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BOARD # 187: Transforming Engineering Education: Evaluating the Impact of Integrated, System-Based Learning Studios on Student Engagement and Learning Outcomes

Mohammed A. Alrizqi, Cornell University

Mohammed is a PhD Candidate in Mechanical Engineering at Cornell University.

Dr. Allison Godwin, Cornell University

Allison Godwin, Ph.D. is the Dr. G. Stephen Irwin '67, '68 Professor in Engineering Education Research (Associate Professor) in the Robert Frederick Smith School of Chemical and Biomolecular Engineering at Cornell University. She is also the Associate Director of the Cornell NanoScale Science and Technology Facility and a McCormick Teaching Excellence Institute Research Fellow. Her research focuses on how identity, among other affective factors, influences diverse groups of students to choose engineering and persist in engineering. She also studies how different experiences within the practice and culture of engineering foster or hinder belonging, motivation, and identity development. Dr. Godwin graduated from Clemson University with a B.S. in Chemical Engineering and Ph.D. in Engineering and Science Education. Her research earned her a National Science Foundation CAREER Award focused on characterizing latent diversity, which includes diverse attitudes, mindsets, and approaches to learning to understand engineering students' identity development. She has won several awards for her research including the 2021 Chemical Engineering Education William H. Corcoran Award, 2022 American Educational Research Association Education in the Professions (Division I) 2021-2022 Outstanding Research Publication Award, and the 2023 AIChE Excellence in Engineering Education Research Award.

Junhyuk Kang, Cornell University
Dr. Beatriz Asfora, Cornell University

Transforming Engineering Education: Evaluating the Impact of Integrated, System-Based Learning Studios on Student Engagement and Learning Outcomes

Abstract

Engineering education frequently grapples with effectively integrating lectures and hands-on lab components across the curriculum. Despite their importance, many lab experiences remain narrowly focused on procedures rather than conceptual applications, limiting students' ability to translate theoretical knowledge into professional expertise. To address this gap, this study evaluates a novel system-based Learning Studio (LS) approach in a mechanical engineering department at a Northeastern R1 institution. Through semi-structured interviews with eight students, we examine whether repeated, hands-on encounters with real-world systems bolster students' confidence, engagement, and conceptual understanding. Findings indicate that LSs foster deeper comprehension of core mechanical concepts, encourage resilience, and clarify career goals, aligning strongly with Kolb's Experiential Learning Theory. These outcomes highlight the promise of iterative, collaborative, and cross-cutting LS to bridge theory and practice in engineering curricula.

Introduction

Historically, engineering has been rooted in practical applications and has strived to bridge the gap between theory and real-world implementation[1], [2]. Given the field's evolving nature, debates on the balance between theoretical depth and practical application remain ongoing [3]. In this context, theoretical knowledge can be used to design, build, and tackle complex problems. However, recent changes have shifted to place more importance on teaching the latest theoretical knowledge [4], [5]. This shift led to less emphasis on the role of labs in shaping future engineers. Yet, laboratories remain essential for bridging theory with hands-on application and problem-solving skills.

However, traditional engineering labs often prevent students from meeting these goals. First, they were designed to follow a set of patterns or standard procedures in a fixed amount of time. These restrictions limit the students' creative thinking and reduce the complexity of tasks to routine operations. Second, labs are prone to minimizing student engagement, as indicated by T. M. Louw [6], who found that students exhibited disengagement in laboratory experiments by dividing learning into two phases: memorized data collection followed by analysis and reporting. Such learning prevents students from actively engaging in experiments and drawing a link between theoretical ideas gained in other modules and how they were used in the lab. Lastly, most engineering laboratories were designed at the course level, which usually fails to link different aspects of curricula and inevitably undergo a process of becoming more procedural, rote, and homogeneous.

Such minimal exposure can impede the development of robust professional expertise among engineering graduates. Many of the largest industry customers complain that recent graduates from undergraduate engineering programs cannot engage in the collaborative design of complex engineering systems. This concern aligns with findings from studies such as Passow [7], who emphasized the importance of collaborative skills in effectively contributing to designing and developing multidisciplinary engineering systems, where technical competence and teamwork are inseparably intertwined.

In response, a mechanical engineering department at a research-intensive institution in the Northeastern United States implemented a novel approach to experiential learning: "Learning Studios (LS)." Introduced in the Fall of 2022, these studios integrate multiple courses around real-world engineering systems. By designing a collaborative, hands-on environment, the department aimed to foster continuous engagement, encourage iterative learning, and link theoretical concepts across disciplinary boundaries.

Literature Review

Introduction to the Problem of Disconnected Labs

The integration of real-world systems into engineering education and the growing emphasis on a multidisciplinary educational approach traces back to the National Academy of Engineering (NAE) "Engineer of 2020" report[8]. Subsequent work [9] has shown that many institutions reexamined their curricula to align with these recommendations, and resulting efforts have taken various forms across mechanical engineering (ME) departments nationwide. Despite these developments, many engineering labs remain largely procedural, limiting students' ability to connect theoretical knowledge across courses and hindering the formation of robust professional expertise. This core challenge drives the need for more holistic, system-focused lab experiences that span multiple disciplines and provide repeated exposure to real-world systems.

