Implementing Hands-On Manufacturing Education at Scale: A Curriculum Transformation in Mechanical Engineering

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Abstract

The School of Mechanical Engineering at Purdue University has undertaken a significant curricular transformation to modernize its undergraduate design and manufacturing course sequence. A new sophomore-level design course, which integrates foundational manufacturing processes and design-for-manufacturing principles, has replaced a traditional course offering, which emphasized conceptual design but offered limited opportunities for hands-on maker experiences. This initiative represents the first stage of a broader effort to align the curriculum with evolving industry needs and to provide students with meaningful, scalable, hands-on experiences early in their academic journey.

The new sophomore-level course introduces students to manufacturing environments through a structured progression of hands-on and CAD/CAM fabrication experiences. It begins with the fabrication of functional products using conventional machining tools such as lathes, mills, sheet metal, and woodworking operations, allowing students to develop a fundamental understanding of tolerances, SOPs, and shop practices. This is followed by modules on CNC machining, CAD/CAM integration, metrology, and hybrid manufacturing methods. A culminating design-and-build project integrates multiple manufacturing processes, encouraging students to combine creativity with technical rigor.

A key aspect of this transformation is its implementation at scale. As one of the largest mechanical engineering programs in the country, the school must accommodate hundreds of students each semester through machine shop environments, CNC training, and hands-on lab sections. This has required coordinated efforts among faculty, instructional staff, teaching assistants, and technical personnel to redesign spaces, standardize training, and manage logistics for large lab sections while maintaining individualized learning experiences. The course also incorporates structured safety training, equipment scheduling systems, and assessment methods that balance efficiency with rigor and pedagogical depth.

Feedback from industry and alumni has been an important aspect in shaping the course objectives and content. Employers and graduates have consistently emphasized the value of early exposure to real manufacturing environments, noting that graduates who are comfortable with scalable maker skills are better prepared for internships, co-ops, and full-time positions. Student feedback has also been instrumental, including collaboration with ME-affiliated student organizations. Early pilot offerings of the course have shown strong engagement, with students highlighting the value of hands-on work, the clear connection between design decisions and outcomes, and the quality of prototyping and fabrication results. Students emphasized the importance of direct fabrication experience, noting that “hands-on experience with CNC machines was very valuable” and provided exposure they “would not have gotten otherwise.” This feedback has informed refinements in instructional pacing, lab capacity planning, and support structures for students with little prior shop experience.

The integration of industry-informed case studies contextualizes design and manufacturing decisions. Industry guests present real product development scenarios, offering students insight into professional practice in a manageable and scalable format.

The presentation will focus on implementing this curriculum change at scale, including instructional design strategies, infrastructure modifications, training protocols, and feedback mechanisms. It will highlight the perspectives of students, alumni, and industry partners, and address key challenges such as maintaining instructional quality, ensuring equitable access to equipment, coordinating large instructional teams, and balancing technical depth with logistical constraints. Lessons learned offer insights for other large programs seeking to integrate meaningful, hands-on manufacturing experiences early in the curriculum while navigating challenges of scale.

1. Introduction and Literature Review

As required by ABET, graduating engineering students must attain "an ability to apply engineering design to produce solutions that meet specified needs..., an ability to function effectively on a team..., and an ability to develop and conduct appropriate experimentation…" (p. 6). These gains must also be realized in "a culminating major engineering design experience that 1) incorporates appropriate engineering standards and multiple constraints, and 2) is based on the knowledge and skills acquired in earlier course work" (ABET, 2024, p. 7). Based on these requirements and to develop the necessary skills for success in later coursework, the School of Mechanical Engineering sought to modernize its sophomore-level design and manufacturing course to better serve students through meaningful, scalable, and hands-on manufacturing experiences.

Scholarship related to implementing hands-on, active learning, and laboratory-style courses into the Mechanical Engineering curriculum is not new. For example, beginning in 1997, both the United States Air Force Academy and the University of Texas at Austin used hands-on activities to enhance their mechanical engineering curricula, particularly the design methodology course offerings (Jensen et al., 2003). These courses utilized reverse engineering, redesign, and original design projects, and students reported increased interest in course content, particularly in the machine design area. At Ohio Northern University, transitioning to more hands-on laboratories saw students self-report a better understanding of technical content, such as PCLs and frequency response, as well as increased exam scores (Yoder et al., 2004). Further, students at Newcastle University, UK, reported that project- and team-based learning opportunities were valuable to their professional development, increased their satisfaction and achievement, and gave them opportunities to form supportive and collaborative relationships with peers (Joyce et al., 2013). As shown, hands-on, laboratory-style learning opportunities for mechanical engineering students offer many opportunities to prepare for their future careers and build necessary skills.

