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Work In Progress: Trust in Simulation-Aided Design: Building Pedagogical Credibility Through Experimentally Validated Ansys Workflows

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Work In Progress: Optimizing Engineering Education with Simulation: Teaching Core Concepts through Integrated Case Studies and Ansys Analysis

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Abstract – Simulations are only as meaningful as the experiments they reflect. In engineering education, this principle underpins the development of appropriate trust in digital tools that increasingly shape how students learn, analyze, and design. This paper presents a structured, three-tier pedagogical framework for cultivating trust in simulation-aided design through experimentally validated case studies developed collaboratively between the University of Waterloo and Ansys Part of Synopsys. The framework intentionally integrates analytical modeling, physics-informed exploratory simulation, and experimental verification to ensure that simulation credibility is earned through consistency with governing equations and measurable physical behavior.

The case studies span multiple engineering domains including solid mechanics, fluid mechanics, thermodynamics, heat transfer, vibrations, electromagnetics, and biomechanics, and are implemented across undergraduate and graduate levels through both course-integrated and co-curricular activities. Each activity begins with simplified analytical estimation to establish governing principles and limiting behavior. Students then engage in exploratory simulation using a software package called Ansys Discovery, where boundary-condition sensitivity and modeling assumptions can be interrogated in real time. Finally, physical experiments provide tangible reference points that anchor interpretation and reveal where simplifications or modeling choices materially influence results.

A representative example includes a vacuum-cleaner-driven Venturi tube, where students observe how Bernoulli's principle governs the interplay between pressure and velocity in an internal fluid flow with varying cross sectional area, and subsequently replicate and refine the system within a staged CFD environment. Reduced-order exploratory solutions are compared to higher-fidelity convergence-driven results, reinforcing that simulation accuracy is progressive and dependent on mesh, turbulence modeling, and boundary conditions. Similarly, a 3D-printed cross-flow heat exchanger and transient thermal studies using specialized filaments demonstrate how simulation can be used both predictively and inversely to reconcile material properties with experimental measurements.

Affective data collected from over 800 participants across nine engineering disciplines indicate consistent increases in self-reported confidence, curiosity, and conceptual clarity following participation. Distribution across academic levels and a normalized prior experience index suggest that the framework is adaptable to varied stages of curricular maturity regardless of engineering discipline. Importantly, students did not report reduced engagement with analytical methods; rather, simulation was perceived as a tool for testing assumptions and examining sensitivity within a structured reasoning process.

Collectively, this work demonstrates that trust in simulation-aided design is not determined by software accessibility or computational speed, but by pedagogical structure. When analytical framework, exploratory simulation, and experimental validation are explicitly linked, students develop confidence grounded in physical reasoning yet enhanced with the depth of visualization enabled by the computational tools.

Keywords: Experiential learning, Simulation, FEA, CFD, Modeling.

Introduction

Simulation tools are increasingly central to engineering design practice, yet their role in engineering education remains nuanced. While modern software enables rapid exploration of complex physical phenomena, the pedagogical challenge lies not in access to simulation, but in cultivating appropriate trust in computational results. Without grounding in theory and validation, simulation risks becoming either a black-box authority or a superficial visualization tool. Previous work has demonstrated the effectiveness of combining virtual simulations with physical experiments to enhance student engagement and understanding [1], and highlighted the benefits of using industry-standard simulation tools alongside traditional lab activities to provide students with real-world problem-solving experiences [2]

This paper presents a structured, three-tiered pedagogical framework for simulation-aided design education that explicitly integrates analytical modeling, physics-informed simulation, and experimental verification [3]. The framework is implemented through a series of experimentally validated case studies developed collaboratively between the University of Waterloo and Ansys, and deployed across multiple engineering domains including solid mechanics, fluid mechanics, thermodynamics, heat transfer, vibrations, electromagnetics, and biomechanics. Rather than replacing analytical methods, simulation is positioned as an intermediate reasoning layer that allows students to explore sensitivity, boundary conditions, and physical intuition prior to experimental validation. Trust in simulation is therefore not assumed, but earned through agreement between analytical predictions, computational results, and physical measurements. This work examines how such a structure influences student confidence, understanding, and design judgment.

