Do Engineering Students Still Value Physical CAD Education? A Review Perspective on Relevance in The Digital Era

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ABSTRACT

The rapid transition to online and blended learning in the field of engineering education has prompted significant enquiries regarding the significance of the ongoing traditional Computer-Aided-Design (CAD) instruction. This review assimilates findings from service, randomised controlled trials, mixed-methods studies and systematic reviews to assess students' perceptions, learning outcomes and skill acquisition across various delivery modes. Research shows that online CAD courses are flexible and have similar academic performance to in person classes, but students always prefer physical laboratories or studios because they provide immediate help, opportunities to work together and opportunities to improve psychomotor skills. Meta-analysis of virtual labs and immersive technologies (AR/VR/XR) shows that they can greatly improve understanding of concepts and motivations (Hedges' g ≈ 0.68). However, it is stressed that these technologies should be used in conjunction with, not instead of, hands-on experiences. Studies on Project-Based-Learning (PBL) show that when physical team work environments work well together with digital tools, students learn more technical and soft skills. Integrity and assessment challenges remain in remote environments, although adaptive strategies help to reduce risks. Overall, the results point to a hybrid model as the best option. Physical CAD education is still important and relevant, not as a legacy practice but as a strategic base for social learning and real-time design. Online modules that expand access and depth of preparation should be added. This mixed approach is in line with the goals of Industry 4.0, ensuring that future engineers are both digitally fluent and have hands-on experience.

Keywords: Computer-Aided Design (CAD) Education, Online vs. Face-to-Face Learning, Students' Perception and Engagement, Blended Learning in Engineering, Psychomotor Skills and Hands-on Training, Industry 4.0 and Digital Manufacturing.

INTRODUCTION

The swift proliferation of digital delivery in higher education has rekindled a fundamental inquiry for engineering programs: Do the students continue to appreciate physical in person CAD instruction in an age of omnipresent online resources? Evidence from engineering and STEM education indicates that modality preferences are complex although online participation and blended formats have significantly increased since the pandemic. Students perceptions of support interaction and hands on skill development frequently vary across modalities (Bright & Vogler, 2024; Sun, 2023). Mixed-methods and comparative studies indicate a transition from a predominant preference for in- person classes to a more balanced distribution, with face to face instruction appreciated for human interaction and immediate instructional assistance and online learning valued for its flexibility and accessibility (ASEE, 2023; Asgari et al., 2021). Meta-analysis indicate that a well-structured blended learning can yield superior achievement compared to conventional instruction underscoring the potential for hybrid CAD curricula that deliberately combine online advantages with practical application (Bernard et al., 2014; Kazui & Kurtoğlu, 2022).

CAD classes are different from other types of classes because they are very interactive, the teacher and the student need to be at close proximity to each other at the workstation and they often depend on quick feedback loops for modelling intent and error recovery. Research on CAD instruction during COVID-19 indicated that the first-year engineering students generally assessed online CAD delivery as equivalent to our superior to traditional formats. However, they experienced stress and challenges in posing questions highlighting that instructional immediacy and informal troubleshooting are more difficult to replicate in a virtual environment virtually (Dagman & Wärmefjord, 2022; Berselli et al., 2020). Learning designs are important, not just how they are perceived. Project- based-learning (PBL) that uses real world problems and integrated CAD/CAE workflows has consistently improved both technical and soft skills (communication and collaboration). This shows how important physical studios and team spaces are for fostering collocated iteration critique and tacit know how (Webster, 2017; Ramírez de Dampierre et al., 2024). Systematic reviews of project-based-learning in engineering emphasize the necessity for comprehensive assessment and CDIO aligned environments, often physical that facilitate the conceived, design, implement and operate cycles integral to professional CAD practice (Ramírez de Dampierre et al., 2024).

One of the core reasons to keep teaching CAD in person is that studio service laboratories help people learn psychomotor skills, like using devices peripherals and fabrication, communal sense-making and situated problem-solving that are difficult to fully virtualize. Recent synthesis of online laboratories indicate that simulation virtual and remote lab methodologies enhanced accessibility and conceptual comprehension yet seldom serve as complete substitutes for practical experience rather they are most effective as supplementary components within integrated ecosystems (Tomeo-Reyes et al., 2025; Li & Liang, 2024). Meta-analytic evidence shows that virtual labs can significantly boost motivation and engagement and they can also improve performance however the evidence strongly suggests that virtual labs should be used in addition to physical experiences not instead of them (Li et al., 2024). This is in line with CAD studios that combine screen-based modelling peripheral devices like 3D mouse and tablets and nearby making facilities. Moreover, gamified virtual labs and interactive tutorials can enhance confidence and improved test costs demonstrating that online elements can effectively prepare students for intensive in person sessions (Wu et al., 2024).