In 2004, the National Academy of Engineering envisioned *The Engineer of 2020*, a vision that saw the skills and abilities that future engineers would need to be successful (National Academy of Engineering, 2004). *The Engineer of 2020* was envisioned to emphasize creativity during the design process, which has been actualized in one way using maker spaces. Maker spaces began as a creative outlet for individuals to access prototyping and building equipment such as 3D printers, laser cutters, and traditional hand tools (Barrett et al., 2015). As the idea of maker spaces caught on and prices of equipment such as 3D printers went down, maker spaces have become more popular avenues to build and sustain interest in design and manufacturing. We have sought to use maker spaces in conjunction with traditional manufacturing techniques such as lathes, mills, woodworking, and sheet metal bending to form a well-rounded, hands-on laboratories which follow similar paths as MIT, Stanford, and Northwestern (Wilczynski, 2015). Our intended outcomes of the maker spaces and hands-on laboratories are supported by industry and academia. In fact, "157 stakeholders from the manufacturing industry (37 percent of the respondents) and academia (63 percent of the respondents) highlighted the importance of practicums and other experiential learning activities in preparing students for careers in advanced manufacturing; 88.9 percent mentioned internships and 80.6 percent mentioned hands-on laboratories" (Committee on Strengthening the Talent for National Defense et al., p. 37, 2023). However, a particular challenge we face regards scaling maker spaces and hands-on laboratories to a large student population, and we present our efforts to do this below.

Our course redesign is similar in some ways to what Clayton et al. (2010) published about their course redesign at Villanova University; however, some key differences are worth noting. First, Clayton et al. (2010) detail 10 one-to-two-week projects over the course of their semester, which relate directly to the lecture content being covered in those weeks. Our students complete several weekly projects aimed at developing manufacturing skills, which can then be used to complete a team-based project over the final half of the semester. Second, our course must accommodate many students, given the size of the sophomore mechanical engineering cohort compared to Villanova, and specific challenges are presented later. Finally, the content has changed to meet the industry needs of today, specifically with respect to Industry 4.0 and the budding Industry 5.0, and to accommodate the maker space resources that students find valuable.

It is worth reviewing here the evolution of the manufacturing and design course sequence at Purdue University. As shown in Figure 1, the Design course sequence in 2024 and earlier was mapped to begin in the fourth semester with ME 26300: Introduction to Mechanical Engineering Design, Innovation, and Entrepreneurship (Purdue University School of Mechanical Engineering, 2024). This course focused on conceptual design principles such as concept generation, decision-making, and product and process design steps while offering limited opportunities for hands-on maker experiences. The redesigned course sequence shown in Figure 2 shows the transition from ME 26300 to two separate courses, MFET 16300 / ME 16400 and ME 26400 (Purdue University School of Mechanical Engineering, 2025). MFET 16300 / ME 16400: Graphical Communication and Spatial Analysis focuses on visualization, sketching, graphic standards, and problem-solving strategies for engineering design, while ME 26400: Introduction to Manufacturing for Mechanical Design carries students through from conceptual design to actual design and manufacturing processes in a hands-on, active learning environment with a laboratory course component. The focus of this paper is on ME 26400, and further details related to the creation and implementation of the course are provided in the following section.

Figure 1: Previous design course sequence.

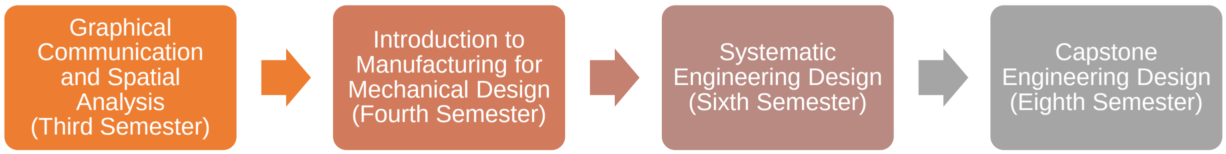

Figure 2: Current design course sequence.

2. Course Context, Educational Objectives, and Instructional Design

The course described in this paper is a second-year Mechanical Engineering experience centered on manufacturing and maker skills through a fully integrated lecture, laboratory, and project model. It occupies a key position in the curriculum and serves as the first environment in which students are asked to think and act as engineers rather than as problem solvers working toward predefined answers. The course enrolls several hundred students each year and is required for all mechanical engineering majors.

The educational objectives extend beyond technical exposure to manufacturing processes. The course is intentionally structured to develop three intertwined dimensions of professional formation. The first is foundational maker and manufacturing skills, including machining, CAD/CAM, sheet metal forming, metrology, woodworking, and basic electronics. The second is early design for manufacturing reasoning, where students learn to evaluate geometry, materials, and tolerances through the lens of producibility and manufacturability. The third is professional behavior, including teamwork, communication, iteration, and accountability.

Unlike traditional lecture-driven models, the course treats students as engineers in training from the outset. Success is framed not as the ability to reproduce a correct answer, but as the capacity to engage in open-ended problem solving under realistic constraints. This shift is communicated explicitly in the syllabus, grading structure, and daily instructional practices. Students are expected to prepare, collaborate, manage time, and respond to feedback in ways that mirror professional engineering environments. The course thus serves as a gateway to the design and manufacturing sequence, establishing both technical foundations and industry standards for subsequent project-based courses.

Upper-level manufacturing processes courses in mechanical engineering are traditionally grounded in manufacturing science. They emphasize analytical descriptions of cutting mechanics, heat generation and transfer, fluid flow in casting and molding, deformation and failure in forming, and microstructural evolution during processing. In mechanical engineering curricula, these courses are intentionally positioned after substantial prerequisite coursework in thermodynamics, heat transfer, fluid mechanics, solid mechanics, dynamics, and materials science, and they are most effective when taught to juniors or seniors who can engage with this analytical framing.