Background and Motivation

Traditional laboratory instruction often emphasizes procedural completion over conceptual interrogation. Students may execute experiments correctly without understanding why results behave as they do, while simulation-based instruction can risk the opposite, where visually compelling results are accepted without sufficient scrutiny of assumptions. Prior work in engineering education has demonstrated the value of active and inquiry-based learning, as well as the benefits of case study–driven instruction. Recent developments in real-time simulation environments further enable exploratory learning, but also raise concerns regarding overreliance on computational output. Addressing these concerns requires pedagogical structures that make the limitations, assumptions, and governing physics of simulation explicit.

Related work by Tyler et al has explored complementary dimensions of design and materials education, including the use of case studies, simulation-supported learning, and active, inquiry-driven instructional approaches in undergraduate engineering curricula [4]–[6] These prior studies have examined how materials selection frameworks, software-supported active learning environments [7], and design-focused outreach activities can influence student engagement, perception of engineering, and conceptual understanding. Collectively, this body of work emphasizes accessibility, contextual learning, and the role of computational tools in supporting design reasoning, particularly in materials-centered and multidisciplinary settings. The present study builds upon these foundations by explicitly addressing an unresolved challenge that spans these efforts: how students develop *trust* in simulation-aided design workflows. Rather than focusing on tool adoption or curricular integration alone, this work advances the conversation by articulating a structured, three-tiered pedagogy that links analytical foundations, exploratory simulation, and experimental verification to cultivate engineering judgment and responsible use of simulation in design decision-making. The intent is not to teach the extraneous details of software operation, but to develop engineering judgment through constrained exploration, and understand the methodology of engineering simulation which is transferrable to other problem domains.

Pedagogical Framework

The simulation activities referenced in this study were delivered as structured, 180 minute workshops consisting of (i) a brief analytical introduction to the governing physics, (ii) guided exploratory simulation using Ansys Discovery with predefined boundary conditions, and (iii) facilitated comparison to experimental or reference data, often in small-group settings. Affective and perception-based data were collected using a short post-workshop survey consisting of Likert-scale questions targeting prior experience, confidence in interpreting simulation results, and perceived trust in simulation relative to analytical and experimental methods. Trust in simulation was operationalized through students' self-reported agreement with statements regarding their ability to interpret, question, and validate simulation outputs rather than accept them as authoritative. All reported responses (e.g., n = 113 for prior experience in Figure 5) correspond to voluntary submissions from workshop participants across the same survey delivery and cohort structure.

The proposed framework consists of three intentionally ordered components.
First, students are introduced to simplified analytical models that capture the governing physics of the system. These models establish expectations, assumptions, and limiting behavior, and provide a reference against which more complex results can be evaluated. Second, students engage with physics-informed simulation using Ansys Discovery in an exploratory mode. Simulation is not used to bypass theory, but to test its applicability under more realistic boundary conditions, geometries, and loading scenarios. Real-time feedback allows students to observe how changes in constraints, material properties, or flow conditions influence system behavior, reinforcing cause-and-effect reasoning. Third, experimental verification anchors the learning process. Physical demonstrations and measurements provide tangible reference points, allowing students to assess where analytical simplifications break down and where simulation predictions align with reality. Trust in simulation emerges when consistency is observed across all three tiers.

Case Study Implementation

Case studies were selected to emphasize tangible physical systems with clear governing principles and measurable outputs. Examples include a vacuum-cleaner-driven Venturi tube[8], a 3D-printed cross-flow heat exchanger, a tuning fork vibration experiment [8], a walking crutch structural analysis, and a charcoal barbecue heat transfer study. Each case study follows the same pedagogical sequence: analytical estimation, exploratory simulation, and experimental comparison. Boundary condition sensitivity is deliberately emphasized, particularly in fluid and thermal systems where induced backpressure or heat losses significantly influence outcomes. Students are encouraged to reconcile discrepancies rather than seek exact agreement, fostering critical evaluation skills.