Existing Approaches to Hands-On Mechanical Engineering

One approach has been to emphasize project-based learning (PBL), by replacing existing laboratory experiments or supplementing courses that previously lacked a lab component. PBL is a dynamic, student-centered approach to education that emphasizes students' independence, critical thinking, goal-setting, teamwork, communication, and reflection in practical settings[10]. For example, one university [11] restructured its entire ME curriculum to include a new entry-level course centered around hands-on work with machines and electronics. In this course, students build and test a system throughout the semester, developing skills that will be applied in later years. However, PBL classes are typically linked to a single course, focusing on a single-semester project with limited opportunities for repeated or cross-course engagement.

Other institutions have adopted or expanded Vertically Integrated Projects (VIP) programs, a cross-year model for undergraduate research where students can earn academic credit by signing up for classes linked to a different VIP "team" [12], [13]. Although VIP integrates multiple class standings and can extend over more than one semester, it is often elective, restricting participation to those who opt in and aligning primarily with research labs.

Additionally, several students seek hands-on experience through competition teams (e.g., SAE, robotics), but these are often co-curricular and can be competitive or capacity-constrained, leaving some students unable to participate and preventing broad access. As a result, not all students benefit from the deeper engagement offered by such teams.

Gaps in Existing Approaches
While PBL, VIP, and competition teams each help bridge theory and practice, they often address only parts of the overall challenge. PBL tends to be course-specific and revolves around a single-semester project, VIP usually remains elective and closely tied to faculty research, and competition teams are extracurricular endeavors that can exclude students due to competitiveness or limited capacity. Consequently, many undergraduates do not receive sustained, curriculum-wide exposure to real-world systems that reinforce theoretical concepts across multiple courses or semesters.

Learning Studios Model

LSs respond to these gaps by integrating hands-on work with real-world systems into the core academic curriculum**,** rather than keeping them elective or confined to a single course. Unlike typical PBL classes, LS activities rely on fully operational systems (e.g., combustion engines) as the foundation for modular tasks designed to build skills iteratively across different ME courses. Additionally, the LS model focuses solely on educational objectives, ensuring that every student— rather than a select few like VIP —experiences repeated and progressively deeper engagement with the same engineering system.

This approach combines theoretical instruction with practical experimentation, fostering deeper engagement with engineering fundamentals. As illustrated in Figures 2 and 3, the LS model employs real-world systems like forklifts to reinforce key mechanical engineering concepts. By revisiting these systems across multiple courses, students continuously refine their understanding through hands-on tasks, structured discussions, and guided analysis.

A core feature of LSs is the expert–learner dynamic, where students at varying levels interact, rotating between learning and mentoring roles. Example systems—including drones, wind turbines, and satellites—serve as tangible anchors for mechanical engineering education. Each LS consists of four main components: (1) a fully operational engineering system, (2) advanced tools for system analysis, (3) simplified models for conceptual reinforcement, and (4) structured discovery modules.

By integrating LSs across multiple courses, students develop sustained engagement with engineering problems, fostering a sense of belonging and professional identity. This model encourages them to return to the same instructional space in different contexts, reinforcing their learning through repeated exposure. For further details on LS implementation, see Appendix 1.

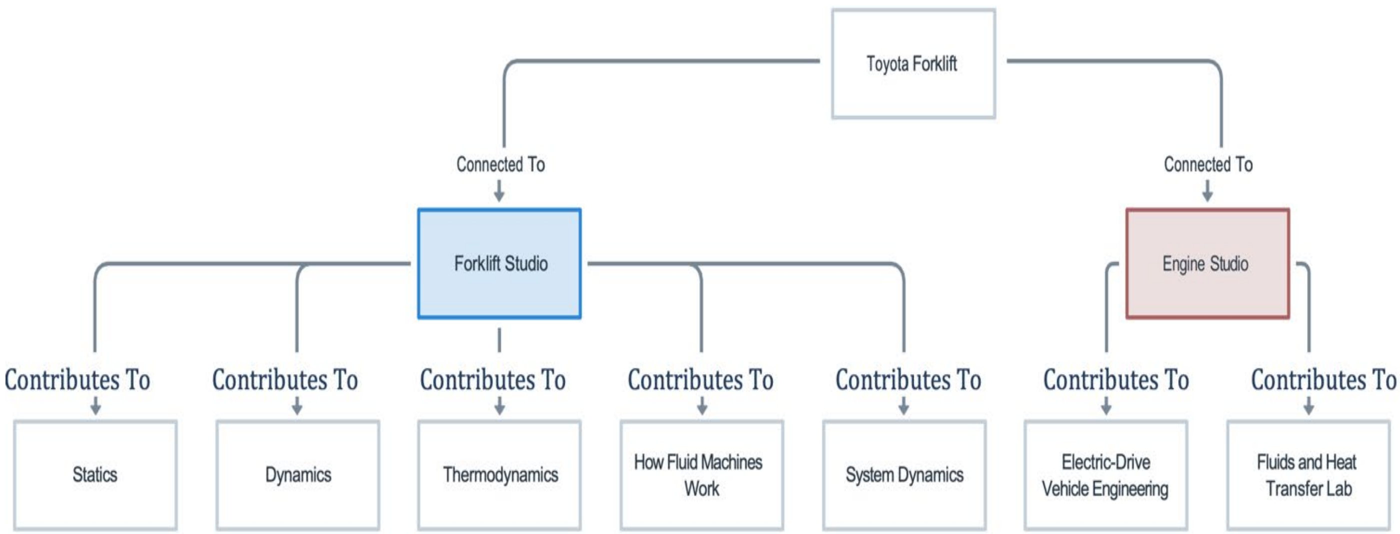

Figure 1. Flowchart of Learning Studio Integration – This diagram illustrates how a flagship system (e.g., a forklift) is deconstructed across multiple integrated ME courses.