Lastly, the industry 4.0 imperative changes CAD education to focus on integrated digital imperative changes CAD education to focus on integrated digital manufacturing and CAD/CAE ecosystems. ASME and Autodesk have both said that there is a skill gap and that school should include digital twins, simulation and sustainability in their curricula, along with hands-on projects and industry involvement. These are all suggestions that depend on both physical and digital learning spaces (ASME, 2024; Autodesk, 2024). Systematic reviews of immersive technologies (VR/AR/XR) demonstrate substantial positive impacts on comprehension and engagement in higher education, and the whole potential to reduce barriers for novice CAD users. However, even in this context, the most effective designs integrate immersive experiences within broader hybrid frameworks the encompass tangible artefacts, team critic, and actual equipment (Kumar & Gorai, 2025; Huang & Tseng, 2025; Talha et al., 2025). Even though online and hybrid learning models are becoming more popular in engineering education, there isn't much agreement on whether these methods do a good job of replicating the hands-on and group work that is a big part of traditional CAD instruction. The move to digital platform makes people worry about learning new skills, staying interested, and keeping the hands-on skills that are important for professional practice.

METHODS

2.1 Survey Based Quantitative Approaches

Numerous studies examining the efficacy and significance of online versus traditional CAD education have utilised structured service and questionnaires to assess student perceptions and educational outcomes. While COVID-19 was ongoing, Dagman and Wärmefjord (2022) put forward an evidence-based use study using student service to measure levels of stress comma perceived learning efficacy and satisfaction of online CAD courses. To evaluate and compare the goal clarity, quality of teaching, assessment techniques and more in person and an online format, Sun, (2023) used Course Experience Question (CEQ) and Online Course Experienced Question (OCEQ). Often use Likert-scale items to measure attitudes regarding engagement, interaction and technical support (Bright & Vogler, 2024). Extensive comparative studies such as Leopard (2001) and Zohaib et al. (2023) employed the use of descriptive statistics, the T- test, and regression analysis to identify significant differences in student performance and student preference between modalities.

2.2 Experimental and Mixed-Methods Designs

In addition to surveys, numerous researchers have employed quasi experimental and randomize control designs to evaluate the differences in learning outcomes between online and traditional CAD instruction. For instance, Peng et al. (2020) utilised a pre-test/ post-test design to evaluate the effects of student-centred pedagogical methods in CAD courses, assessing both technical competencies and attitudes towards lifelong learning. Arias et al. (2018) and Cheung et al. (2023) employed random assignment to mitigate self-reflection bias in their comparison of online and face-to-face sections, examining exam scores an improvement metrics. Mixed-methods studies, like Bright and Vogler (2024), combined quantitative performance data with qualitative interviews to look into why students think physical labs are better for learning hands on skills. These designs frequently triangulate data sources and surveys, performance metrics and interviews to augment validity (Ediyanto et al., 2025).

2.3 Qualitative and Systematic Review Approaches

Qualitative research has been essential in revealing the intricate experiences of CAD learners. Gelmez and Arkan (2022) utilised the Activity-Centred Analysis and Design (ACAD) Framework to present in online CAD learning. Phenomenographic interviews, utilised by Brink et al. (2022), investigated educator's intentions and students' experiences in teaching "through CAD" as opposed to "to use CAD". Systematic reviews, like Murillo Manrique and Sánchez Ayte (2025), used PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to put together new ideas in CAD education, like virtual reality and cloud-based platforms, and how they affect physical relevance. This reviews frequently integrate meta analytic methodologies with thematic coding to discern trends in hybrid learning and the persistent significance of physical laboratories for the cultivation of psychomotor skills skills (Abualadas & Xu, 2022; Tomeo-Reyes et al., 2025).

RESULTS AND DISCUSSION

3.1 Students' Perception and Satisfaction Across Modalities

In many different situations, students say they are happier with face-to face instruction because they are able to get help right away whereby they can see dear teacher, and the teaching signals are clearer. At the same time, they also value the flexibility of online modes. Digital tools are very efficient, but recent studies based on evidence show that students' "satisfaction" is often based on many factors, such as how easy it is to access the tools and their technical mastery.

3.1.1 The Conflict Between Effectiveness and Stress

Dagman and Wärmefjord (2022) found that students were satisfied with online CAD courses that were equal to or better than offline ones and likely enjoyed the flexibility. However, all this was happening under a background of heightened their psychological pressure. Findings from the survey data indicate that the unavailability of timely face-to-face instructor feedback which was part of the conventional 'over-the- shoulder' CAD coaching, leads to high levels of stress and a sense of difficulty challenging complex technical questions online.