Figure 1 highlights a critical pedagogical challenge in teaching thermal–fluid systems: the inherent difficulty of spatially visualizing three-dimensional fluid–fluid interfaces within even seemingly simple heat exchanger geometries. In physical laboratory apparatuses, these interfaces are entirely hidden, and students must infer internal flow behavior from limited inlet and outlet measurements, often relying on idealized assumptions. The cross-flow heat exchanger used in this case study, while geometrically compact and experimentally accessible, contains overlapping air and water channels whose internal interaction regions are nontrivial to conceptualize using traditional two-dimensional schematics or textbook-style plate heat exchanger analogies. The simulation model resolves this challenge by distilling the geometry into clearly defined fluid domains through volume extraction, allowing students to explicitly see where convection in each fluid stream interacts through conduction in the solid walls. Importantly, this abstraction does not sacrifice physical fidelity; rather, it preserves the essential three-dimensional nature of the flow paths, induced backpressure, and heat transfer surfaces that are absent in simplified analytical examples. By visualizing internal velocity fields, temperature gradients, and conjugate heat transfer effects that are experimentally inaccessible, students gain a realistic yet comprehensible representation of the system. This clarity supports deeper reasoning about boundary condition placement, flow restrictions, and pressure losses, reinforcing why experimentally measured mass flow rates and outlet temperatures are highly sensitive to geometric and operational constraints.

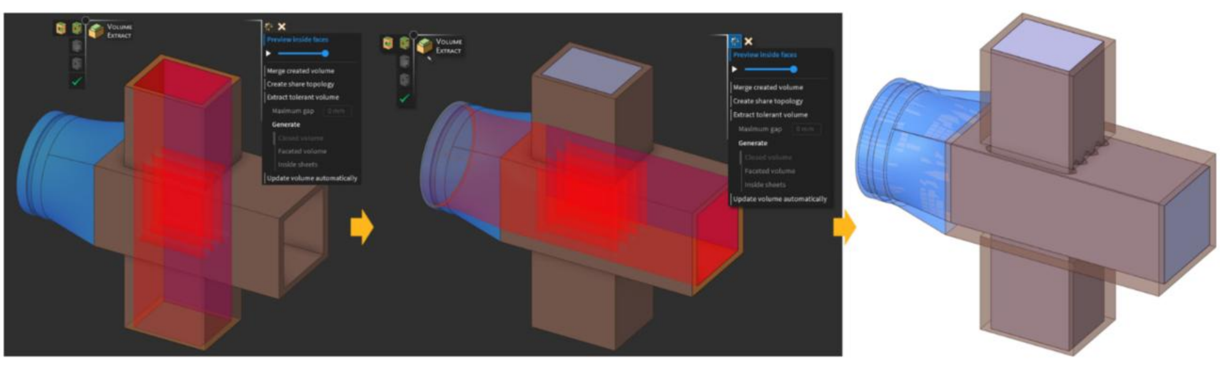
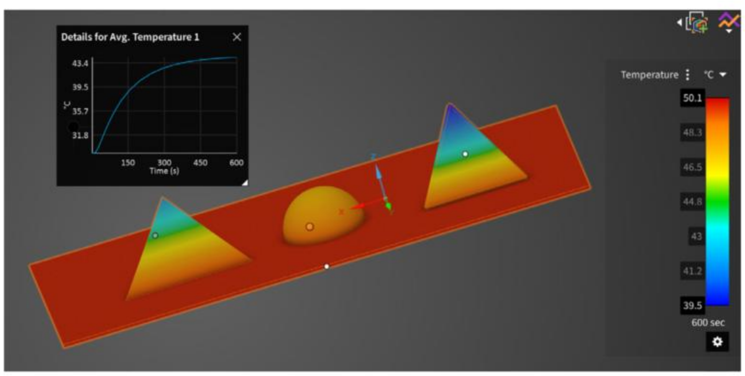


Figure 1 - Geometry preparation and volume extraction process used to separate the air and water flow domains in a cross-flow heat exchanger for conjugate heat transfer analysis.