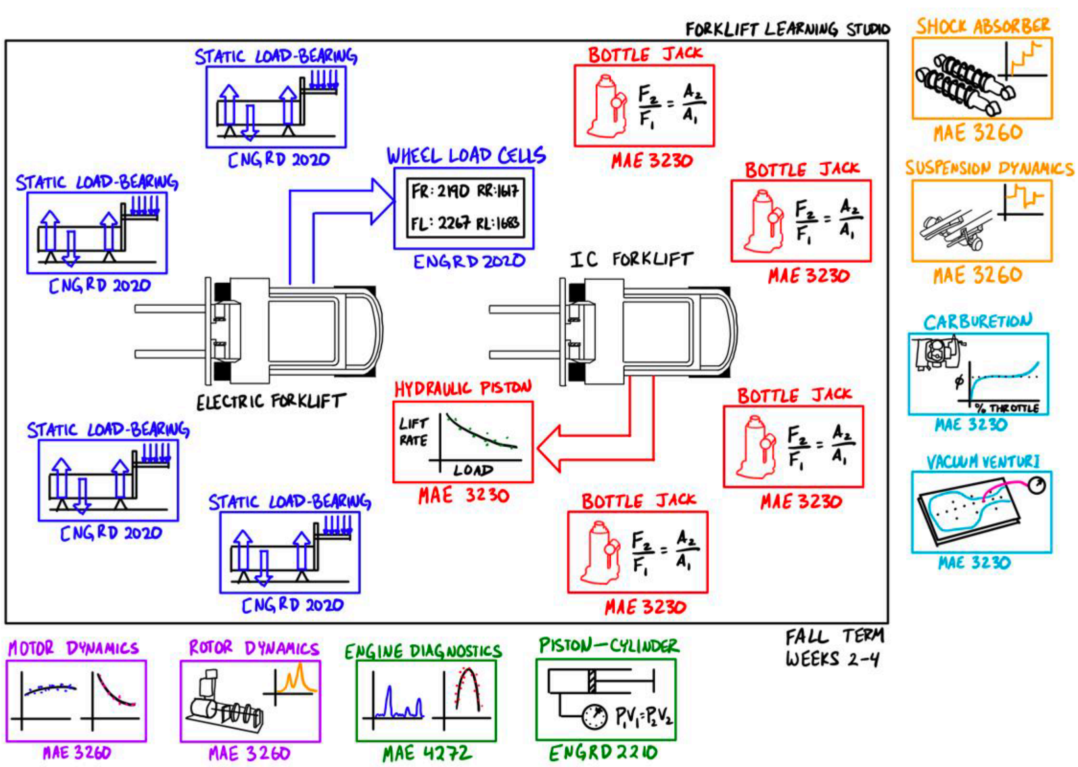

Figure 2. Forklift Learning Studio Activities. *This diagram shows how multiple engineering courses integrate within the Forklift Learning Studio. ENGRD 2020 (Statics) students measure tire loads using force plates, while MAE 3230 (Fluid Mechanics) students analyze hydraulic force amplification and pistons. Additional topics like motor dynamics and engine diagnostics align with relevant courses, providing hands-on learning that connects theoretical concepts across disciplines.*

Experiential Learning Theory Framework

Experiential learning is typified by Confucius' famous saying, "I hear and I forget; I see and I remember; I do and I understand" [14]. The concept of experiential learning posits that one can learn effectively by immersing oneself directly into real-world experiences. In other words, it is a way to learn by doing, and several studies revealed that experiential learning is an effective strategy that led to a significant improvement in students' skills and abilities [15], [16], [17]. One of the predominant experiential learning theories is Kolb's theory, which posits that for humans to learn effectively, they need to go through four main progressions: Concrete Experience (CE), Reflective Observation (RO), Abstract Conceptualization (AC), and Active Experimentation (AE). It illustrates that one first needs to have hands-on experience, called Concrete Experience, which forms the basis for the next stage, Reflective Observation. This reflection is then assimilated and distilled into the third stage, Abstract Conceptualization.

Kolb's stages lead to Active Experimentation, guiding the creation of new experiences. These four stages portray two dialectical modes: Grasping Experience— taking in or perceiving information—which appears in CE and AC; and Transforming Experience—processing and acting upon information—which appears in RO and AE [18]. Figure 3 [19] depicts the four stages. It is important to note that Kolb's model is not static. Instead, it is dynamic and cyclical because learning is not a one-time event. It is a continuous process where each stage feeds into the next, contributing to the development of skills and knowledge.

