The Future of Engineering Education
2024 Annual Conference & Exposition
Oregon Convention Center
Portland, OR . June 23 - 26, 2024
ASEE
Paper ID #41073

The Mini-Mill Experience: A Self-Paced Introductory Machining Exercise for Mechanical Engineering Students

Prof. Jenni Buckley, University of Delaware

Dr. Buckley is a Professor of Mechanical Engineering at University of Delaware. She received her BS (2001) in Mechanical Engineering from the University of Delaware, and her MS (2004) and PhD (2006) in Mechanical Engineering from University of California, Berkeley. She is the Co-Founder and President of The Perry Initiative, an organization focused on diversifying the talent pipeline in engineering and orthopaedics.

Dr. Amy Trauth, American Institutes for Research

Amy Trauth, Ph.D., is a Researcher at the American Institutes for Research (AIR) and Affiliate Faculty in the Department of Mechanical Engineering at the University of Delaware. Her research focuses on inservice and preservice teacher education and inclusive, accessible learning environments for students in P-16 STEM education.

Dr. Alexander John De Rosa, University of Delaware

Alexander De Rosa is an Associate Professor in Mechanical Engineering at The University of Delaware. He gained his Ph.D. in Mechanical Engineering from The Pennsylvania State University in 2015, where he worked on experimental combustion research applied to gas turbine engines, and his M.Eng. in Mechanical Engineering from Imperial College London in 2010. Alex's research focuses on the transfer of learning between various courses and contexts and the professional formation of engineers.

The Mini-Mill Experience: A Self-Paced Introductory Machining Exercise for Mechanical Engineering Students

Jenni M. Buckley PhD[1,2], Amy Trauth PhD[1,3], Alex De Rosa PhD[1]
[1]University of Delaware, College of Engineering
[2]University of Delaware, College of Education and Human Development
[3]American Institutes for Research

Introduction

Practicing mechanical engineers interface with machinists to design and manufacture components in metal and other engineered materials. Direct, hands-on exposure to precision machining operations, like mill and lathe work, helps engineering students design manufacturable components and graduate as professionals who are better able to collaborate with machinists, operators, and other members of a manufacturing team [1]. Although the benefit of direct experience with machining is indisputable, programs struggle to implement "shop" experiences with fidelity for a variety of reasons, including: (1) constraints on equipment, staffing, and material resources, particularly for large-enrollment classes; (2) long gaps in the curriculum between machining experiences, leading to loss of manufacturing competencies; or (3) a generational shift in incoming students' prior experiences such that a familiarity with hands-on construction and basic tools cannot be assumed [2, 3]. As a result, mechanical engineering undergraduate programs provide inadequate opportunities for students to develop the machining competencies that they may need in industry [4-6].

The engineering education literature contains a variety of machining exercises for mechanical engineering students. The MIT Stirling Engine Project [2], developed over 20 years ago and adapted by others [7], was designed to provide middle years students with experience in manual mill, lathe, and CNC mill operations, as well as stock hardware, fits, and tolerances. Other engineering educators have presented projects of similar complexity, including a fast-return actuator [8], compressed air engine [9], and ceiling hoist [10]. These projects are typically implemented in standalone lab settings [7] or embedded within junior year machine design courses [3, 10] and students work in groups to manufacture their prototype from a common, instructor-specified design. Implementation of machining projects has been linked to improved course evaluations [3, 11] and enhanced understanding of theory-based course material [10]; however, prior studies do not present evidence of improvement in students' self-efficacy with regards to specific machining skills nor do these prior studies adequately demonstrate the transferability of machining skills to later courses.

From a learning perspective, there are several issues with machining exercises for mechanical engineering students in extant literature. First, the exercises were mostly conducted with students working in teams [7-10] rather than individually. Although it more resource efficient, placing students in teams can limit individual skill development, particularly when students enter the course with differences in prior learning experiences and self-efficacy in hands-on skills [12]. Additionally, machining projects in existing literature are rather unforgiving for first-time learners in terms of complexity (e.g., multiple parts with tight tolerances) and choice of materials (e.g., steel or aluminum). With few exceptions [9, 13], there is little mention of scaffolding of students' machining experiences, such as moving them from simple parts that introduce basic mill operations such as tool change or face milling to designs with more complex features and tight tolerances. Lastly, existing literature does not make clear the instructional techniques used to teach students' shop skills. In light of the aforementioned complexity of these projects, one can reasonably assume students were closely coached and monitored, thus limiting their opportunities to develop enduring competencies in machining. While coaching is absolutely necessary when students are first learning to safely use high powered shop equipment, the degree of direct intervention would ideally fade as students' skills progress [14], allowing them to develop core skill mastery and agency as learners through direct use of a range of machining techniques.