As mechanical engineering programs respond to industry demand, ABET expectations, and national calls for more authentic design experiences, many have moved manufacturing earlier in the curriculum. When this shift occurs, the traditional manufacturing science structure becomes misaligned with student preparation. Sophomore students generally lack the mathematical and physical background needed to engage meaningfully with formal analytical models, yet the literature on hands-on learning and maker spaces consistently emphasizes the value of early exposure to physical making. The central problem is not whether manufacturing belongs at the sophomore level, but how to translate manufacturing science into maker-oriented skills without reducing the course to vocational tool training detached from engineering judgment. Thus, converting an upper-level manufacturing science course into a sophomore-level maker skills course is not meant to be a reduction in rigor, but rather a structured translation.

2.1 Instructional Design: Integrating Theory with Practice

Traditional manufacturing textbooks emphasize analytical models and assume substantial prerequisite knowledge, making them poorly suited as primary texts for sophomore maker courses. More effective instructional resources emphasize processes, visuals, heuristics, and decision-making. Internally developed laboratory manuals tailored to local equipment and safety culture often play a central role. In this context, the course slides, laboratory manuals, and a design-and-build project function as the primary instructional texts.

A central feature of the course is the tight coupling of lecture content with hands-on laboratory work. Rather than treating lectures as abstract theory and labs as isolated skill sessions, the course is organized around a just-in-time instructional model. Core manufacturing concepts are introduced in the lecture immediately before students encounter them in the shop.

Lecture modules are derived from standard manufacturing texts, such as Kalpakjian and Schmid or Groover, but are intentionally reframed around actionable concepts. For example, before the sheet metal laboratory, students are introduced to bend allowance, minimum bend radius, springback, and tool selection. These topics are not presented as formulas to memorize, but as design variables that determine whether a part can be manufactured successfully. Similar alignment occurs across machining, CAD/CAM, woodworking, and metrology.

To reinforce this integration, physical artifacts are brought into the lecture environment. Students handle tools, examine material samples, and inspect components before entering the shop. This tactile exposure reduces abstraction and anchors terminology in physical experience. By the time students arrive in the lab, they have formed a conceptual model of the process and its constraints.

This structure shifts the cognitive burden from discovery under pressure to informed execution. Students enter labs with clearer expectations, greater confidence, and a stronger sense of purpose. Lecture no longer functions as a parallel stream of information, but as a preparatory stage in a continuous learning cycle that flows from concept to action and back to reflection.

2.2 Project-Based Structure and Experiential Learning Environment

The course is organized around a semester-long team project that integrates multiple manufacturing processes. Each laboratory module introduces a new capability that feeds directly into the evolving project. Students do not complete isolated exercises; rather, every skill is framed as a contribution to a tangible artifact that they design and build.

This project-centered architecture supports progressive scaffolding. Early labs emphasize safety, measurement, and basic fabrication. Subsequent modules introduce machining, forming, and digital manufacturing. Each stage requires students to revisit earlier decisions, adjust geometry, and reconcile design intent with manufacturing reality. Iteration is not treated as failure but as a normal and expected part of engineering work.

Professional communication is embedded throughout the semester as well. Teams submit technical memos, participate in structured design reviews, and produce a final report and presentation documenting both product and process. These deliverables mirror industry practice and reinforce the idea that engineering work is inseparable from documentation and justification.

The learning environment is deliberately collaborative. Studio-style lectures, in-class activities, and team-based labs create a social structure in which students learn from one another and through an established structure of peer-mentors. The course culture emphasizes shared problem-solving, peer support, and collective progress. Students consistently describe the experience as more engaging and more demanding than traditional courses, and they often note that the visible connection between lecture, lab, and project gives meaning to each component.

3. Implementation: Converting an Upper-Level Manufacturing Science Course to an Entry-Level Maker Skills Course

3.1 Retooling Manufacturing Curriculum

A productive approach to course conversion is to treat manufacturing science as an implicit structure rather than explicit analytical content. In this model, the underlying physics and mechanics remain present, but they are encountered through observation, comparison, interpretation, and reflection rather than derivation. The intellectual substance of manufacturing is preserved, even though equations and formal homework problems are intentionally minimized.

3.1.1 Experiential Learning of Manufacturing Science

This translation is achieved by shifting instructional emphasis from calculation to physical phenomena. Instead of asking students to compute cutting temperatures or predict forces from first principles, students are asked to observe surface finish, chip morphology, dimensional accuracy, and tool wear while varying process parameters. Heat transfer, friction, and material behavior remain central to the experience, but they are encountered through controlled experimentation and reflection. Students begin to associate cause and effect in a way that mirrors professional engineering practice, even in the absence of advanced theory.

A second shift involves moving from prediction to interpretation. Upper-level manufacturing science courses emphasize predictive modeling, while sophomore maker courses emphasize explaining observed outcomes. Students are asked to reason why a thin feature deflects during machining, why a welded assembly distorts, or why a formed part exhibits springback. This form of reasoning directly supports ABET expectations related to experimentation, data interpretation, and problem solving, while remaining accessible to students early in the curriculum.

Finally, the course emphasizes process windows, constraints, and trade-offs. Manufacturing science often defines feasible operating regions through analytical models. In a sophomore context, these same ideas appear as safe operating procedures, fixturing limitations, tolerances, material compatibility, and machine capability. Students learn that manufacturing processes impose design constraints and that effective engineering solutions emerge from understanding and respecting those constraints.