Several studies have applied experiential learning and Kolb's theory across different engineering fields. In 2012, researchers in a mechanical engineering department used Kolb's learning cycle to design different lab activities in the mechanics of materials course [20]. They surveyed 31 students to assess their preferred Kolb stage of learning. The results revealed that about 60% of the students prefer learning through the concrete experience stage, while the remaining 40% was distributed over the other three stages.

Another study by Li and colleagues [14] applied experiential learning theory to restructure the design project and workshops in a machine design elements course to improve the students' engagement and learning experiences. The findings showed a dramatic increase of 155% in the satisfaction rate with the course and 142% in the perceived teaching effectiveness, as reported by the students. These results demonstrated that experiential learning significantly improved student engagement and learning experiences.

In LS, Kolb's theory applies across the activities. For example, in the forklift studio, students disassemble and reassemble different components of the forklifts. This assignment allows them to investigate different mechanical properties and how they fit into larger systems. For example, in the fluid mechanics course, some students might interact directly with a Venturi vacuum system. In contrast, others might study the aerodynamic forces applied by a spinning-cylinder Flettner rotor. These assignments particularly integrate the stages of reflective observation and concrete experience. Students get hands-on experience with mechanical concepts by physically interacting with the forklift's components. By observing the effects of vacuum systems and aerodynamic forces, they can consider these concepts' theoretical underpinnings and practical applications.

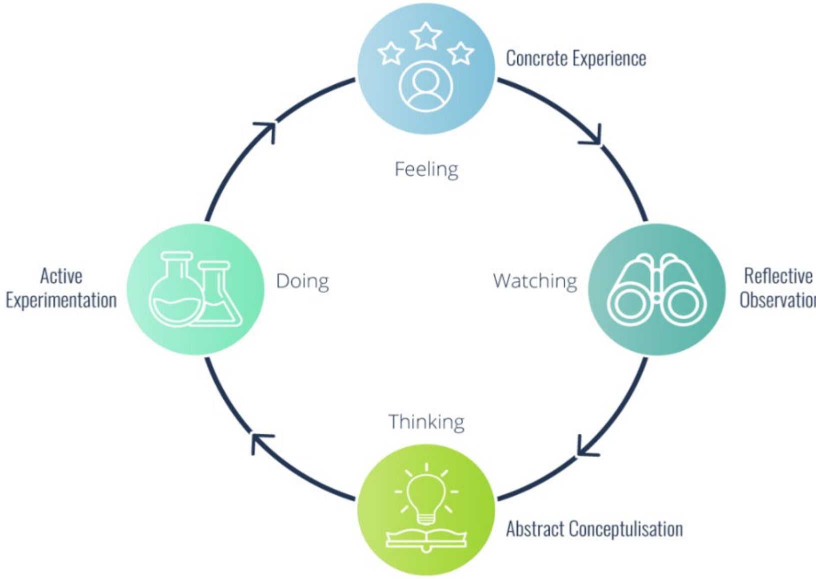

Figure 3. Kolb's Experiential Learning Cycle from [19]

Research Aim and Research Questions

Research Aim

This study examines the impact of LS on mechanical engineering students' experiences. Specifically, it investigates whether and how they enhance practical skills, confidence, and engagement compared to traditional laboratory settings. Additionally, the research explores how LS facilitates an experiential learning environment and aligns with Kolb's Experiential Learning Theory within mechanical engineering.

Research Questions:

1. What is the impact of LS on mechanical engineering students' practical skills, confidence, and engagement compared to traditional laboratory settings?

2. How do LS facilitate the stages of Kolb's Experiential Learning Theory among mechanical engineering students?

This research contributes to the academic community by investigating how state-of-the-art LSs, featuring real-world engineering systems, affect mechanical engineering students' experiences. By closely evaluating these innovative learning environments, the study provides valuable insights that can inform curriculum design and potentially enhance experiential learning practices in the mechanical engineering field specifically, and more broadly in engineering education.

Methodology

To answer the research questions and explore the impact of LS on mechanical engineering students' experiences, a qualitative interpretive research design was employed. This paradigm is appropriate when seeking to understand the subjective meanings individuals assign to their experiences [21]. The aim is to capture the depth of the students' interactions with the LS by focusing on their personal narratives.

Development of the Interview Protocol

The interview protocol was originally designed to understand student motivation in LS. The interview protocol leveraged Expectancy-Value-Cost (EVC) [22]. This theory posits that students' achievement choices are influenced by their expectations of success and the subjective value they assign to tasks, which includes intrinsic value, attainment value, utility value, and cost. While analyzing the data, the emphasis on how experiential learning influenced students emerged. Kolb's Experiential Learning Theory (ELT) emphasizes a cyclical process of learning involving experience, reflection, conceptualization, and experimentation, aligning closely with the students' narratives. Shifting to ELT enabled richer data interpretation and provided insights into how LS facilitated the experiential learning cycle. We note this change because while the protocol allowed for a rich investigation of the experiential learning cycle, it was not originally designed for this purpose, and some findings may be limited as a result.

The semi-structured interview protocol was designed based on a set of established qualitative research practices followed by several studies in the literature[22], [23], [24]. Semi-structured interviews are advantageous because they provide a balance between guided questions and the flexibility to explore emergent topics [23]. Open-ended questions encouraged participants to share detailed accounts of their LS experiences that included perceptions, emotions, and reflections.