Distributed Scaffolds to Promote Student Skill Development

In learning environments where students are expected to acquire complex sets of knowledge and skills, distributed scaffolding can support the differential needs of students and their success in completing project-based tasks [15]. Here we define scaffolding as material and pedagogical support provided by instructors that is calibrated to students' current level of skill and helps students complete tasks that they would otherwise be unable to accomplish alone [16]. Material scaffolds are those purposefully designed and embedded in instructional materials in ways that anticipate difficulties students might encounter during learning. Pedagogical scaffolds can be planned or spontaneous. For example, a spontaneous pedagogical scaffold might be personal support by an instructor or knowledgeable peer often deployed in the moment when a student is in need of additional support. Using pre-planned guiding questions by an instructor during a learning activity is an example of a planned pedagogical scaffold. Offering in-the-moment feedback about student progress during a learning activity is an example of a spontaneous pedagogical scaffold. Azevedo et al. [17, 18] referred to these types of scaffolds as fixed and adaptive, respectively. Although fixed, material scaffolds are necessary to support student comprehension of a learning task and promote self-regulation to task completion, Azevedo et al.'s research and others [19-21] have shown that the integration of adaptive, pedagogical scaffolds catalyzes student performance, especially those with low prior knowledge or skill.

Distributed scaffolds in project-based learning in the early years of postsecondary engineering programs has indicated positive student outcomes related to academic engagement, performance on key assignments, and development and use of fabrication and prototyping skills necessary for the profession. Allam et al. [22] found scaffolding in freshman engineering project-based learning yielded greater than normal student engagement in all phases of design and in overall project management. Carpenter et al. [14] also implemented scaffolds in project-based learning in freshman engineering design. Their results indicated that gradually tapering or "fading" adaptive, pedagogical scaffolds by the instructor advanced greater student mastery of design skills needed to complete project activities. Similarly, Cheville and Welch [19] found that integrating scaffolded project management activities in a pre-capstone electrical engineering design course produced positive changes in student mastery of course learning outcomes and increased successful completion of design projects by student teams. Overall, prior literature suggests that providing the right amount of material and pedagogical scaffolding, and fading this distributed scaffolding over time, provides learners with balanced supports that increase independence and competence in the use of engineering knowledge and skills.

The Mini-Mill Experience

In this study, we present a novel shop exercise for mechanical engineering students, called the mini-mill experience, which is focused exclusively on manual mill training. This hands-on experience can be embedded in early-years design courses. Addressing shortcomings in previously published engineering education literature, the mini-mill experience is completed by students individually, and it is designed to take every student from a beginning mill user to an experienced one by having them independently manufacture a basic part.

The mini-mill experience was designed as a stand-alone exercise within an introductory mechanical engineering design course that involved both lecture (2 credits) and laboratory (1 credit) sessions. Learning objectives for the mini-mill experience were to: (1) learn the safety and controls of a manual milling machine and basic milling operations that included fixed, material scaffolds designed by the course instructor; (3) practice reading and manufacturing from standard engineering drawings; and (2) independently apply knowledge of milling machine controls and operations to create a basic part with adaptive, pedagogical scaffolding from teaching assistants and machinists. All deliverables for this exercise were individually completed by students and required a mixture of hands-on activity, written reflection, and online training and survey completion. In total, the mini-mill student deliverables represent 3% of the total course grade, roughly equivalent to a weekly homework assignment in the overarching course. The mini-mill experience began one quarter of the way through the semester (week 4 of 15) after students were introduced to standard engineering drawings in class and homework assignments. The assignment lasted approximately six weeks and was administered during both weekly lab meetings and out-of-class time.

The mini-mill experience involved several stages. First, students watched a training video that covered the parts of the mill, basic controls, and safety. Students then completed a multiple-choice quiz after watching the video, and passing the quiz was a requirement of proceeding to the next part of the assignment. As part of a regularly scheduled lab session, students received hands-on training on a mini-mill (Figure 1, left), with each student operating their own machine. With intensive coaching from instructors, students manufactured a common part from a machinable wax block (Figure 1, right). Manufacture of this part – called Part 1: Guided Manufacture Exercise – required students to face off two edges, perform a tool change from an endmill to a drill bit, and drill a hole. Completion of safety training and Part 1 constituted 10% of the mini-mill experience grade.