3.1.2 Industry-Aligned Instruction and Context

As noted above, professors of practice in this course work with industry to connect course content with real-world applications. A distinguishing feature of the course is the intentional integration of practicing engineers into core instructional modules. Guest participation is not treated as informational alone; rather, industry experts deliver required content aligned with the syllabus and course outcomes.

In the manufacturing foundations sequence, engineers present core material on topics such as geometric dimensioning and tolerancing, tolerance analysis, and inspection. These sessions cover datums, feature control frames, true position, and practical interpretation of drawings, content already specified in the course learning outcomes. What changes is the frame. Students see these tools as they are used in high-reliability systems and production environments rather than as abstract notation. In addition, these interactions provide a two-way platform for other student-industry engagement, such as sponsored capstone design projects and internship opportunities.

Similarly, in the design sequence, engineers deliver required modules on user-centered design, rapid prototyping workflows, and failure modes and effects analysis. These lectures are timed to coincide with early design reviews, allowing students to immediately apply formal tools such as voice-of-customer translation, risk matrices, and prototype planning within their own projects. Case-based learning further strengthens authenticity. Students work in teams on real industrial scenarios that involve trade-offs among cost, time, performance, and manufacturability. They receive direct feedback from practicing engineers, who evaluate not only technical feasibility but also reasoning and communication.

Students consistently report that these experiences clarify why formal methods matter. Hearing from engineers who use these tools daily transforms them from academic requirements into professional instruments. Industry partners, in turn, observe high levels of engagement and frequently extend their involvement through recruiting, design reviews, and project sponsorship.

3.2 Roles of Faculty, Technical Experts, and Other Stakeholders

Questions about who should teach a sophomore maker-oriented manufacturing course frequently arise when departments consider curricular change. These discussions often frame the decision as a choice between research-active faculty, professors of practice, or vocational experts, such as machinists and technicians. The maker space literature and prior curricular reform efforts suggest that this framing is incomplete, as effective implementation depends on complementary roles rather than substitution.

3.2.1 Instructional Team

Machinists and technical staff bring deep procedural expertise that is essential for safe and scalable instruction. Primary functions include laboratory execution, safety oversight, and equipment training. Their knowledge of machine operation, setup efficiency, tooling, and safety practices enables students to engage confidently with equipment and ensures consistency across laboratory sections. These contributions directly support professional responsibility and safety outcomes emphasized by ABET.

Research-active faculty contribute in a different but equally critical way. Even when they do not possess the same level of manual proficiency as a machinist, faculty provide conceptual integration, engineering judgment, and curricular coherence. They connect individual manufacturing processes to broader ideas, such as design for manufacturability, material process property relationships, and system-level trade-offs. They also position the course within the broader mechanical engineering curriculum, explicitly linking early hands-on experiences to later analytical courses, capstone design, and professional practice. Faculty are most effective when they focus on engineering decisions rather than tool operation alone.

Further, **professors of practice** can play an important role when their industry experience closely aligns with course objectives and institutional context. Professors of practice are uniquely positioned to connect the course content and learning objectives with what the industry looks for in graduates. For example, in this course, our professors of practice often interface with industry partners to facilitate guest lectures that overlay industry expertise with course content. As well, professors of practice often work with the Office of Professional Practice and support students as they search for internships and co-ops at the yearly job fairs – once again connecting the design and manufacturing skills students learn in the course to real-world opportunities. Lastly, professors of practice can build partnerships with industries that eventually lead to sponsored capstone design projects. Sponsored projects offer a reciprocal opportunity where students get to work on highly specific and identified design challenges, and industry representatives work closely with students nearing graduation and applying for jobs.

Lastly, **teaching assistants** provide students with peer mentorship and instruction as they work through the lab sessions and final project. Teaching assistants serve as supervisors during the lab sessions by providing background on the exercises that will be completed, shadowing students as they work with lab materials, and assisting students alongside the machine shop staff. Teaching assistants review the lab processes two weeks ahead of time so as to be prepared to best assist students during the lab session. Additionally, teaching assistants review students' lab memos, project deliverables, and mentor teams through challenges such as communication issues, unequal distribution of work, and design iterations. As a peer mentor, often having completed the course themselves or had considerable design experience elsewhere, teaching assistants reduce the barrier between students and the experts – machinists and technicians, research-active faculty, and professors of practice. By working closely with the student teams through the projects, teaching assistants also instill valuable insight and advice as the sophomore-level students transition into junior design and eventually their capstone design projects, further supporting the efficacy of design courses at this level.

3.2.2 Course Coordination and Development

When determining roles and responsibilities in a sophomore-level maker manufacturing course, programs benefit from distinguishing between course leadership and laboratory execution. Analogies such as the distinction between an electrician and an electrical engineer are useful in clarifying these roles. An electrician may be more skilled at executing wiring tasks, just as a machinist may be more fluent at operating a manual lathe. The engineer's responsibility, however, lies in system design, constraint evaluation, and integration of competing requirements. In the maker-oriented manufacturing course, faculty do not replace machinists. Instead, they interpret hands-on practice through an engineering lens that aligns with program outcomes and long-term student development.

