ($M = 0.72$, $SD = 0.28$), Hands-On ($M = 0.64$, $SD = 0.25$), and Control (Traditional lecture) ($M = 0.61$, $SD = 0.24$). See Table 1. 2 below:

4.3. LCDLM and Learning Performance

To address the second research question, a one-way ANCOVA was conducted to compare the effect of LCDLM types on posttest scores controlling for prior knowledge (pretest). There was a statistically significant effect of LCDLM types on posttest scores, $F(2, 849) = 11.81$, $p < .001$, partial eta squared = .032. Results showed that the mean score for the Hydraulic Loss group ($M = 0.67$, $SD = 0.02$) outperformed both the Venturi group ($M = 0.65$, $SD = 0.19$) and the Double Pipe group ($M = 0.58$, $SD = 0.20$). No significant difference was found between the Venturi and Double Pipe conditions. Although the differences were statistically significant, the small effect sizes (partial $\eta^2 = .014$ and .032) indicate that Implementation accounted for only a small portion of the variance in learning performance (posttest scores). This suggest that other factors may have contributed to the student learning performance. See Table 1.3 below:

Table 1.2 LCDLM Implementation Types ANCOVA.

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.	Partial Eta Squared
Pretest	2.23	1.00	2.23	37.43	0.00	0.039
Implementation	0.75	2.00	0.38	6.33	0.00	0.014
Error	54.36	914	0.06			
Total	441.66	918				

Table 1.3 LCDLM ANCOVA.

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.	Partial Eta Squared
Pretest	2.25	1.00	2.25	37.15	0.00	0.042
LCDLM	1.43	2.00	0.71	11.81	0.00	0.032
Error	51.34	849	0.06			
Total	414.93	853				

5. Discussion

Present research examined the effect of LCDLM Implementation types on undergraduate student engineering learning. Contrary to previous research, we found that the virtual LCDLM implementation had outperformed both hands-on and lecture-based methods, which is particularly notable. This contrasts with prior research reporting that hands-on LCDLM activities yielded greater learning gains than virtual implementations (Reynolds et al. 2022). and with studies suggesting no significant difference in effectiveness between physical and digital implementations (Van Wie et al. 2022). The findings indicate that, in this context, well-designed virtual environments can simulate hands-on experiences effectively and, in some cases, surpass them in promoting learning outcomes.

This result suggests that well-designed virtual environments can effectively simulate—and in some contexts surpass—hands-on learning. A plausible explanation is that virtual LCDLMs offer a structured, distraction-free environment where students can work at their own pace, revisit demonstrations, and focus on key concepts without the logistical demands of physical setups (Sweeney et al. 2022). They also expand access to complex or abstract phenomena difficult to replicate physically (Li and Liang 2024) and can enhance motivation and engagement, particularly for students with limited prior hands-on experience (Mahendra and Killis 2025). Imperatively, deep students' engagement with academic contents through virtual learning experiences is linked to high positive learning outcome (Yanik et al. 2021). These benefits align with research on the scalability and accessibility of virtual methods during periods of limited physical interaction, such as the COVID-19 pandemic (Van Wie et al. 2022; Merchant et al 2014), and with evidence that consistent, repeatable experiences support learning without the constraints of physical resources or time (Winn 1993). The findings also suggest that hands-on instruction, without additional scaffolding, may be no more effective than traditional lectures—a conclusion consistent with evidence that minimally guided, discovery-based activities often yield limited gains without sufficient instructional support (Sweller, Kirschner and Clark 2007). Future research should investigate the conditions under which virtual methods are most effective.

Consistent with past research, we found hydraulic loss module outperformed other types of LCDLMs (Double pipe & Venturi meter) in learning performance (Durak, 2023; Watson et al. 2022). Students with higher engagement—especially those interacting with modules like hydraulic loss—demonstrated significantly greater posttest gains

(Reynolds et al. 2022). This suggests that modules with high concept specificity allows students to grasp key concepts more effectively, leading to improved learning performance (Khan et al. 2022, Van Wie et al. 2022). These finding highlights how different LCDLMs contribute uniquely to student learning and cognitive processing. While LCDLMs have generally been shown to enhance engagement (Khan et al. 2022; Watson at el. 2022), our study extends this understanding by demonstrating that certain module types—such as the hydraulic loss module—may yield greater learning gains. One possible explanation is that the hydraulic loss module addresses foundational concepts with clear, observable cause-and-effect relationships, making it more accessible to students. Its relatively straightforward design may also reduce extraneous cognitive load, allowing learners to focus on core principles and applications. This suggests that the cognitive complexity and instructional clarity of individual modules play a critical role in their effectiveness.