Figure 2, illustrates how material selection and property estimation were intentionally leveraged to support a scalable, student-centered experimental platform while reinforcing the three-tiered pedagogical structure of analytical grounding, simulation-based exploration, and experimental validation. A copper-filled PLA filament was selected to enhance conductive heat transfer while remaining compatible with low-cost FDM manufacturing, enabling rapid fabrication of repeatable test specimens and heat exchanger components. The effective specific heat capacity of the composite filament was first estimated analytically using a rule-of-mixtures formulation, establishing an explicit link between constituent material properties and expected thermal response. This analytically informed estimate was then embedded within a transient thermal simulation of simple three-dimensional geometries subjected to a known convective boundary condition, allowing students to explore heating and cooling behavior in real time. By comparing simulated temperature–time curves with experimentally measured data from multiple specimen geometries, students were able to iteratively tune thermal conductivity and convective losses, effectively using the simulation in an inverse manner to infer material properties. This process not only validated the simulation model but also demonstrated how discrepancies between prediction and measurement can reveal manufacturing variability, surface effects, and boundary-condition sensitivity. As a result, simulation transitioned from a forward-prediction tool to an active reasoning instrument, helping students understand how material behavior, geometry, and environmental conditions collectively shape transient thermal response.

$$\mathrm{C_{p\_filament}} = \left(\frac{\mathrm{m_{PLA}}}{\mathrm{m_{filament}}}\right)\mathrm{C_{p\_PLA}} + \left(\frac{\mathrm{m_{Cu}}}{\mathrm{m_{filament}}}\right)\mathrm{C_{p\_Cu}}$$



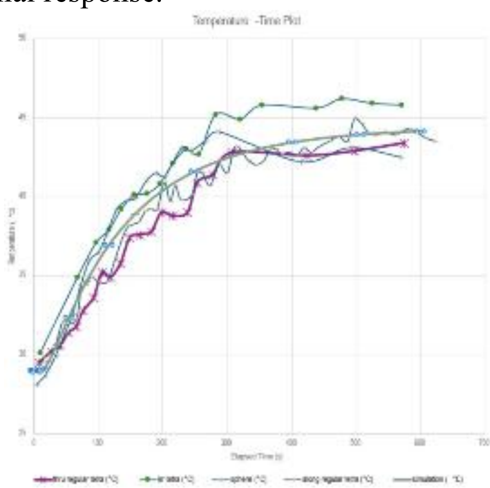


Figure 2 - Illustration of the three-tiered pedagogical approach applied to a 3D-printed composite filament. The effective specific heat capacity is first estimated analytically using a rule-of-mixtures formulation (top), then applied within a transient thermal simulation of simple geometries with a prescribed convection coefficient to explore heating and cooling behavior (left), and finally validated against experimental temperature–time measurements to confirm material property assumptions (right).

Previous work highlighted the use of a Venturi tube activity to connect analytical fluid mechanics with experimental measurement and exploratory CFD, demonstrating how boundary-condition sensitivity and flow acceleration could be made tangible to students through a simple, physically intuitive system [8]. The present study extends this approach by embedding the activity within a broader, three-tiered framework that emphasizes simulation fidelity, experimental validation, and trust in simulation-aided design.