In practice, this means designing laboratory activities around questions of manufacturability, tolerance selection, failure modes, and process selection. Standardized setups, fixtures, and safety protocols are developed in collaboration with technical staff, allowing faculty to concentrate on interpretation and reasoning. Students do not require their instructor to be the most skilled welder or machinist in the room. They benefit more from guidance on why joint design influences distortion, how process choices affect dimensional control, and how manufacturing constraints shape upstream design decisions. This approach aligns closely with ABET student outcomes related to design, experimentation, and problem solving. It also reinforces the role of faculty as engineering educators rather than vocational trainers, while still delivering authentic hands-on experiences. Lastly, many engineering graduates will likely work closely with machinists in their jobs – early collaboration and learning from these experts positions engineering students to be effective in their future jobs by recognizing and utilizing machinists' expertise and using concurrent engineering best practices.

4. Assessment and Results of Course Implementation

To evaluate the effectiveness of the redesigned sophomore-level manufacturing course, we analyzed end-of-semester course evaluations across multiple sections (N = 307 students total across datasets), including both Likert-scale responses and open-ended student feedback. The results reveal a consistent pattern: hands-on laboratory experiences are highly effective, while course organization and coordination at scale remain key challenges. This student feedback is presented below to provide insight into what students found helpful and what can continue to be improved. The following statistics and statements are based on students from three course sections from Fall 2025.

4.1 Student Demographics and Context

The course primarily serves sophomore mechanical engineering students, with over 82% of respondents identifying as sophomores (≈16% juniors) and nearly all students enrolled as part of their required curriculum. This context is important, as most students enter with limited prior exposure to manufacturing environments, reinforcing the importance of accessible, hands-on instruction early in the curriculum.

4.2 Student Perceptions and Instructional Effectiveness

The overwhelming majority of students (N=307 respondents) agree (~53%) or strongly agree (~27%) that the projects or laboratories aided them in achieving the course objectives, as seen in Figure 3. Further, most students (N=275 respondents) agree (~46%) or strongly agree (~43%) that the content of the labs is a worthwhile part of the course, as seen in Figure 4. These ratings are significantly higher than those for course organization or exams, indicating that experiential learning is the primary driver of student-perceived learning. Student comments strongly reinforce this finding:

- “The labs were very useful… and helped with my understanding of manufacturing.”
- “Getting hands-on experience with setting up automated CNC machines was very valuable… it lets students understand how to use some of the most powerful maker machines on campus.”
- “The initial labs are very informative and good practice in manufacturing techniques that I would not have gotten otherwise.”

These responses indicate that the course successfully achieves its primary objective: providing meaningful, early exposure to manufacturing processes in a way that builds both confidence and technical intuition. Student feedback reveals several consistent themes. Learners perceive the course as grounded in real practice, with lectures that connect theory to real-world use. They describe the instructional environment as accessible and supportive, noting that instructors and assistants are present, approachable, and invested in their progress. Students emphasize the coherence of the course structure. Many explicitly reference the alignment between lecture and lab, reporting that concepts introduced in class directly prepare them for shop work. This coherence reduces fragmentation and increases the perceived value of both components. Additionally, the learning climate is frequently characterized as inclusive and collaborative. Students describe an environment in which teams support one another and anxiety is managed constructively. This is particularly salient in high-stakes project contexts, where uncertainty and failure are inherent.

Although the lab sessions were received positively and aided students’ performance in the course, there are continued opportunities for improvement. Specifically, students (N=307 respondents) disagreed (~31%) or strongly disagreed (~29%) that the course was well organized, as seen in Figure 5, and was attributed to facilitating the logistics of this type of lab at scale. The students found that instructors (e.g., lecturers, teaching assistants, and machine shop staff) effectively communicated, answered students’ questions, and cared about student learning in the course with more than 84% rating agree and strongly agree (Figure 6).

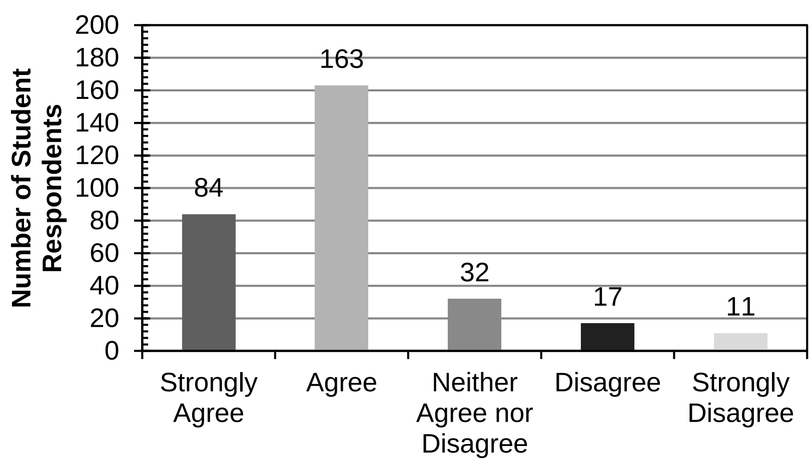

Figure 3: The projects or laboratories aid me in achieving the class objectives.