The protocol included three parts: 1) the logistics information, such as the recording procedures and approximate interview duration; 2) the research overview, and 3) the core questions. The core questions contained two levels, primary questions and follow-up questions. The sequence of primary questions was progressive, leading from warm-up questions to establish rapport to deeper, emotionally weighted topics, and finished with lighter themes. Follow-up questions were utilized to provide specificity and additional detail of the primary questions to fully answer the research questions.

Participant Selection and Sampling Strategy

A purposive sampling method to select participants who had firsthand experience with LS [25]. The criteria for participant selection were:

- **Program Enrollment:** Students currently enrolled in the mechanical engineering program.
- **LS Engagement:** A different range of engagements with LS across studio types
- **Demographic Diversity:** Stratification by class standing (sophomore, junior, senior), gender, and race/ethnicity to ensure a diverse representation of perspectives.

Eight mechanical engineering students met these criteria and voluntarily agreed to participate. This sample size aligns with qualitative research norms, which allows for primary exploration of individual's lived experiences with a phenomenon [26]. Table 1 presents the demographics of the students and the LS they completed by the time of the interview. Participants selected their own pseudonyms; however, if they opted not to choose one, the researcher assigned a pseudonym.

Table 1: Participant Self-Reported Demographics and Learning Studio Completion

Participant	Class Standing	Gender	Race/Ethnicity
Sarah	Senior	Woman	Asian
Jasmine	Sophomore	Woman	Asian
Ryan	Senior	Man	White
Kwami	Senior	Man	African American
Zaher	Master	Man	African American
Kevin	Senior	Man	Hispanic, Latino/a/x, or Spanish origin
Charlle	Sophomore	Woman	Asian and Hispanic, Latino/a/x, or Spanish origin
Alexandra	Senior	Woman	White

Data Collection

Pilot testing was initially conducted on the interview protocol with one participant to ensure quality and improve the interview structure. The protocol was subsequently refined and modified based on feedback from this testing. Semi-structured interviews were then conducted with each participant, lasting approximately 45 minutes.

Verbal and non-verbal probing techniques were used as follow-up questions. Examples of verbal probing included repeating the participant's points, expressing interest through verbal agreements, or indicating awareness of certain information. Non-verbal probing involved silence, allowing participants to think aloud.

All interviews were conducted in private settings to ensure confidentiality and were audio-recorded with participant consent. The study received approval from the Institutional Review Board [23].

Data Analysis

An inductive thematic analysis was conducted following Braun and Clarke's [27] six-phase framework. This approach was chosen because it allows themes to emerge directly from the data, which is essential when exploring under-researched areas [25], [28].

1. **Familiarization:**
   One team member transcribed all interviews verbatim with the help of an AI tool. Team members then read the transcripts multiple times to immerse themselves in the data.
2. **Generating Initial Codes:**
   Team members independently coded the data using MAXQDA software. Open coding was employed to avoid imposing preconceived categories.
3. **Searching for Themes:**
   Codes were collated into potential themes based on patterns observed across participants.
4. **Reviewing Themes:**
   Themes were reviewed and refined through team discussions, ensuring they accurately reflected the data and were distinct from one another.

5. **Defining and Naming Themes:**
   Clear definitions and names were assigned to each theme to capture their essence.
6. **Producing the Report:**
   Themes were organized into a coherent narrative addressing the research question.

Mitigating Biases and Ensuring Credibility
The study employed several methodological strategies to enhance credibility and mitigate potential biases. These included investigator coding to consensus efforts and maintaining an audit trail. Investigator consensus involves independent analysis by more than one researcher with discussions of interpretation and claims made across the team until consensus is reach [29]. An audit trail was also maintained, with detailed records of data collection and analysis decisions to ensure transparency and replicability.

Results

Overview of Themes
The findings highlight three key themes where the LS positively impacted students' experiences: (1) Enhanced Learning, (2) Confidence and Resilience, and (3) Refining & Expanding Career Goals.

Theme 1: Enhanced Learning
Participants reported enhanced learning, a deeper understanding of mechanical engineering concepts, and increased exposure to real-world engineering systems. For example, Sarah found the LS helpful for visualizing and grasping concepts that were difficult to learn solely from lectures and textbooks. She mentioned:

> They definitely helped me understand… visualize how the airflow… especially for Schluter imaging… it's like, as you move, there's airflow that you get to see, like… in our daily we don't really get to see what they are.

Theme 2: Confidence and Resilience
It was evident that LS helped students build confidence in their abilities, overcome feelings of inadequacy, and discover an intrinsic enjoyment of the learning process. This satisfaction led them to engage deeply with course material and develop a sense of competence in mechanical engineering. Moreover, this growth helped improve students' overall learning mindset. The confidence they built throughout the LS enabled them to face and overcome both academic and personal challenges, thus contributing to their personal development and resilience.

Theme 3: Refining & Expanding Career Goals.
The findings also highlight how the LS served as a catalyst, enabling students to refine their career aspirations by exploring interests more broadly and clarifying likes and dislikes. This theme emerged most prominently in the Reflective Observation stage, as participants applied theoretical lessons to real career questions.