Figure 3 illustrates how simulation fidelity is intentionally staged to support the development of student confidence in both the governing physics and the numerical assumptions embedded within computational models. The upper result, generated using *Explore* mode in Ansys Discovery, employs a reduced-order, GPU-accelerated solver that solves simplified and partially linearized governing equations to provide physically consistent, real-time feedback. This mode allows students to rapidly interrogate the influence of boundary conditions, such as inlet velocity and downstream pressure constraints, and immediately observe qualitative changes in the internal velocity field within the Venturi geometry. At this stage, the emphasis is not on numerical precision, but on reinforcing cause-and-effect reasoning and helping students recognize how flow acceleration, contraction, and diffusion emerge from conservation principles under idealized assumptions. The lower result transitions the same geometry and boundary conditions into *Refine* mode, where a convergence-driven CFD solver resolves non-linear physics with increased mesh fidelity and stricter numerical controls. Here, students are confronted with the realities of mesh sensitivity, residual convergence, and solver stability, and begin to appreciate how quantitative accuracy depends on modeling choices that were previously abstracted. By explicitly comparing these two solution regimes, students learn that simulation accuracy is not binary but progressive, and that trust in numerical results must be earned through validation and refinement rather than assumed. This staged progression aligns directly with the three-tier pedagogical framework presented in this work, where analytical expectations guide initial understanding, exploratory simulation builds intuition and boundary-condition awareness, and high-fidelity refinement supports quantitative validation and responsible design decision-making.

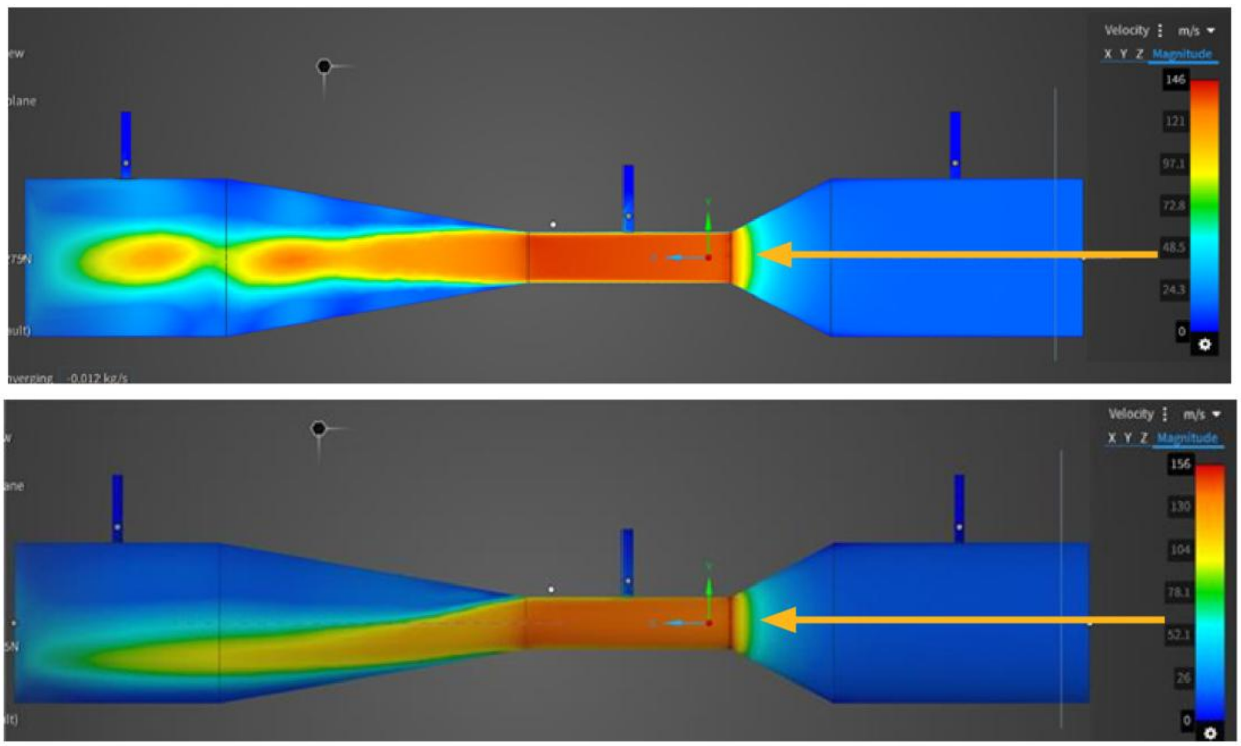


Figure 3 - Effect of physics/mesh fidelity on velocity prediction in an internal flow (venturi tube). (Top) is reduced order solver (known as "Explore" mode using simplified and linearized governing equations. (bottom) convergence driven physics with non-linear physics known as "Refine" mode in the CFD solver.