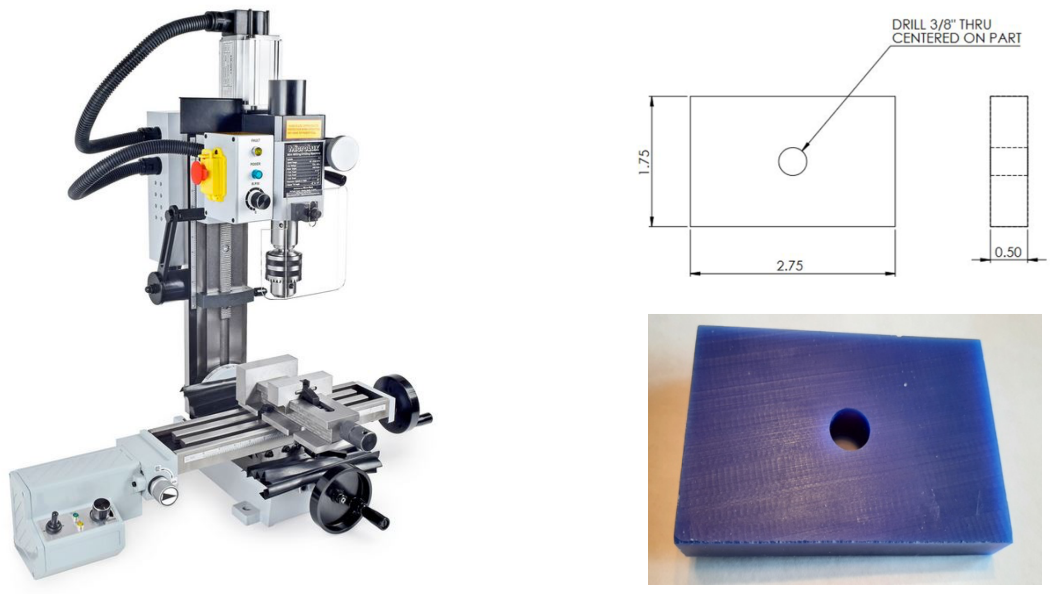

Figure 1: (left) Tabletop mini-mill (R8 Miniature Milling Machine, MicroLux) used for this exercise; (right) common part made from machinable wax for Part 1: Guided Manufacture.

The second part of the mini-mill experience, called Part 2: Independent Manufacturing Exercise, involved students independently using the mill to manufacture pre-designed parts out of wood. There were nine different wooden parts from which students could choose (see Figure 2), all of which were based on a popular commercial toy set, the *Construction Set in a Box* by Melissa & Doug®. Parts were categorized by machining complexity as either beginner, intermediate, or advanced. Students received equivalent credit regardless of their choice of part. A standard engineering drawing was provided for every part that included orthographic projection, isometric view, dimensions, and complete title block. Part 2 was a self-paced, out-of-class time exercise that took place over six weeks. Students reserved a mini-mill for one-hour sessions during regular shop hours (9 am – 5 pm, Monday through Friday). Shop instructors were purposefully hands-off with students as they worked on Part 2, intervening only if there was a safety issue. Students could make as many attempts as necessary to complete their part. Stock wood and appropriate tooling were readily available, and students also had access to sandpaper, hand tools, and a belt sander. Completion of the hands-on portion of Part 2 constituted 45% of the mini-mill experience grade.

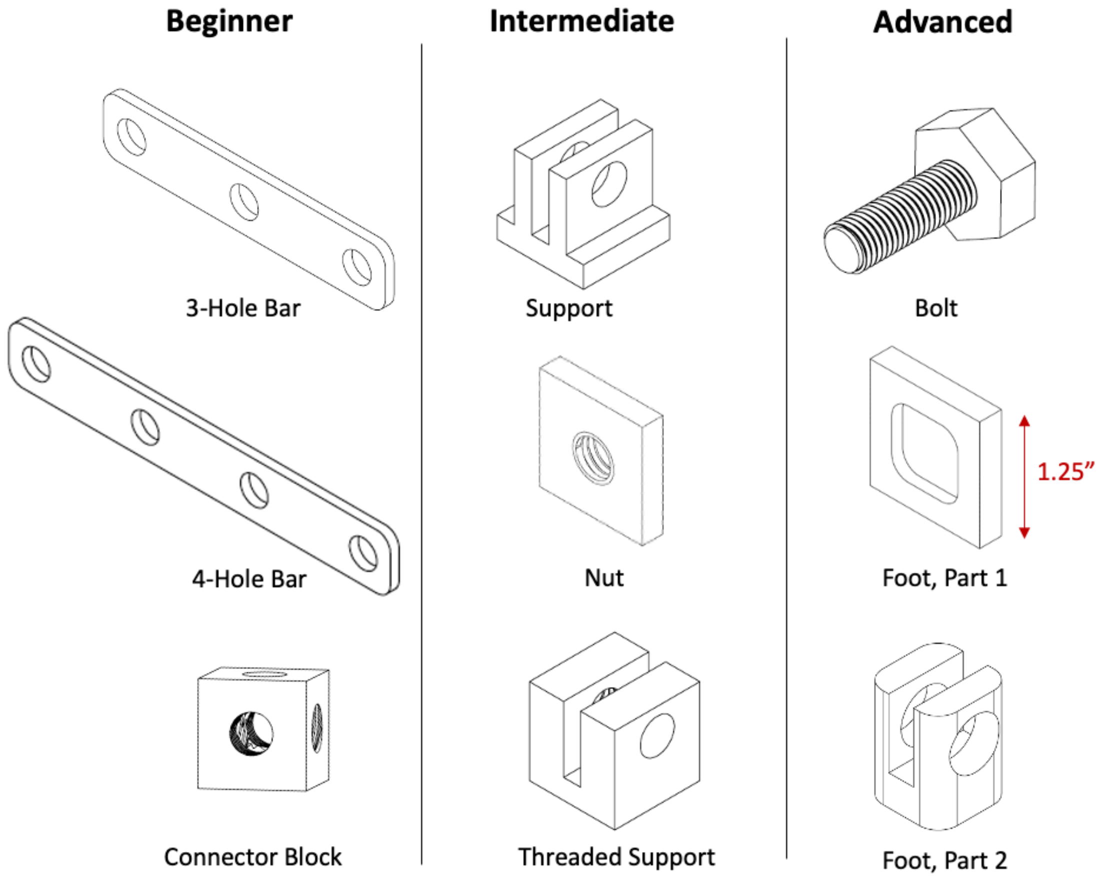

Figure 2: Designs for Part 2: Independent Manufacturing Exercise were reverse-engineered from a commercial toy set (*Construction Set in a Box* by Melissa & Doug®). All parts are shown at the same scale.