Mapping Experiences to ELT Stages
Concrete Experience (CE) and Reflective Observation (RO)
Several participants frequently demonstrated their involvement in integrating hands-on activities with reflective observation activities. This was illustrated by their interactions with different

complex mechanical systems, such as exploring the airfoil mechanisms. For example, one of the senior standing students, Ryan, reflected on a hands-on engine project. He talked about the significant understanding gained from physically tearing down the engine in the forklift studios and stated:

> I really liked that… to tear down an engine and look at all the parts. Definitely helped me understand how engine worked a lot better, which I think, if I would have gotten something else and did not ever look at an engine, I think that would have been a bit of a failing on the mechanical engineering department.

Another interviewee, Kwami, mentioned his engagement in practical activities in the Motion Studio. Kwami discussed how he directly applied classroom concepts to real-world flight dynamics by experimenting with gliders:

> For flight dynamics, we got to throw a wide range of different gliders to in a motion capture studio to exhibit behavior that we have been learning about in class. So, whether it is figuring out how to get a glider to stall and then using the data to try and see if we can compute a lot of these variables that we have been talking about in class, like the lift coefficient, the drag coefficient.

Lastly, Charlle shared insights into how it was interesting to see the drones in the Motion Studio. Specifically, she discussed her experiences with flight controls and mentioned,

> I guess learning about how drones work, stuff like flight controls, even just simple things, like how to build them, how to wire them. I mean, you see drones everywhere, or just the, you know, things that have motors. So, it's cool to be able to see that.

Such experiences closely align with Theme 1 (Enhanced Learning) and Theme 2 (Confidence and Resilience), as participants not only engaged in hands-on tasks but also developed self-efficacy through repeated, concrete successes.

Reflective Observation (RO) and Abstract Conceptualization (AC)

Students' reflections lead to deeper conceptual understanding, as they begin to synthesize their observations into coherent theoretical frameworks. This synthesis is clearly articulated by a Kevin reflecting on the practical application of fluid dynamics:

> I think seeing it in like a real-world application made it something more digestible for me. Because, you know, reading about… Navier-Stokes equation is boring, whereas if you see how, it applies to a real thing, it is objectively more interesting.

Moreover, Jasmine, a sophomore student, highlighted how the LS provided clarity about mechanical engineering, which allowed her to better understand their interests and potential areas of focus. They said:

> I think the learning studio helped me experience more about mechanical engineering and helped me get a feel for what Mechanical Engineering would be like. And that is a lot clearer… whereas it would have been more difficult for me to outline that.

These reflections tie to Theme 1 (students deepen their learning) and Theme 3 (refining career goals), showing how reflection can shape academic and professional aspirations.

Abstract Conceptualization (AC) and Active Experimentation (AE)
The transition from conceptualizing to experimenting is a dynamic process where students apply their developed theories to real-world challenges. A poignant example is given by Zaher who engaged in the analysis and scripting of engine timings using MATLAB:

> I think courses that have a Learning Studio component, you get to see… the difference between real-world and theoretical like results. So like for the forklift dynamometer, we had to think about the timing of the engine. We had to look at all those different signals, and we had to write a whole MATLAB script on how to get an Otto cycle out of all of that data.

Ryan also reflected on the depth of engineering knowledge applied in professional settings, comparing academic and workplace applications:

> I think sometimes… depends on what engineering you go into, not like discipline per se, but like where you find yourself… sometimes we go into more depth than you actually would if you were working with certain people... So if you were doing a startup per se, some of the Learning Studio stuff might go into more depth that you would do. But obviously, if you are one of hundreds or dozens of engineers working on an engine, then it might be a more similar or deeper level of depth there like optimizing for every spare 10th of a percent in an engine efficiency.

The instances reinforce Themes 1, 2, and 3—students learn hands-on technical skills (Theme 1), grow confident in applying theoretical knowledge (Theme 2), and even begin to discern how their skill depth aligns with future career directions (Theme 3).

Discussion and Implications

LS reduce student anxiety over failing with real-world systems and applications
Our data suggest that LS have significantly enhanced students' educational experiences by fostering a hands-on environment where they can iteratively design and analyze real-world standards of engineering design and practice and make constructive mistakes that advance students' engineering proficiency. One major obstacle inhibiting students from tackling these overwhelming tasks is the students' anxieties associated with making mistakes or failing the assigned task [30], [31]. However, identifying the failure modes of a system is one of the main underlying principles of engineering design, so students must become accustomed to the practice of failing and learning from those failures. From the interviewee's responses, it is evident that LS helped students build confidence in their abilities, overcome feelings of inadequacy, and find intrinsic satisfaction and enjoyment in the learning process. This led them to engage deeply with the material and develop a sense of competence in mechanical engineering. The observed expression of students' increased competency in engineering design is also consistent from Bandura's Self-Efficacy Theory [32], which emphasized the role of mastery experiences in building confidence and competency.

Kevin, a senior student, reflected on how participating in the LS helped him overcome self-doubt and build confidence in his engineering abilities. He shared, “I was just generally not as intelligent or experienced or naturally good at engineering as they were, so I think just the general experience itself allowed me to work through my own issues.” This quote illustrated how the collaborative and hands-on nature of the LS provided Kevin with opportunities to engage deeply with the material, practice skills, and realize his competence.