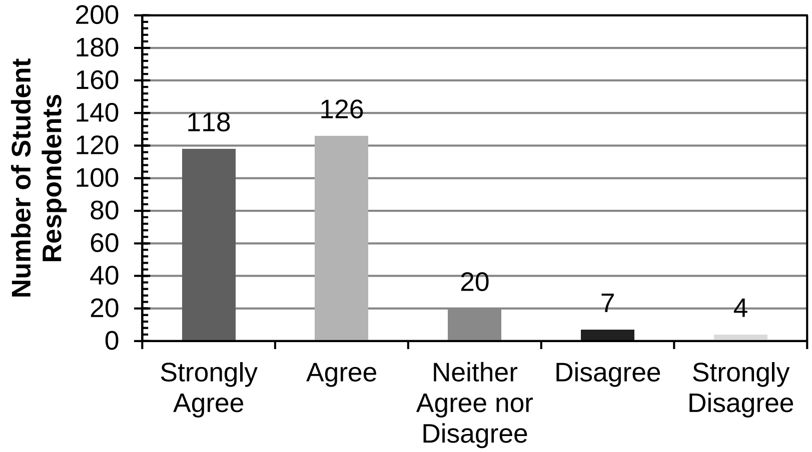

Figure 4: The content of the lab is a worthwhile part of this course.

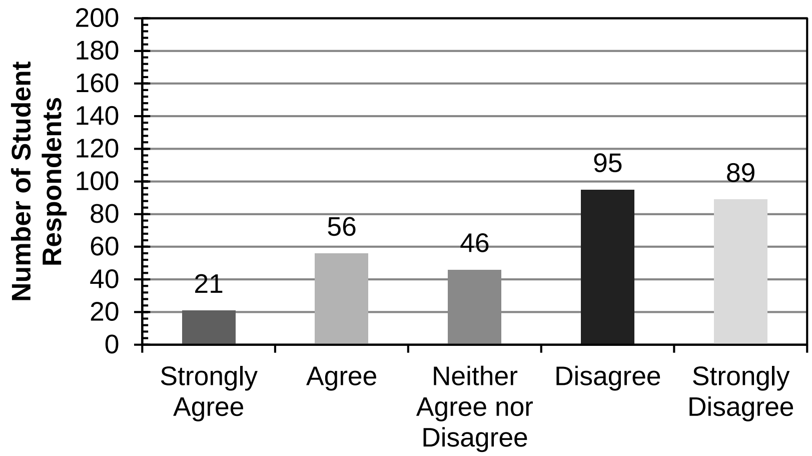

Figure 5: The course is well organized.

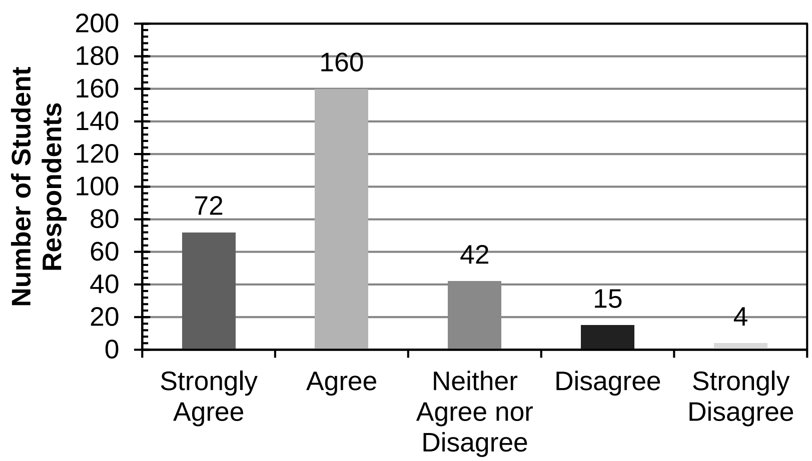

Figure 6: The instructors seem to care about my learning in this course.

In addition to responding to survey items, students were also given the opportunity to provide qualitative feedback regarding improvements that could be made to the course. Much of the student feedback, as evidenced by the survey responses in Figure 5, related to the organization of the course and the rollout of the final project. For example, several students noted that moving the timeline forward for starting the final project would be helpful: “If the final project was introduced and actually started two weeks before it really began, this would have spread out the work load over more time,” “I think it would be nice to have less labs and start the final project earlier in the semester,” and “I think starting the final project a week earlier would be very helpful for avoiding crowding in the ME shop.” This feedback was acted on, and we provide details about our revised course structure in the following section.

Students also mentioned the benefits they received from the labs, which support the survey results in Figures 3 and 4. For example, one student noted that: “The labs do a great job of providing practical opportunities to demonstrate manufacturing operations, the instructions were clear and the assistants were all helpful when needed,” while another stated, “Overall, the labs were set up well and I learned a lot from them. I do not think any lab should be removed because they all contribute to hands on expierence with machinery that is directly applicable to future endeavors.” Even though the organization and structure of the course can continue to be improved, it is heartening to receive feedback from students valuing the practical and hands-on nature of the lab sessions.

4.3 Integration of Lecture, Laboratory, and Project-Based Learning

A central objective of the course redesign is the intentional integration of lecture content, laboratory activities, and the semester-long design-and-build project through a just-in-time instructional model. Student responses suggest that this integration is generally effective in principle, though uneven in execution across sections.