Importantly, the degree of student control over mesh generation and model fidelity is intentionally scaffolded according to experience level and implementation context. In introductory offerings, the baseline geometry, turbulence model, and initial mesh are provided to reduce cognitive overload, allowing students to focus on boundary-condition sensitivity and qualitative flow behavior. Even in this structured format, students are guided to refine mesh locally and observe how solution stability and velocity contours change, particularly in regions of heightened sensitivity such as the diverging section downstream of the Venturi throat where adverse pressure gradients, possible flow separation, and elevated levels of turbulent kinetic energy can amplify non-uniform flow behavior. In intermediate or more advanced implementations, students build the geometry and mesh from first principles, explicitly exploring element density, near-wall refinement, and turbulence modeling choices to evaluate convergence and solution robustness. This graduated exposure reinforces that simulation fidelity is neither fixed nor automatic, but a controllable modeling decision. By allowing students to interrogate where mesh sensitivity and turbulence assumptions materially influence results, trust in the CFD model becomes conditional and evidence-based rather than implicit "assumed knowledge" on behalf of the student.

Student Outcomes, Discussion and Observations

Affective data collected from over 800 students across multiple disciplines indicate consistent increases in self-reported confidence, curiosity, and conceptual clarity following participation in these activities. A description of the distribution of student discipline is shown in Figure 4 participation spanned nine engineering disciplines, with Mechanical Engineering representing 36.7% of respondents and Mechatronics 16.3%, while 30.7% identified as "Other," reflecting interdisciplinary or non-traditional program affiliations or simply those students who chose not to disclose a home department. Collectively, more than 60% of respondents originated outside a single disciplinary concentration, supporting the claim that the framework resonates beyond a narrowly defined "mechanical" cohort. Similarly, academic level distribution demonstrates representation across all years of study, with approximately 34% of respondents in first year (1A and 1B), 16.8% in second year (2A and 2B), and meaningful participation from upper-year students. This breadth across both discipline and academic maturity suggests that the workshop model is adaptable to varied curricular stages and not restricted to a specific cohort or specialization.

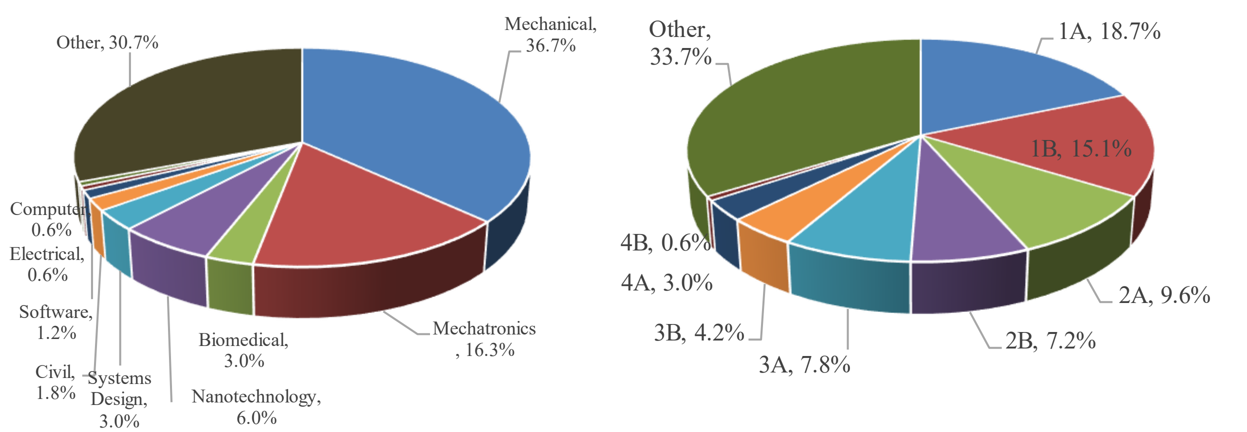


Figure 4 - Distribution of simulation workshops spanning 7 academic terms, with greater than 800 students who attended but where only n=166 students chose to submit a response. (Left) is the distribution of student discipline and (Right) is the distribution of academic engineering level (I.e.1B is a 1st year student in their second, or "B" term of that year).