After completing Part 2, students submitted a written brief that included three components. First, students composed a "standard operating procedure" of the manufacturing steps that they took to make the part, specifically describing tooling, mill operations, and critical measurements. Second, they included a neatly staged photograph of their final part and a brief assessment of its quality and functionality. Students were required to comment on whether the critical part dimensions matched the provided engineering drawings. Lastly, students documented a quality and safety check. For quality, they compared final dimensions of their part to the provided drawings. The safety check involved performing a sharp edge test according to the ASTM F963-11 Toy Safety Standard. Completion of the Part 2 reflection was worth 45% of the mini-mill experience grade.

The primary aim of the mini-mill experience was for students to learn and independently apply basic safety, controls, and operations for a manual mill, and to develop confidence for doing so. As such, our research questions sought to address these constructs:

1. To what extent was the mini-mill experience associated with positive student perceptions of their skills for and confidence in machining basic parts?
2. To what extent is the mini-mill experience scalable in early-years mechanical engineering courses?

To discern the effectiveness of the mini-mill experience in developing students' machining skills, we gathered and analyzed data on student completion rates for safety training, guided machining (Part 1), and independent machining (Part 2) exercises. To determine student confidence in machining, we collected responses on a voluntary, end-of-assignment survey which prompted students to rate their confidence in identifying equipment, performing mill operations, and perceived likelihood of skills transfer to future design projects. To better understand intervention scalability, we monitored resource use for the mini-mill exercise.

Methods

Study Context. The study took place in a large-enrollment introductory design course which enrolled second semester freshmen mechanical engineering students at a mid-sized university in the Mid-Atlantic region. Course topics included CAD fundamentals, engineering drawings, common materials and hardware, and other additive and subtractive manufacturing modalities, such as 3D printing, laser cutting, and basic carpentry. Total enrollment in the course was 187 students. The course was taught as a single lecture section complemented by multiple lab sections of approximately 30 students each. One faculty member taught the course, supported by two master machinists for the mini-mill exercise and approximately ten undergraduate teaching assistants who helped with all course grading, office hours, and hands-on exercises. This study took place during the first year of implementation of the mini-mill experience.

Data Collection and Analysis. This study relied primarily on a voluntary end-of-experience student survey, which was developed by the research team. In the survey, no personally identifiable information was collected from student respondents. This was an intentional feature of the survey as we wanted to minimize social-desirability bias in students' responses. The voluntary survey response rate was 66% (N=123) of the students enrolled in the course. There were four survey components. In the first part, students were asked to rate their level of experience with mill work prior to the course. Ratings were on a 4-point Likert scale that ranged from "no experience" to "expert." Students were then asked to rate their level of confidence in their ability to identify tooling and parts of the mill (e.g., e-stop, speed control, endmill) on a 4-point Likert scale from very confident to very unconfident. In the second part of the survey, students were prompted to rate their confidence level with various mill operations on the same 4-point Likert scale from very confident to very unconfident. In the third part, students were asked to rate the utility of the mini-mill experience as an engineering student on a 4-point Likert scale from strongly agree to strongly disagree. In the last part, students were prompted to respond to three open-ended questions that asked them to provide advice to other novice mill users and to offer a balanced critique of the experience. Survey responses were analyzed using descriptive statistics for Likert-scale responses and thematic analysis of written responses on open-ended questions [23]. Repeated Chi-Squared tests were used to determine if exercise completion or prior mill experience affected student responses for identifying parts of the mill, performing mill operations, or perceived utility of the exercise as a whole (JMP Pro 17, $p<0.05$ for significance).

We also monitored completion rates of the three elements of the assignment, namely, safety training, Part 1: Guided Manufacture, and Part 2: Independent Manufacture. Our team tracked materials costs and personnel time used during the mini-mill experience as an estimation of the exercise's scalability at other institutions.

Results

The resources required to administer the mini-mill experience in a large-enrollment (N=187) course were fairly modest. Six mini-mills (R8 Miniature Milling Machine, MicroLux) were purchased, along with all required fixtures and tooling, at a one-time cost of approximately $12,000. Consumable goods, which included stock pine wood, machinable wax, and sandpaper, were approximately $2 per student. The exercise began on Week 4 of the semester and concluded six weeks later. It was supervised by a rotating group of two machinists and ten undergraduate teaching assistants, each working a maximum of 10 hours per week.

Student participation in all components of the mini-mill experience was fairly high. All students completed safety training, and all but one student completed Part 1: Guided Manufacture. Part 2: Independent Manufacture was completed by 86% of students enrolled in the course. Figure 3 shows examples of parts produced by students during Part 2 of the mini-mill exercise.

Figure 3: Examples of students' work for Part 2: Independent Manufacture exercise: (left) connector block (beginner level), (middle) support (intermediate level), and (right) bolt (advanced level).