Another student, Sarah, reflected on embracing the learning process despite initial worries: “I was so worried that I didn't know much about it... it's okay, like, if I don't know fully, just like as I learn, I get to learn on my own.” This quote suggests that students confronted and overcame academic and personal challenges, building resilience and adaptability through their LS experiences.

The attenuation of student anxiety to acceptable levels and consequent improved appreciation for the engineering design process could be attributed to the nature of the collaborative projects in the LS, which required students to engage in peer projects, where they explained concepts to one another. While Kolb’s experiential learning theory does not explicitly discuss the need for peer-peer discourse or collaborative learning for the student to grasp and transform knowledge, shared experiences are a substantial learning experience that is essential for knowledge creation by the student [33]. This not only reinforced their understanding but also enhanced their communication skills and confidence.

This aspect of peer teaching in LS resonates with Vygotsky’s Social Development Theory [34], which emphasizes that cognitive development is significantly enhanced through social interaction. By explaining concepts to peers, students operate within their Zone of Proximal Development, which can facilitate deeper learning. Additionally, these findings align with educational theories such as Bandura's concept of self-efficacy [35], which emphasizes the importance of belief in one's capabilities. The LS provided mastery experiences and social modeling opportunities that enhanced students' confidence and motivation.

However, it is important to note that while LS fostered a supportive environment for most, it is essential to recognize that collaborative settings can also lead to social loafing or reliance on more active group members. Future implementations should consider strategies to ensure equitable participation.

Students’ experiences and alignment with ELT

This study's findings from the LS highlight significant engagement in the Concrete Experience (CE) and Reflective Observation (RO) stages of the ELT. The responses demonstrated that LS impacted students across Kolb’s Experiential Learning Theory stages. Participants engaged in concrete experiences by interacting with physical systems, reflected on their learning processes, conceptualized theoretical knowledge, and, in some cases, actively experimented with design and application.

This dynamic process underscores the interconnectedness of Kolb’s Experiential Learning Theory stages and demonstrates how they are integrated into the LS. They are crucial for foundational experiences and reflections, aligned with previous literature emphasizing the importance of hands-on and reflective learning in engineering education. LS establishes a critical base for deeper learning processes by effectively engaging students in these initial stages.

However, the findings also reveal a gap in explicit evidence for Active Experimentation (AE) stages. This gap may be attributed to the nature of the EVC-based interview questions, which perhaps did not sufficiently probe into areas encouraging students to articulate their experimental actions. Limitations may also exist due to variability in participants' experiences and the depth of engagement with LS.

Implications for Curriculum Design and Engineering Education

The implementation of LS has positively impacted students' practical skills, confidence, engagement, and ability to connect theoretical concepts with real-world applications. These outcomes support the integration of LS into mechanical engineering curricula to effectively bridge the gap between theory and practice.

LS offered robust experiential learning opportunities by engaging students with operational engineering systems like forklifts, wind turbines, and motion capture systems. This engagement enhances students' ability to apply theoretical knowledge practically, deepens their understanding of complex concepts through direct observation, and fosters intrinsic motivation by increasing interest and engagement.

Moreover, the collaborative environment within LS allowed students to benefit from peer learning to enhance their understanding and communication skills. It also supported building self-efficacy and developing resilience through mastery experiences and social modeling in a supportive setting.

The interdisciplinary nature of LS aided in breaking down traditional curricular silos, enhancing integration across different domains. By organizing learning around systems spanning multiple courses and revisiting instructional spaces in various contexts, students experience reinforced learning and a deeper understanding over time. This structure will equip the students when they graduate to solve complex systems that incorporate multiple principles.

Based on our results of the efficacy of this approach, curriculum designers could consider developing system-oriented learning spaces integrating complex engineering systems across multiple courses. Courses should be structured to guide students intentionally through all ELT stages, balancing hands-on experience, reflection, conceptualization, and experimentation. Encouraging active experimentation and reflective practices can further enhance learning outcomes. Adopting LS can transform engineering education by enhancing student engagement and retention, aligning education with industry needs, and fostering a continuous improvement mindset.

It is worth mentioning that while the benefits are clear, Implementing LS presents challenges. For instance, it is resource-intensive, requiring substantial equipment, space, and faculty training investment. Additionally, it necessitates a shift to non-traditional assessments to effectively measure targeted learning outcomes. Lastly, scalability and classroom size pose challenges, as adapting LS to larger classes or different institutional settings may require innovative solutions to maintain effectiveness.

Limitations and Future Directions

One of the limitations of this study involves the methodological constraints of using EVC-based interviews to analyze engagement across the ELT stages. While effective in capturing Concrete Experience, Reflective Observation, and Abstract Conceptualization elements, these interviews may not adequately capture data relevant to Active Experimentation. This limitation could affect the comprehensiveness of the findings, particularly in understanding how students transition from experiential learning to abstract reasoning and practical application. In addition, a limited number of participants may not capture different variables that influence the engagement with the ELT stages, which could reduce a full understanding of the range of student experiences and transferability of LS to other similar contexts.