Students frequently described strong alignment between lecture topics and laboratory activities, noting that conceptual material introduced in class directly supported their performance in the shop. For example, one student commented “I liked how the professors introduced all the labs and the lectures early was relevant to the labs.” This perceived coherence reduces fragmentation between instructional modes and reinforces the value of both lecture and laboratory components. As described in Section 4.2, students consistently emphasized that the course is grounded in real practice and that lectures help contextualize hands-on work.

However, this alignment was not universally experienced. A subset of students reported disconnects between lecture content and laboratory objectives. Another student commented, “The lectures were very disconnected from the labs and provided little to no insight into the main objective of the class.” Quantitative results reinforce this mixed perception. While laboratory-related items received strong ratings, supporting instructional structures were rated more moderately; assignments aided objectives - mean ≈ 3.2 - 3.5 out of 5 and exams aided objectives - mean ≈ 3.0 - 3.4 out of 5.

These findings suggest that while the pedagogical model of integrated learning is effective, its implementation depends heavily on coordination across instructors, timing of content delivery, and consistency across sections. At scale, maintaining tight coupling between lecture and laboratory remains a nontrivial challenge.

4.4 Industry-Relevant Learning and Professional Context

Student feedback strongly supports the value of integrating industry perspectives into the course. Guest lectures and case-based instruction were frequently cited as enhancing both relevance and engagement. Comments include "The GE and Busch speakers really showed some practical application of using DFM during product design" and "the lectures were a good blend of practical manufacturing knowledge and firsthand experiences from guest speakers in industry." These responses indicate that students are not only exposed to manufacturing processes but are also able to situate these processes within real engineering workflows, including design for manufacturability, production constraints, and product lifecycle considerations. Importantly, this industry integration appears to reinforce the course's broader educational objective: helping students transition from viewing engineering as abstract problem-solving to understanding it as decision-making under real-world constraints.

4.5 Student Engagement and Learning Environment

Beyond technical skill development, the course appears to significantly influence student engagement and perception of engineering education. Students consistently described the course as distinct from traditional theory-based classes. For example, comments include "I like how it's like a break from regular theory classes… but I'm still learning important skills" and "Class is fun and engaging… I'm still learning important skills." These responses suggest that the course plays a role in early professional identity formation, providing students with a tangible sense of what it means to "do" engineering.

Additionally, students frequently characterized the learning environment as collaborative and inclusive. As noted in Section 4.2, students reported that instructors and teaching assistants were approachable and invested in their success, contributing to a supportive atmosphere even in high-stakes project settings. This is further supported by instructor-related ratings, where more than 84% of students agreed or strongly agreed that instructors cared about their learning.

4.6 Course Organization and Implementation Challenges

Despite strong performance in hands-on learning and engagement, course organization emerged as the primary limitation of the implementation. Across multiple sections, students reported low ratings for course organization; mean = 2.3 - 2.8 out of 5. Consistent with the survey data, qualitative feedback highlights challenges related to communication, scheduling, and coordination. Student comments include "I felt very frustrated with the lack of structure and communication… due dates and assignments were constantly changing."

In addition, students identified specific structural issues related to the timing and rollout of the final project. Comments state, "If the final project was introduced and actually started two weeks before it really began, this would have spread out the workload…" and "I think starting the final project a week earlier would be very helpful for avoiding crowding in the ME shop." These concerns reflect the inherent complexity of delivering resource-intensive, hands-on instruction at scale, where coordination of facilities, instructional staff, and student teams must be tightly managed.

Importantly, student feedback suggests that dissatisfaction is not directed at the course content or learning model, but rather at the logistical execution. This distinction is critical: the underlying pedagogical approach is validated, while implementation systems require refinement. In response to this feedback, adjustments were made to the course structure, including earlier introduction of the final project and redistribution of workload across the semester. These changes are discussed further in the following section.

4.7 Scalability and Programmatic Impact

The instructional model described in this work has expanded beyond a single course offering and now serves as a foundational component of the mechanical engineering curriculum. At full implementation, the course supports approximately 1,200 students annually, with instruction delivered through a coordinated team of more than 40 undergraduate and graduate teaching assistants. Scaling the course to this level required the development of robust instructional infrastructure, including: standardized laboratory modules, formalized safety training and certification, common grading rubrics and deliverables, and structured teaching assistant training programs. These systems ensure that instructional quality is system-dependent rather than instructor-dependent, enabling consistent delivery across sections and semesters. The model is being adopted at a second campus, where new and existing faculty, along with a large cohort of teaching assistants, are using shared systems, training materials, and lab structures.

In parallel, the course has established sustained engagement with industry partners. More than a dozen companies and alumni participate annually through guest lectures, design reviews, and recruitment activities. These relationships extend the impact of the course beyond the classroom, connecting early undergraduate experiences with internships, co-ops, and capstone design opportunities.

The key outcome is that experiential, maker-centered learning is no longer an isolated innovation but a scalable, program-level feature. The course serves as a gateway into the broader design and manufacturing sequence, aligning early skill development with downstream educational and professional experiences.

5. Implications for Engineering Education

This work suggests several broader implications. First, early exposure to structured making reshapes how students understand engineering. By encountering ambiguity, iteration, and physical constraints in their second year, students develop professional identity earlier and with greater realism. Further, the tight coupling of theory and practice improves conceptual transfer for students, as evidenced by (Yoder et al., 2004). When abstract concepts are introduced in anticipation of immediate use, students are more likely to internalize them as tools rather than as content.