Among survey respondents, the majority (77%) reported having no prior experience with the mill before the mini-mill exercise. Nine percent (9%) of students identified as novices with limited prior experience, 13% as intermediate users, and <1% (1 student) as an expert. After completing the mini-mill experience, students indicated a substantial amount of confidence in their ability to identify basic parts of the mill. More than 95% of respondents were very confident or somewhat confident that they could successfully identify the e-stop, axis lock, speed control, and parallels on the mill. Fewer students, but still a majority, indicated they were very confident or somewhat confident they could identify an endmill (82.6%), a collet (83.3%), and a spindle (83.3%). Although there was a trend towards those with no experience feeling less able to identify some parts, there was no statistically significant difference in perceived ability to identify parts by experience level [Chi-Sq(9, N = 144) = 5.79-14.20, p=0.12-0.74]. Similarly, students' prior experience level was not correlated with completion of Part 2: Independent Manufacture [Chi-Sq(3, N = 144) = 5.14, p=0.16].

Students' confidence in their ability to perform specific mill operations varied by operation type (Figure 4). Students reported highest confidence in their ability to face off parts, create through holes, and positioning parts using the mill's x-y-z controls and parallels. Students were least confident in tapping holes and creating a channel or recess in a part. Compared to students with perceived intermediate and expert level expertise, self-reported novices and those with no prior mill experience were significantly less likely to feel confident in performing the following operations: (1) removing and installing tools from the spindle (Chi-Sq(9, N = 144) = 17.54, *p*=0.04), and (2) choosing appropriate spindle speed and depth of cut (Chi-Sq(9, N = 144) = 21.33, *p*=0.01). There was no significant difference in confidence related to mill operations between students who did and did not complete the Part 2 assignment (Chi-Sq(3, N = 144) = 0.40-5.15, *p*=0.16-0.82).

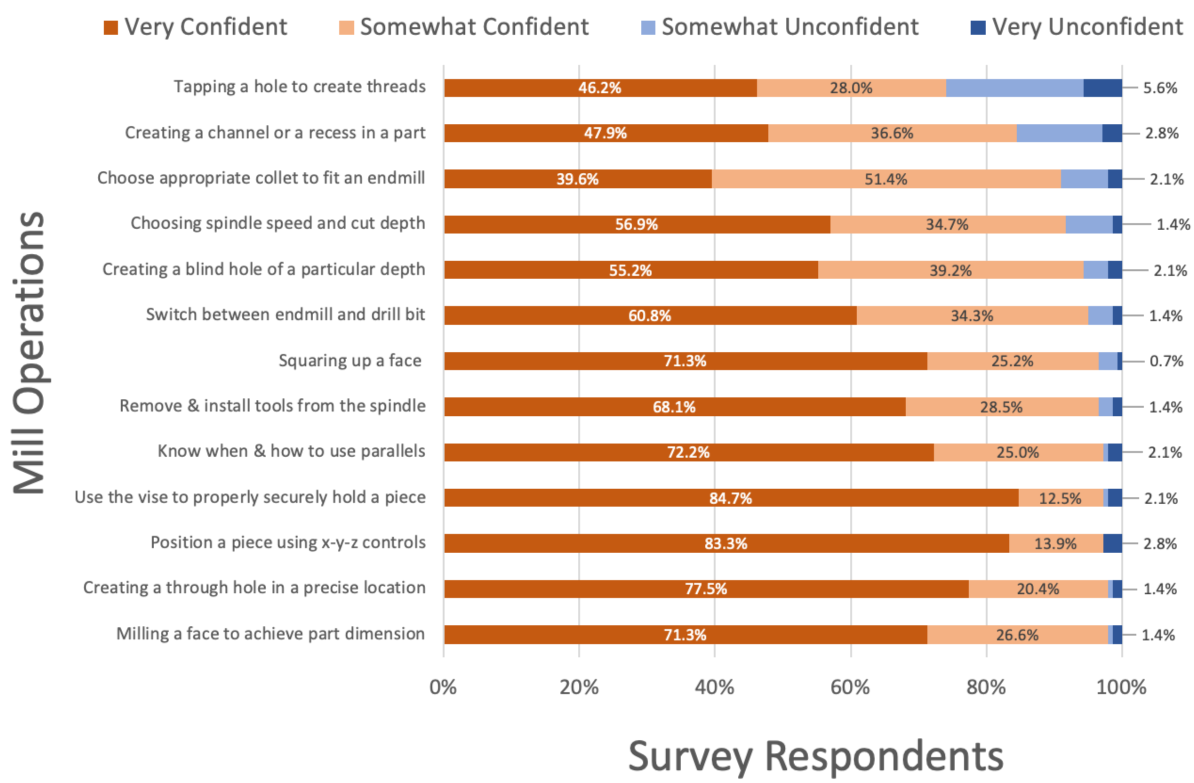

Figure 4: Survey results showing students' self-confidence for various mill operations (N=144).