Student self-assessment of prior experience was collected using a five-point ordinal scale and encoded numerically (1 = none at all to 5 = a great deal) and is shown below in Figure 5. To enable term-level comparison and longitudinal visualization across independent cohorts, responses were normalized to give a prior experience index (ranging between 0 and 1). This index was not intended as a precise measure of competence, but rather as a proxy for perceived familiarity and exposure to simulation-based analysis prior to workshop participation. While Likert responses are ordinal in nature, they were treated as approximately interval-scaled for descriptive cohort analysis and trend interpretation. Across Winter 2024 through Summer 2025, the mean prior experience index remained relatively stable between approximately 0.35 and 0.40 out of 1, indicating that the majority of participants entered with limited exposure. Beginning in Fall 2025 and more notably in Winter 2026, the mean index increased to approximately 0.45 and 0.68, respectively, which represents a relative increase of 75% from their baseline experience level. Although cohorts differ across terms, this upward shift suggests increasing prior exposure among participants, potentially reflecting growing curricular integration, repeat attendance, and broader awareness of simulation-based activities within the engineering community. The data also anecdotally shows that that an incubation period exists between initial exposure and students' self-recognition of increased experience. Educational psychology literature has documented that early exposure to complex tools can initially heighten awareness of knowledge gaps rather than confidence, a phenomenon consistent with the Dunning–Kruger effect [9], [10]. In this context, early workshop participants may not immediately perceive growth in experience despite gaining exposure. The more pronounced increase observed approximately one academic year later may therefore reflect both accumulated exposure and more calibrated self-assessment as students transition from novice familiarity toward more informed competence.