Second, industry-aligned instruction can enhance rigor without diluting academic control. By embedding practitioners within required modules, courses retain ownership of outcomes while benefiting from authentic context. National Academy of Engineering reports, including *The Engineer of 2020*, emphasize attributes such as creativity, practical ingenuity, adaptability, ethical responsibility, and lifelong learning. Early (i.e., freshman and sophomore) maker-centered manufacturing courses directly support these attributes by normalizing iteration, failure, teamwork, and engagement with physical systems early in the undergraduate experience. Students learn that engineering involves working within constraints, learning from imperfect outcomes, and refining designs based on evidence, which is further reinforced by the authentic context of industry-aligned projects using maker spaces and hands-on activities.

From an accreditation perspective, sophomore maker skills courses provide early opportunities for students to demonstrate ABET outcomes related to engineering design, experimentation, interpretation of results, and teamwork. Importantly, these outcomes are addressed without prematurely introducing advanced analytical content. This preserves curriculum content scaffolding while strengthening student preparation for later coursework and professional practice.

Finally, scalable experiential models are feasible in large-enrollment programs when supported by intentional instructional design, TA infrastructure, and modular content. The course described here demonstrates that hands-on manufacturing education does not need to be boutique. With appropriate systems, it can become a core, high-impact element of a modern Mechanical Engineering curriculum.

6. Lessons Learned and Next Steps

Taken together, the assessment results indicate three primary outcomes. First, hands-on laboratories are highly effective in supporting student learning and confidence in manufacturing processes. Second, the integration of industry context enhances relevance and engagement, helping students connect coursework to professional practice. Third, scalability introduces coordination challenges, with course organization and communication representing the primary areas for improvement. These findings suggest that while experiential learning scales successfully from a pedagogical perspective, the limiting factor shifts to operational complexity. As enrollment increases, challenges related to scheduling, equipment availability, instructional coordination, and project management become dominant factors influencing student experience.

6.1 Lessons Learned from Implementation at Scale

The experience of running multiple course and lab sections with more than 300 students provided several important insights into the constraints of delivering hands-on manufacturing education at scale. A primary challenge involved laboratory access and makeup sessions. During Fall 2025, students who missed lab sessions were accommodated through additional open lab time on Fridays. While effective at moderate scale, this approach will not be sustainable as enrollment increases, particularly in Spring 2026 when lab utilization approaches full capacity. This highlights the need for more structured and scalable approaches to handling absences and incomplete work.

A second recurring issue was equipment availability and downtime. Because most machines operate at or near full capacity during scheduled lab sessions, even minor disruptions, such as a CNC mill going offline, resulted in cascading delays. Students were often required to wait for access to equipment, creating bottlenecks that affected both individual progress and overall lab flow. While manageable at smaller scale, these disruptions become significantly more impactful as throughput increases.

Similar constraints emerged in the final project phase, particularly with shared resources such as CO_2 and fiber laser cutters. Demand for these machines exceeded expectations, with a large proportion of teams selecting fabrication methods that relied on the same equipment. Although batching multiple teams' parts into single cutting operations improved efficiency, it also introduced risk: errors in a single setup affected multiple teams simultaneously. Additionally, longer-than-expected lead times for materials and machine access contributed to project congestion near the end of the semester. Collectively, these observations reinforce a key lesson: in large-scale, hands-on courses, system-level constraints (equipment, scheduling, coordination) dominate over individual instructional factors.

6.2 Instructional and Curricular Opportunities

Beyond logistical challenges, the course also revealed opportunities for strengthening the instructional model. One important direction is the integration of research-active faculty expertise into sophomore-level instruction. By leveraging the course conversion framework described earlier, faculty with backgrounds in areas such as materials processing, thermal systems, or manufacturing science can translate advanced topics into accessible, hands-on experiences. This approach preserves technical rigor while making content appropriate for early-stage students. This model also expands instructional capacity. By enabling a broader range of faculty to contribute to the course, programs can increase enrollment while maintaining alignment with disciplinary expertise and emerging industry needs.

6.3 Next Steps and Future Work

Based on these lessons, several targeted improvements are planned for future iterations of the course. From a course structure perspective, adjustments will include: (1) introducing the final project earlier in the semester to better distribute workload; (2) reducing late-semester congestion in shared fabrication resources; and (3) improving alignment between lecture, lab, and project timelines. From an operational standpoint, future efforts will focus on: (1) developing scalable strategies for lab makeup sessions; (2) increasing redundancy in critical equipment where possible; and (3) improving scheduling systems to reduce bottlenecks and idle time. From a research and assessment perspective, future work will move beyond end-of-course evaluations toward longitudinal analysis. Planned efforts include tracking skill development from sophomore through senior year; evaluating how hands-on experiences influence performance in upper-level courses; assessing the impact of manufacturing skills on internship and co-op readiness; and engaging industry partners to refine learning outcomes based on workforce needs.

6.4 Broader Implications

As the course continues to evolve, the overarching goal is to transition experiential, maker-centered learning from an isolated innovation to a sustainable, program-level feature. The results presented here suggest that this is achievable, provided that sufficient attention is given to the operational systems required to support large-scale implementation.

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