On the whole, students agreed the mini-mill experience was a useful exercise for them (Figure 5). Over 80% strongly agreed or somewhat agreed they could now make a basic part, explain safety practices to others, and compare and contrast milling with other fabrication techniques like drilling, sawing, and sanding. A total of 90% of students strongly agreed or somewhat agreed that they were looking forward to using a mill to make parts in future courses and 89% strongly agreed or somewhat agreed that they were not intimidated or afraid to use the mill. Students with no prior mill experience were less likely to strongly agree with the statement "*I am not intimidated or afraid to use the mill to make a part*" [Chi-Sq(9, N = 144) = 18.85, *p*=0.03]. That said, only 10.8% of students with no prior experience disagreed with this statement, and this is in-line with rates for other experience levels. There was no significant difference in responses with self-reported mill experience level to other general statements about mill usage (see Figure 5) [Chi-Sq(9, N = 144) = 4.92-8.18, p=0.51-0.84]. Similarly, completion of Part 2 did not affect responses for general statements about mill usage [Chi-Sq(3, N = 144) = 3.20-7.08, p=0.07-0.36].

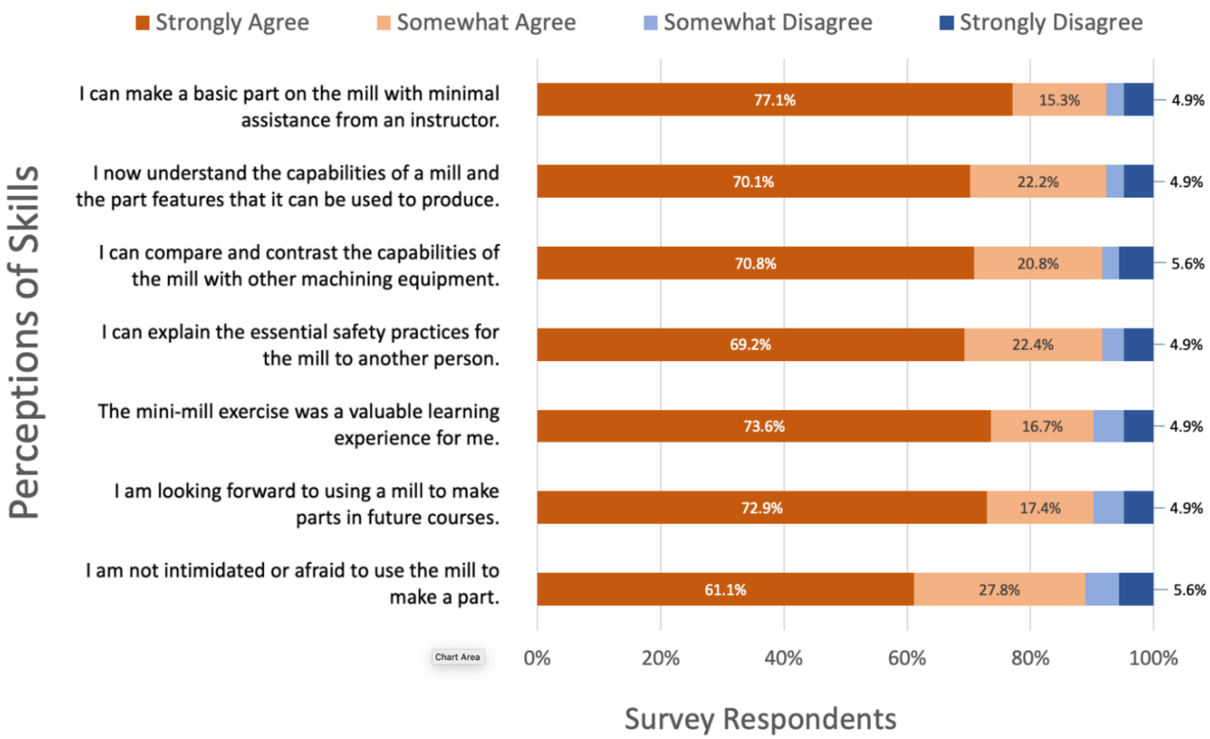

Figure 5: Survey results for students' perceptions of their skills related to the mini-mill (N=144).

Students' written responses on end-of-survey questions were subjected to thematic analysis [23]. When asked what advice they would give to someone just learning how to use a mill, students stressed: (1) the need to proceed slowly and methodically (n=45); (2) the need to review instructional materials before the activity (n=31); and (3) recommendations to ask questions of the instructional staff if unsure of how to proceed (n=33). Twenty-nine (29) participants also disclosed that they were initially apprehensive and/or intimidated, that this lack of confidence was unfounded, and that they suggest others not be scared and open themselves to this experience. In terms of the positive aspects students took from the experience, they saw value in learning a new manufacturing skill (n=60) and many found the experience to be fun and enjoyable (n=21). The hands-on nature of the activities was also discussed (n=11) and the extensive support and time spent learning from the instructional team was highlighted (n=16). In terms of potential improvements to the mini-mill experience, participants suggested that general accessibility of the machines was a problem in some capacity (n=23), be it available hours or number of open machines. The timing of the activity within the semester was also suggested as problematic with several students indicating a desire to start the mini-mill experience earlier (n=10). Interestingly, there was strong support for additional fabrication activities to be included in the experience (n=29), a result that suggests students wanted more activities and time with the equipment. There was no observable correlation between students who wanted more activities to be included and prior levels of experience with milling, e.g., students who considered themselves experts were generally not those asking for more machine time or advanced part options. Several students also asked for more resources and learning materials to be provided online (n=9), and some participants asked for milling activities in general to be further integrated into the course as a whole (n=6).