3.1.2 Quality of Experience: In-Person vs. Online

Sun (2023) used Course Experience Questionnaire (CEQ) and the online version (OCEQ) to measure the differences. Their findings reveal that while online learning leads to more flexibility of location and easier access to learning materials, in many areas, such as teaching quality and clarity of goals, it does not match face-to-face learning.

- Skill Acquisition: Students believed that face-to-face formats were the better option for practical technical skill acquisition.
- Social Competency: The lack of peer-to-peer touch in digital environments resulted in lower scores in social competence, particularly in situations of collaboration problems.

3.1.3 Variables for Engagement and Technical Support

Bright and Vogler (2024) investigated the roles of technical assistance and interactive engagement in more depth. Using the Likert scale items, the researchers concluded that student attitudes were affected by reliability. As noted by the research, even a strong CAD curriculum cannot please students if technical defect (software lag, installation issues) is not resolved. Additionally, that support structure functions more efficiently in a usual lab environment.

3.1.4 Differences in Performance and Preferences for Different Modes

Leopard (2001) and Zohaib et al. (2023) did much comparative research that gives these ideas their statistical weight. These studies used t-tests and regression analysis to find:

- The Foundation Effect (Leopard, 2001): Regression analysis revealed that fundamental proficiency in 2D drafting serves as a significant predictor of success in 3D modelling ($p<0.05$). The research showed that learners with previous physical drafting experience received, on average, 15% higher marks on complicated assembly tasks than those who started with 3D only. The more proficient you are with basic CAD tools like AutoCAD, the more favourable your opinion will become about the advanced tools like REVIT. This indicates that students proficient in basic drafting typically introduced via physically are rigorously structured manual techniques exhibit enhanced confidence and diminished resistance when transitioning to intricate digital formats.
- Performance Gaps (Zohaib et al.,2023): Zohaib used T-test to compare final design scores and found that students in hybrid a traditional format did 12.4% better on “design-from-scratch test”. On the other hand, students who only worked online who are more likely to use trial-and-error modelling, which led to 22% more geometric mistakes in their final submission even though they finished faster. This indicates that the digital-only modality may foster a copy paste all trial-and-error approach instead of profound design thinking.

3.2 Learning Outcomes and Achievement

In the assessment of effective CAD education using quantitative metrics such as exam averages and pre-test or post-test improvements, the literature offers a complex equivalency that frequently depends on external factors

3.2.1 The Class Size Variable in Face-to-Face (F2F) Success

Although numerous studies indicate no overall disparity, detailed data reveals that physical presence confers in smaller cohorts a substantial advantage in smaller cohorts. Cheung et al. (2023) conducted A randomised study with 725 students enrolled in seven courses, revealing that although synchronous online and face-to-face (F2F) outcomes were statistically comparable on a macro level, a “Class Size Effect” was observed:

- F2F superiority: In classes with 25 or fewer students, F2F groups did much better on the final exam than their online counterparts ($p<0.05$).
- Diminishing Returns: The performance gap got smaller as class sizes got bigger. This suggests that the main benefit of physical CAD education is the personalized, high frequency feedback that is only possible in small lab settings.

3.2.2 Standardized vs. Instructor Specific Metrics

Arias et al. (2018) delineate a difference between general knowledge and profound, instructor-led expertise. In randomized assignment model:

- Instructor-Specific Gains: The F2F students had a 6-8% higher improvement on post-test items that the instructor made specifically to test complex problem-solving.
- Standardized Parity: there was no major difference in the results of standardized, multiple choice questions. This means that online CAD modules are good for teaching "where to click" (standardized knowledge) but face-to-face F2F teaching is better for teaching "why to design" (complex synthesis).

3.2.3 The COVID-19 "Lab" Proxy and Academic Integrity

The pandemic forced in person lab courses to shift to remote formats. It was a unique "stress test" for CAD education. According to Onyeaka et al. (2024), although raw performance gains (final grades) did not differ statistically between the face-to-face and remote cohorts, there was a worrying trend regarding academic integrity.

- Plagiarism Metrics: Analyses on Turnitin and CAD metadata revealed that online groups were much more "similar" than face to face groups.
- The Supervision Gap: The absence of proctoring in digital CAD exams, i.e. one-on-one supervision of students, has led to a 15-20% increase in flagged submissions, which raises the question of whether "equivalent" online grades truly indicate that students have the same level of mastery, or simply that they are working together more often without permission.