Future research should address these methodological limitations by incorporating a broader range of qualitative and quantitative data collection methods. Techniques such as direct observation, diaries, or digital trace data could provide deeper insights into how students engage with all stages of the ELT cycle, especially AC and AE. Additionally, longitudinal studies could examine the long-term impacts of LS on student outcomes, providing a more detailed understanding of how experiential learning influences career readiness and professional development in engineering fields. Expanding the scope of research to include diverse educational settings and comparing the impacts across different engineering disciplines could also help tailor experiential learning approaches to specific educational outcomes and industry requirements.

Conclusion

This study demonstrates that LSs positively impact mechanical engineering students' practical skills, confidence, and engagement. By aligning educational experiences with Kolb's Experiential Learning Theory, students progressed through CE, RO, AC, and, to a lesser extent, AE. The themes of Enhanced Learning, Confidence and Resilience, and Refining & Expanding Career Goals emerged consistently within this cycle. The LSs provided hands-on experiences real-world engineering systems, fostering deeper understanding and professional identity development.

Students reported increased confidence, resilience, and clarity in career aspirations. These findings underscore the value of integrating system-based, collaborative learning environments into engineering curricula in order to bridge theory and practice more effectively. Overall, this work highlights the promise of LS in enhancing student engagement, motivation, and career readiness—advancing the broader goal of training engineers who can thrive in complex, real-world contexts.

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Appendix: Learning Studios (LS) Overview

This appendix provides an overview of the LS model, including studio types, physical layouts, student interactions, and example activities.

LS Element	Description
Studio Types	**1. Forklift Studio** Focuses on real-world mechanical systems, enabling students to apply concepts from Statics, Dynamics, and System Dynamics. **2. Wind Turbine & Engine Studios** Allows exploration of Fluid Mechanics, Thermodynamics, and Heat Transfer through wind tunnel and engine experiments. **3. Motion Studio** Emphasizes motion capture, 3D tracking, and flight dynamics for courses such as System Dynamics and Flight Vehicle Dynamics.
Integration Across Courses	Each studio connects multiple courses, helping students move fluidly between learner and expert roles. For example, seniors might mentor juniors in projects linking Statics, Fluid Mechanics, System Dynamics, Dynamics, Thermodynamics, Heat Transfer, and Flight Vehicle Dynamics. This cross-level engagement reinforces theoretical principles with hands-on practice and supports continuous skill development.
Engagement Modes	- **Fully functional system applications** (e.g., working forklift, wind turbines) - **Modern instrumentation and characterization** (e.g., sensors, data acquisition tools) - **Model systems** (simplified setups for deep investigation of specific principles) - **Guided discovery modules** (structured yet flexible tasks promoting self-directed, hands-on learning)
Physical Layout	- **Forklift Studio:** 8 tables surrounding a central forklift for mechanical analysis and hands-on engine work. - **Wind Turbine & Engine Studios:** Wind tunnels, internal combustion engines, and dynamometers for fluid and thermal system experiments. - **Motion Studio:** 14 infrared cameras and Optitrack Motive Software for 3D motion tracking, plus available computers and workbenches for drone/quadrotor development.
Student Interactions	Students work in groups of 2–5, depending on the activity, fostering dynamic peer interactions. This mentorship model promotes peer learning, leadership development, and real-world problem-solving skills.

Equipment	- Forklift engines - Vacuum venturi fixtures - Axial fans - Internal combustion engines - Wind tunnels - Dynamometers - Motion capture systems - Drones, CubeSats - Various sensors for real-time data collection
Learning Outcomes	- **Enhanced engagement:** Students develop stronger motivation and engagement through different tasks. - **Interdisciplinary understanding:** Courses are integrated to show how theories intersect in real-world applications. - **Deeper conceptual grasp:** Reinforces classroom theory with hands-on experimentation and iterative learning cycles. - **Continuity:** Students revisit components (e.g., engines, wind turbines) in multiple courses, solidifying long-term retention.
Examples of Activities	- **Forklift Combustion Engine Analysis:** A thermal analysis of the combustion engine in a forklift. Student groups take their learned experiences from thermodynamics, fluid mechanics, and heat transfer coursework to generate thermodynamic curves and internalize how each component or task of the engine (*e.g.* ignition order, fluid transport vessels, in-line 4-cylinder design, etc.) is intentionally designed. **- Forklift Engine Take-Apart and Reassembly:** An optional activity where groups of three to four students take apart and reassemble the Toyota Forklift's engine. The activity exposes students to various power transmission parts (*e.g.* camshafts, geartrains, fuel injectors, gas pistons and cylinders, etc.), gives students a real and spatial understanding of how an engine is assembled, and explains each part's design rationale. - **Fluid mechanical relations to forklift subsystems:** Various group interactive kits that fixate on a particular application of fluid mechanics into the forklift are provided to the students. Examples include vacuum venturi kits to demonstrate the underlying theory behind a carburetor and hydraulic jack to demonstrate how hydrostatic pressure is utilized in a forklift's mast and hydraulic system for force amplification. **- Motion Tracking of a Simple Pendulum:** Students are divided into groups of 3-4 to discuss and reason through modeling assumptions for the system, as well as the impact of real-world systems that may not meet those assumptions. They then collect 3D data using the motion capture system, and compare it with their theoretical models and simulations, gaining insights into engineering concepts such as approximations in models, trade-off in design choices and system performance and limitations.