Figure 6: Select student responses to free-response survey questions: (a) "What advice would you give to someone who is just learning how to operate a mill?"; (b) "What are the positive aspects of this mill training exercise?"; and (c) "How could we improve this exercise for future years?"

(a) Take your time and use the machine slowly, mistakes might happen but it's a learning process.

(a) I now feel more confident in my ability to make complex parts on the mill.

(b) I learned how to use a mill for the first time and now I am confident about using them in the future.

(b) I feel a lot more comfortable doing manufacturing on the mill, which is huge as I had no experience prior.

(c) This exercise could be improved by increasing the availability of mini-mill TAs for the weeks just after the first training exercise.

Discussion

This paper presents a novel shop exercise for mechanical engineering students, called the mini-mill experience, which addresses the need for a hands-on, introductory machining experience that can be embedded into early-years courses. The mini-mill experience assumes no pre-requisite experience with machining, and it is completed individually by each student at their own pace with the end goal being independent operation of a manual mill to make simple parts. The mini-mill experience was successfully piloted in our large-enrollment freshmen year mechanical engineering design course, where it ran predominantly as an out-of-class time activity. The set-up costs were relatively modest, largely due to the use of hobby-grade mini-mills and wood, rather than metal stock. Trained teaching assistants were able to support student learning alongside machinists, which allowed the exercise to be scaled to a large class size.

The results of our evaluation indicate that the mini-mill experience is an effective introductory machining exercise for fostering students' confidence for basic manual mill operations. The vast majority of students independently manufactured a part even though they had no prior experience with a mill. As a whole, students felt confident in their ability to identify critical parts of the mill and to perform basic mill operations, with confidence for some more complex mill operations (e.g., choosing spindle speed) differing by student experience level. The mini-mill experience may have helped to normalize use of heavy machinery in the shop as evidenced by the majority of student responses indicating they were not intimidated by the mill and were looking forward to future shop exercises. Findings from student comments on the survey suggest that the adaptive, pedagogical approach rather than direct instruction used by instructors led to perceptions of mastery that may carry forward into future design courses. Interestingly, we found no difference in confidence between students who partially completed (Part 1 only) and fully completed the mini-mill exercise. While we suspect that this is mainly attributable to the partial completion group (n=20) being under-powered, further work by our group will attempt to disaggregate the effects of both guided (Part 1) and independent (Part 2) manufacturing exercises.

The mini-mill experience bridges a gap in the mechanical engineering curriculum as it relates to hands-on manufacturing instruction. Prior studies have introduced manufacturing exercises where students create tightly toleranced, multi-part prototypes [2, 7-10]. While impressive, these exercises may not be optimal for students with little to no prior shop experience. Work by Lalley et al [13], Malicky et al [8], and Keifer et al [1, 24] acknowledged the need to scaffold manufacturing experiences, starting with simple geometries and manual techniques and building towards assemblies and CNC equipment.

The mini-mill experience was designed as a student's first exposure to machining, and it was purposefully designed to provide a balance of direct instruction (Part 1: Guided Manufacture) and independent operation (Part 2: Independent Manufacture). Furthermore, there is value in the fact that the exercise is designed to be completed individually, rather than in groups as with prior studies [7-10]. Research by our own group [12] has demonstrated the importance of individual manufacturing experiences, which boost student self-efficacy for hands-on tasks, especially for students with low baseline self-efficacy in this area. Moreover, our findings are supported by prior research on distributed scaffolding in learning environments [15, 20, 21], which indicate fixed, material scaffolds can offer an initial introduction to knowledge and skills needed to orient students to safe mill operations. However, adaptive, pedagogical approaches are critical to ensure each student can complete the task with responsive support intended to foster deep learning that is transferable to future projects. Though team-based assignments conserve resources, the logistics of the mini-mill experience make it possible to offer a meaningful machining exercise to students individually, with reasonable constraints on equipment, material, and personnel. The use of hobby-grade, manual mini-mills as "training wheels" for full-sized milling machines allows programs to purchase a fleet of mills that require no specialized power or air hook-ups and can be safely monitored in part by trained teaching assistants.

There are several strengths and some caveats to the work presented in this paper that should be addressed. The curricular design of the mini-mill experience explicitly promotes skill mastery by scaffolding student manufacture of a common part under direct instructor guidance and then progress to independently manufacturing a more complex part of their choosing. This progression, as well as the written brief at the end of the assignment, were important for solidifying newly acquired skills. Despite effectively doubling the amount of equipment time required for each student, the mini-mill experience was successfully embedded in a large-enrollment course with reasonable expenditures for equipment, materials, and personnel. This can again be attributed to the curricular design and, in particular, use of the mini-mills rather than full-sized units. Lastly, compared to other studies in the literature [3, 11], our study took a robust approach to measuring students' confidence in and perceived skills for manufacturing. That said, our study did not measure growth in student confidence over time, nor did it investigate whether skills acquired during this exercise carry forward into future coursework requiring hands-on machining.