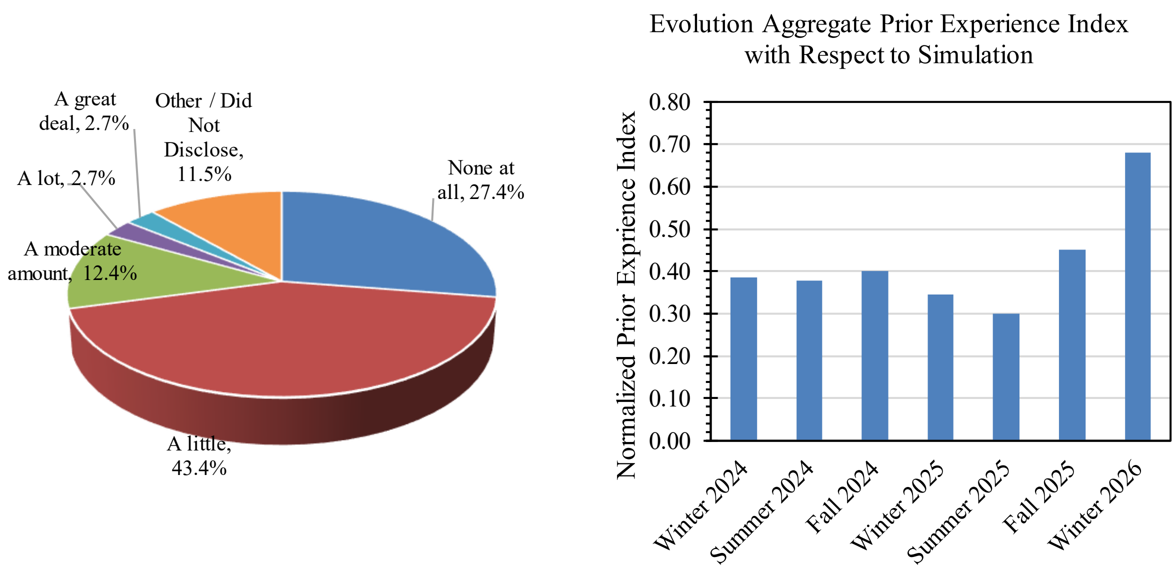


Figure 5 - Student self-assessed "Prior Experience Index" using five point-ordinal scale for several workshops with >800 students who attended but where only n=113 students chose to submit a response. (Left) is a distribution of the students responses to the question "How much experience did you have with the topic before the simulation workshop?" in aggregate. (Right) is the evolution of the normalized prior experience index over the course of 7 academic terms for the entire group of respondents.

Qualitative findings consistently indicated that students' trust in simulation increased once agreement was observed between analytical predictions, computational results, and experimental measurements. Rather than diminishing engagement with first-principles analysis, simulation was frequently described as a mechanism for interrogating understanding and testing assumptions. Students positioned the digital model not as a replacement for theory, but as a tool for examining boundary-condition sensitivity, model limitations, and physical plausibility. This outcome aligns directly with the intended role of simulation within the proposed framework: a reasoning layer embedded within, and accountable to, analytical and experimental validation.

Once validated, simulation models were extended into open-ended design challenges that required trade-off analysis and decision-making under constraints. Students explored competing objectives, such as minimizing pressure drop while maximizing heat transfer, or improving structural efficiency within material and manufacturing limits. In doing so, simulation shifted from a predictive instrument to a design partner, supporting evaluation of alternatives rather than replication of expected results.

Collectively, these findings reinforce that trust in simulation-aided design is not a function of software accessibility or computational power, but of pedagogical structure. When analytical foundations, exploratory simulation, and experimental verification are explicitly integrated, student confidence becomes grounded in physical reasoning rather than computational authority. The framework is demonstrably transferable across disciplines and adaptable to varied curricular contexts. Future work will focus on longitudinal assessment of learning outcomes and extension into multiphysics and capstone design environments.

Conclusions

This work demonstrates that trust in simulation-aided design is not a function of software accessibility or computational power, but of pedagogical structure. By explicitly linking analytical foundations, physics-informed exploratory simulation, and experimental verification, students develop confidence grounded in physical reasoning rather than computational authority. Simulation is positioned neither as a replacement for theory nor as a black-box predictor, but as an intermediate reasoning layer that supports intuition, sensitivity analysis, and critical evaluation.

The experimentally validated case studies presented in this paper show that real-time, exploratory simulation environments can play a meaningful role in engineering education when they are embedded within a clearly articulated analytical and experimental context. Students learn not only how systems behave, but why results change when assumptions, boundary conditions, or modeling fidelity are altered. The staged progression from simplified analytical models, through exploratory simulation, to high-fidelity refinement and experimental comparison helps students recognize that simulation accuracy is progressive and must be earned through validation and convergence rather than assumed.

Affective outcomes collected from a large and diverse student population indicate consistent gains in confidence, curiosity, and conceptual clarity, without a corresponding reduction in engagement with analytical methods. Instead, simulation was perceived as a tool for testing understanding and supporting design decision-making. When extended into open-ended design challenges, validated simulation models encouraged students to engage with realistic trade-offs, reinforcing simulation as a trusted design partner rather than an answer generator.

The proposed framework is transferable across disciplines and scalable to a variety of curricular and co-curricular contexts. Future work will focus on longitudinal assessment of learning outcomes, extension to multiphysics systems, and deeper integration into capstone and graduate-level design experiences. More broadly, this work highlights how carefully structured simulation-based pedagogy can support the development of engineering judgment, not merely technical proficiency, which remains a central objective of design education.

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Appendix A: CASE STUDY FILES

The authors encourage the readers to refer to the Ideas Clinic Workshop database as well as the ~~Ansys Learning hub~~Ansys Educator hub to access the appropriate case study files, experimental SOP's and raw data, as well as the simulation models.