Data show that CAD education currently represents "Surface Equivalency". Though the technical content necessary for the students in passing the mainstream test can be taught via digital platforms, deep-level synthesis and academic rigour cannot be duplicated in a small-scale lab. For engineering students to feel the benefits of physical CAD education, the syllabus must make the most of these small group engagements. Teachers in physical classrooms can inject elements into learning that automated digital teaching modules are not able to do as of now.

3.3 Engagement, Interaction and Teamwork

One of the key arguments in the conflict of "digital" versus "physical" is the ability of an online CAD environment to facilitate the collaborative energy of a physical design studio. Examining the evidence, students can learn the tools on their own but despite this, their professional development mainly engagement and teamwork suffer in isolation.

3.3.1 The "Zoom Fatigue" and Focus Barrier

The abrupt shift to remote learning yielded a substantial data set regarding student endurance. Asgari et al. (2021) discover that the abrupt transition to online engineering education resulted in a considerable engagement deficit:

- Fatigue Levels: More than half of the students said they were "Zoom fatigued" which directly affected how much they participated in CAD demonstrations.
- Concerns about Teamwork: about 42% of students said they were worried about their ability to learn how to work well with others in a virtual setting. They said that digital breakout rooms felt "forced" compared to the natural collaboration of a physical lab.

3.3.2 Instructional Immediacy and Trouble Shooting

The speed of trouble shooting in CAD specific set up affects student confidence. Dagman and Wärmefjord (2022) point out that the open instructor's "physicality" is essential during the "debugging phase".

- The Feedback Gap: Students found it much more frustrating when there was a software "bug" or geometric limit in online formats.

- Persistence: Students continued to attend physical classes to take advantage of immediate instruction, something they couldn't achieve online. By seeing screens for quick 10-second "over-the-shoulder' corrections, teachers offered more value than methods of casual free-for-all. Online learners, on the other hand, were made to wait for scheduled meets all e-mail replies. This gave them the feeling that they might not be able to do complex modelling tasks by 20 to 30%.

3.3.3 Social Interaction and "Good-Teaching Metrics"

Garicia et al. (2021) applied Course Experience Questionnaires (CEQ/OCEQ) to assess the quality of instruction through cross modalities student perceptions. According to their findings:

- Teaching Quality: Students seem to rate good teaching and clarity of goals about 15% higher in face-to-face (F2F) settings. The results show the great difference in social metrics. This happened since there were more social signals and the teacher could adjust the lesson subject depending on how lively the class was.
- The Independence Paradox: Study findings about the independence paradox suggest there was hardly a big difference in scars for independence. This suggests that students may not place the same level of importance on doing something on their own without socialized learning in a real CAD lab, even in an online setting.

3.4 Skill Acquisition: Psychomotor/ Tacit CAD Competencies

According to the results, use of virtual labs and online CAD activities would enhance the concept comprehension of students however, still they do not completely replace the development of psychomotor skills offered in a physical lab or a studio. The complete literature reviews on the online laboratories (simulation/virtual/ remote) states that they provide an advantage in accessibility and theoretical understanding but the inclusion of these laboratories to practical skills is recommended not the replacement of these. CAD trainers and assessors maintain that automatic model checks and screen capture audit trails can prove competencies online (Tomes Reyes et al., 2025).

A meta-analysis comprising 46 studies in engineering revealed that virtual labs significantly predict outcomes (Hedges'g ≈ 0.686) and substantially enhance motivation ($g > 2.8$-3.5) however, they do not yet possess the capacity to fully replace physical labs (Li & Liang, 2024). CAD trainers and assessors maintain that automatic model checks and screen capture audit trails can prove competencies online; however, triangulation with in person artefacts and performance enhances validity (Bojcetic et al., 2021; Johnson & Ye, 2017).

3.5 Project-Based-Learning (PBL), CDIO and Team Skill

The incorporation of Project-Based Learning (PBL) and CDIO (Conceive-Design-implement-Operate) in CAD education has shifted the focus from basic competency on the tools to the development of overall engineering competency. According to the findings of Berselli et al. (2020), students undertaking case projects having industry input, performing static and dynamic analyses are highly satisfied with their work and feel they have mastered appropriate technical skills. The real-world projects bridge the gap between the abstraction of CAD modelling and the real-life engineering constraints. Evidence from ASEE case studies (Webster, 2017) reinforces this conclusion as they show that industry provisioned curriculum combined with team projects not only improves learning gains for all required outcomes but also teamwork and communication outcomes.