Although LCDLMs have been shown to improve learning performance, this study examines whether these improvements are consistent across different implementation types (Kaiphanliam et al. 2021). This research contributes to the field by addressing the limited empirical evidence regarding the replication and validation of the impact of LCDLMs on learning performance, as noted by (Watson et al. 2022). This research enhances our understanding of certain boundary conditions under which different LCDLM types might be optimally employed. These results have significant implications for educational practice, particularly in STEM fields where both hands-on and virtual learning are commonly employed. The demonstrated effectiveness of virtual simulations suggests that engineering programs and instructors should consider integrating more virtual elements into their curricula to complement and potentially enhance traditional instructional methods when using LCDLMs. The virtual element may enhance engineering education by enabling accessible, interactive simulations and remote labs that integrate seamlessly with curricula to potentially improve student engagement and learning outcomes. Furthermore, the finding that virtual LCDLM implementations outperformed both hands-on and traditional lecture approaches in learning performance supports the broader conclusion that the method of content delivery can substantially influence student outcomes. This underscores the importance of deliberately selecting instructional strategies that align with the intended learning goals and the characteristics of the subject matter (Freeman et al. 2014). These results align with the ICAP framework, supporting

the effectiveness of interactive, constructive, and active features in learning tools (Chi and Wylie 2014). Future research should explore the specific features of virtual simulations that contribute most to their effectiveness, as well as how they can be best integrated with other instructional materials to maximize educational outcomes.

6. Limitation and Future Direction

While this study found that virtual implementation types outperformed hands-on and traditional lecture approaches in learning performance, these results are limited to the three LCDLMs analyzed—hydraulic loss, double pipe, and Venturi meter. The Shell & Tube module was excluded because neither the control nor virtual implementation groups participated. Future research should incorporate the Shell & Tube module across all three implementation modes to assess whether the observed advantage of virtual delivery is sustained under expanded conditions. The analysis did not include data on professors and schools involved in the LCDLM implementation, as not all schools participated in each of the LCDLM modules. This omission may limit the depth of understanding regarding how different educational contexts influence the effectiveness of each LCDLM. Future research should aim to collect and incorporate data on the different types of LCDLMs for all schools participating in LCDLM implementations. This comprehensive data set would allow for a more detailed analysis of how varying educational environments and instructional methods impact student learning outcomes across different LCDLM modules and semesters. Although variability between implementations represents a limitation, it also enhances ecological validity by reflecting the diversity of instructional practices likely to occur in real classrooms.

While the present study discussed student engagement, cognitive load, and ICAP framework, it did not incorporate or measure the Community of Inquiry (Akyol and Garrison 2011) or the MVEE model (Putwain et al. 2018) in its design. Future studies may build upon this work by explicitly measuring and analyzing distinct types of engagement (e.g., motivational, volitional, emotional) within a defined theoretical framework to better understand engagement dynamics in diverse learning environments.

The current study drew on a relatively large sample of 918 undergraduate engineering students across eight institutions in the United States, several limitations should be noted. The sample was predominantly composed of white students (73.6%) and juniors (64.8%), which may limit the generalizability of the

findings to more racially diverse student populations or to students at other stages of their academic careers. Additionally, most participants were enrolled in fluid mechanics and thermodynamics courses, which may constrain the applicability of the results to other engineering subdisciplines or non-engineering fields. These demographic concentrations suggest that further research is needed to explore whether the observed effects of LCDLM implementation types hold across more varied educational and demographic contexts. Another limitation of the study is the non-random sampling based on course enrollment and institutional collaboration, which may introduce selection bias. However, instructor training was provided to support consistent implementation across sites. While the use of a control group strengthens internal validity. While the pre- and posttest instruments had been refined and used across multiple semesters, no formal item difficulty analysis was conducted for this study. As such, we did not examine whether specific items were consistently answered correctly or incorrectly. Future research should include item-level analyses to identify patterns in student responses and improve test sensitivity.

The potential of hybrid instructional methods that combine both virtual and physical learning experiences was not explored in the present study. While virtual and hands-on learning approaches each offer unique benefits, hybrid models could capitalize on the strengths of both. Future studies should compare the effectiveness of hybrid versus traditional methods, particularly in improving student engagement and learning performance. Additionally, exploring best practices for implementing LCDLMs in diverse classroom settings will help educators optimize these tools for varied learning environments.

7. Conclusion

In this paper, we examined the effects of different LCDLM implementation modes on undergraduate engineering learning. Students engaged with virtual, hands-on, and lecture-based modules across multiple institutions. The findings point to two main conclusions. First, virtual LCDLMs outperformed both hands-on and lecture-based approaches, highlighting the potential of well-designed virtual environments to achieve similar—and in some cases greater—gains than in-person, hands-on or lecture-based learning environments. This finding suggests the practical value of virtual implementations in expanding access and flexibility, particularly in under-resourced settings.

Second, significant differences were observed among LCDLM types. The Hydraulic Loss module yielded higher posttest scores than both the Venturi

and Double Pipe modules, suggesting that the effectiveness of LCDLMs depends on how well module design aligns with learning objectives and concept complexity. However, the relatively small effect sizes indicate that module type explains only a portion of the variance, pointing to the influence of other factors such as instructional support, student engagement, or prior experience.

Taken together, these findings should guide educators to align module choice with instructional purpose, encourage institutions to invest in virtual modules and faculty training, and signal to policymakers the value of broadening access to scalable, cost-effective tools. Future research should extend LCDLMs to non-engineering disciplines, employ qualitative studies to capture student experiences, develop AI-driven adaptive simulations, and investigate hybrid models that combine virtual and hands-on approaches. Such efforts will strengthen the flexibility, inclusivity, and resilience of higher education.

Acknowledgements

We acknowledge support through NSF IUSE #1821578. Numerous faculty and their students from a variety of institutions participated in the implementation study, for which the co-authors are grateful.

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