In conclusion, we developed an introductory manufacturing experience – the mini-mill experience – that is effective in teaching basic mill operations and promotes students' confidence for future machining experiences. This exercise is cost effective and scalable to large class sizes. In these ways, it is a valuable addition to the existing literature and curriculum on manufacturing education for mechanical engineers. Future research work by our group will focus on measuring gains in student confidence as a result of the mini-mill experience and assessing whether the skills acquired in this exercise are transferable to later manufacturing experiences in our program. As we continue to use this exercise beyond this pilot year, we will also refine the mini-mill experience curriculum to optimize student learning, for instance, increasing the grade weighting for this project to promote completion of both Part 1 and Part 2 and also redesigning the common part to include more tapping and tool change operations, which students still struggle to master. The curriculum and evaluative results presented in this study may be valuable for other mechanical engineering programs looking to embed entry-level machining experiences in early-years courses.

References

[1] S. Kiefer, "Machining Experience in a Freshman Mechanical Engineering Class," 2022.

[2] K.N. Otto and K.L. Wood, "Designing the design course sequence," Mech.Eng., pp. 39, 1999.

[3] J. Wood, M. Campbell, K. Wood and D. Jensen, "Enhancing the teaching of machine design by creating a basic hands-on environment with mechanical ‘breadboards’," International Journal of Mechanical Engineering Education, vol. 33, pp. 1-25, 2005.

[4] S. Danielson, A. Kirkpatrick and E. Ervin, "ASME vision 2030: Helping to inform mechanical engineering education," pp. T1J-1, 2011.

[5] R. Reif, A. Liveris, S.A. Jackson and W.G. Advanced Manufacturing Partnership 20, "Accelerating US advanced manufacturing," 2014.

[6] P.S. Waldrop and H. Jack, "Preparation of engineering and technology graduates for manufacturing careers," Technology Interface International Journal, vol. 12, pp. 79-86, 2012.

[7] N. Allen, M. Cunnington, L. Westra, M. Klein, E. Odom and R. Smelser, "Adapting the MIT Stirling engine project at the University of Idaho, a land grant institution," pp. 7-147, 2002.

[8] D.M. Malicky, J.G. Kohl and M.Z. Huang, "Integrating a machine shop class into the mechanical engineering curriculum: experiential and inductive learning," International Journal of Mechanical Engineering Education, vol. 38, pp. 135-146, 2010.

[9] M. Ssemakula, "Introducing Hands On Manufacturing Experience To Students," pp. 7-747, 2002.

[10] D. O'Connor, "Electric Ceiling Hoist: A Semester Project With Competing Forces to Enhance Student Learning in Machine Design," 2020.

[11] J. Abellán-Nebot V., "Project-based experience through real manufacturing activities in mechanical engineering," International Journal of Mechanical Engineering Education, vol. 48, pp. 55-78, 2020.

[12] A. Trauth, M.G. Headley, S. Grajeda, D. Roberts and J. Buckley, "Individual Design Experiences Improve Students’ Self-Efficacy on Team-Based Engineering Design Projects," 2020.

[13] A. Lalley, M.D. Bedillion, M. Langerman and U.A. Korde, "Early Incorporation of Design for Manufacturing in the Engineering Curriculum," in 2015 ASEE Annual Conference & Exposition, pp. 26.564. 1-26.564. 14, 2015.

[14] M.S. Carpenter, C. Yakymyshyn, L.E. Micher and A. Locke, "Improved student engagement through project-based learning in freshman engineering design," 2016.

[15] N.D. Martin, C. Dornfeld Tissenbaum, D. Gnesdilow and S. Puntambekar, "Fading distributed scaffolds: The importance of complementarity between teacher and material scaffolds," Instructional Science, vol. 47, pp. 69-98, 2019.

[16] D. Wood, J.S. Bruner and G. Ross, "The role of tutoring in problem solving," Journal of Child Psychology and Psychiatry, vol. 17, pp. 89-100, 1976.

[17] R. Azevedo, J.G. Cromley, D.C. Moos, J.A. Greene and F.I. Winters, "Adaptive content and process scaffolding: A key to facilitating students' self-regulated learning with hypermedia," Psychological Test and Assessment Modeling, vol. 53, pp. 106, 2011.

[18] R. Azevedo, J.G. Cromley, F.I. Winters, D.C. Moos and J.A. Greene, "Adaptive human scaffolding facilitates adolescents' self-regulated learning with hypermedia," Instructional Science, vol. 33, pp. 381-412, 2005.

[19] A. Cheville and S. Welch, "The Impact Of Scaffolding On Student Success In A Precapstone Design Course," pp. 14-1224, 2009.

[20] A. Mirkouei, R. Bhinge, C. McCoy, K.R. Haapala and D.A. Dornfeld, "A pedagogical module framework to improve scaffolded active learning in manufacturing engineering education," Procedia Manufacturing, vol. 5, pp. 1128-1142, 2016.

[21] K. Pitkänen, M. Iwata and J. Laru, "Supporting Fab Lab facilitators to develop pedagogical practices to improve learning in digital fabrication activities," pp. 1-9, 2019.

[22] J.N. Phanthanousy, C.A. Whitfield and Y.S. Allam, "Scaffolding provided to engineering students in cornerstone design project scenarios related to practices of expert designers," pp. 25-1141, 2012.

[23] V. Braun and V. Clarke, Thematic analysis, American Psychological Association, 2012, .

[24] S.F. Kiefer, "Machining Experience in a Mechanical Engineering Curriculum," pp. 24-879, 2014.