According to systematic reviews by Ramirez de Dampierre et al., (2024) these advances hinge on the availability of physical workspaces that satisfy the entire CDIO cycle. As a result, students consider the 'Implement' and 'Operate' faces, where physical labs test digital designs, vital for their professional identity. Recent classroom action research which uses Fusion 360 CAD software (Nuryanto et al., 2025; Nik Roseley N.R. et al., 2021) quantitatively proves this, with a mean technical competency score of 88.7/100. The PBL technique is able to improve both the technical and soft skills. Activities involving creativity, collaboration and communication scored between 80 and 85 out of 100 indicating that the "physicality" of team-based, project driven CAD education is a key factor in high student performance and engagement.

3.6 Immersive & Cloud-Based CAD: Adoption, Usability and Performance

As the digital age matures, the bright line between manual drafting and 2D/3D desktop CAD is vanishing. In its place will be an immersive-end everywhere (cloud-native) environments. These technologies are intended to facilitate beginner learning while promoting collaboration at the same time.

3.6.1 Meta-Analytic Evidence of Immersive Efficacy

The most recent extensive syntheses show that immersive reality (XR) has transformed from a fringe novelty to a significant pedagogical tool. The meta-analysis conducted by Kumar and Gorai (2025) of 21 studies and 41 interventions discovered:

- Large Effect Size: Immersive interventions had a big positive effect on learning outcomes, with the value of $d \approx 0.98$ (95% Cl [0.77,1.20]).
- Enhancement of Score: Students who used AR/VR to understand difficult geometry performed better in the post-test with score enhancement up to 26.42% than in 2D instruction.
- Engagement: Huang and Tseng (2025) show that virtual reality (VR) is currently the most popular XR modality in higher education (53%) in systematic reviews. Pupils say that they have much higher self-efficacy and memory retention when designs are included in hybrids instead of justice virtual views (Castillo et all., 2025).

3.6.2 The "Novice" vs. "Expert" Cognitive Load Split

The worth of immersive tools varies depending on skill level. Talha et al. (2025) conducted a comparative study employing the NASA Task Load Index (TLX) to assess the cognitive effort involved in designing with Augmented Reality (AR-CAD) compared to conventional desktop software (SolidWorks):

- Completion Rates: New designers had much higher completion rates in AR-CAD because the direct 3D manipulation got rid of the "interface barrier."
- Metrics for Cognitive Load: The average NASA-TLS score for AR-CAD was 3.09 ± 1.59, which is lower than the 3.38 ± 1.94 score for traditional CAD. However, this this difference was not statistically significant for experts.
- The Expertise Paradox: Experts still preferred traditional interfaces for advanced tasks, saying that using a headset made them "physically tired" and that there aren't any high precision input tools available in XR right now.

3.6.3 Cloud-Based Cad and Industry Productivity

The use of cloud native platforms like Onshape and Fusion 360 has completely changed the way we work, going from file saving to data streaming. Gaha et al. (2021) and later industry reports from 2025 point out:

- Preference Scores: when students were asked to read their preference for collaborative tasks, they gave Onshape software a 59% priority rating, while traditional file-based SolidWorks only got 41%.
- Productivity Gains: Cloud native workflows increased design productivity by 25% by getting rid of file logistics, which include version control, saving and hardware limits.
- Iteration Cycles: with real time Co editing, student teams were able to cut their iteration cycles from an average of 7-10 days to adjust 2-3 days. This brought their academic experience in line with modern agile manufacturing standards.

CONCLUSION

Essentially, the results of existing studies show that online and blended (hybrid) CAD learning models can have learning outcomes equivalent to traditional face-to-face instruction. Such approaches, however, tend to lack the immediacy, social interaction and practical skills development of physical studios. Studies and randomized trials consistently affirm that learners value the flexibility and accessibility of online learning; however, they express concerns about lack of engagement, collaboration, and immediate troubleshooting. Meta-analyses on virtual labs an immersive technology indicate that virtual labs do enhance students' conceptual understanding and motivation. They also note however that psychomotor skills and implicit design skills are best learnt in real labs. Studies on project-based learning show that physically being in the same place together is necessary to achieve both technical and soft skills results.

The evidence suggesting that education in physical CAD is still relevant is compatible in a practical sense, as it is not a remnant from the human past, but as strategic blending, it informs us about social learning, tested skill development and practice in a real world with online modules, which enhance accessibility, flexibility and depth of preparation (Kazui & Kurtoglu, 2022). The objectives of industry 4.0 corresponds with this mixed approach. It ensures future engineers to learn digital skills and the ability to design things in real life. This makes physical CAD education a crucial component of current engineering education.

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