ASEE'S VIRTUAL CONFERENCE
At Home with Engineering Education
JUNE 22 - 26, 2020 #ASEEVC
Paper ID #29057

The Design and Impact of a Combined Makerspace, Wet Lab, and Instructional Design Studio for Chemical Engineering Curriculum

Prof. Anthony Butterfield, University of Utah

Anthony Butterfield is an Associate Professor (Lecturer) in the Chemical Engineering Department of the University of Utah. He received his B. S. and Ph. D. from the University of Utah and a M. S. from the University of California, San Diego. His teaching responsibilities include the senior unit operations laboratory, capstone laboratory, first year design laboratory, and the introduction to chemical engineering. His research interests focus on undergraduate education, makerspaces, citizen science, air quality, and photobioreactor design.

The Design and Impact of a Combined Makerspace, Wet Lab, and Instructional Design Studio for Chemical Engineering Curriculum

Abstract:

The designs of the physical spaces in which we teach have been shown to impact classroom dynamics and student outcomes. This interface between space and pedagogy becomes particularly important in interactive, hands-on, and project-based learning environments. Several models to enhance such environments have been implemented throughout STEM departments, but solutions particular to chemical engineering departments require additional examination.

We have been teaching a chemical engineering design laboratory, primarily directed towards our first year students, over the past six years at the University of Utah. This course was initially taught in a lecture hall and a series of satellite labs, centered around the space used for a unit operations courses. Due to the first-year course's success in achieving learning outcomes and its positive reception by students, we have been able to design and build a combined laboratory, instructional, and maker space specifically meant to facilitate early- and mid-curriculum hands-on project-based learning. For the past three years this first-year course, and several mid-curriculum projects have moved into this space, along with multiple senior capstone projects, bringing about inter-cohort interactions and developing a social hub for the department, as well as facilitating course activities.

In this work, we report on the detailed design of this learning environment, and the lessons learned in the creation of such a multi-use space, specifically for the needs of chemical engineering students and curriculum. We report on how the transition of our first-year design course to this new layout appears to have impacted multiple metrics: student trainings and laboratory skill acquisition, student course performance, team evaluations, course and instructor evaluations, and more. Finally, because the space combines a wet lab, makerspace, and design hall, and activities within range from students socializing to course laboratory activities, safety concerns are unique. We report in this work how general safety and specific equipment trainings may be effectively managed.

Results suggest that significant gains have been realized in student outcomes, both qualitatively and quantitatively, and the results of this work may be used to aid in design of interactive, project-based learning environments for chemical engineering curriculum.

Introduction:

The spaces in which we teach inevitably impact our teaching, and one type of pedagogical space that has become increasingly common in the life of students is the makerspace. Makerspaces have become mainstays on university campuses across the globe and are integral to the education of students throughout colleges of engineering [1]–[5]. These spaces house a variety of machining and rapid-prototyping tools and are meant to facilitate a creative and encouraging atmosphere to allow users to work their way through iterative design cycles [6]–[8]. The type of open-ended design projects that tend to occur in such spaces promote active learning, which has been consistently associated with unique benefits over traditional lecture-based teaching. Such gains include improved learning [9]–[12] and retention [13]; higher student self-assessment of associated courses [12], [14]; and improved retention of students, particularly in underrepresented groups [10], [15]–[17]. However, pitfalls and challenges exist around the development of makerspaces [18] and the culture that may be promoted therein [19]. Of course, care must be taken to consider evidence in the development of such a space for students [20]. Fortunately, a wealth of information exists as to successful marketspace implementations, regarding both the physical contents of the space and its human impact [1], [5], [7], [21]–[23].

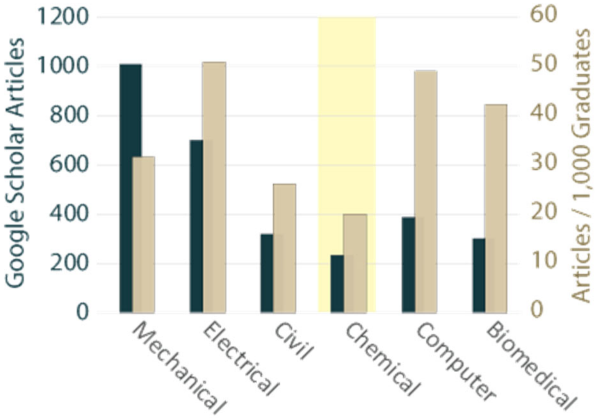

Figure 1: Google Scholar Articles on the Use of Makerspaces in Engineering Curriculum. Dark bars, on the primary axis indicate Google scholar articles using, even once, the terms "makerspace" with each sort of engineering discipline. Light bars indicate those same Scholar articles per 1,000 graduates produced in each discipline in 2018. Chemical Engineering is conspicuously the lowest on each measure.

However, in all the helpful material referenced above, a mention of chemistry or chemical engineering's place in established maker culture is very difficult to find, if not completely absent. It is not, of course, that chemical engineering educators have not made significant and substantive contributions to understanding how best to incorporate fabrication tools and maker-like spaces into chemical engineering curriculum; they certainly have [24]–[27]. However, we have not been as quick as other engineering disciplines to adopt these tools and associated spaces. As of the authoring of this article, in the journal *Chemical Engineering Education*, only one paper can be found to reference "makerspace" or "maker space" and only as an aside [28]. As Figure 1 shows, simply searching Google Scholar for the terms "makerspace" or "maker space" and the most common forms of engineering reveals "chemical engineering" has the lowest number of publications mentioning both terms and has the lowest number of articles adjusted for the size of the discipline (as estimated by the number of 2018 degrees awarded [29]). Figure 1 only includes articles that may reference chemical engineering only once and nearly all ignore the specifics of designing a makerspace to be particularly suited for chemical engineers. In short, as engineers we are relatively late to the makerspace movement, likely due to the complications of incorporating wet chemistry with process design, and a student body that is not often trained on machining tools or expected to develop CAD skills. Regardless, the advances we have made as an engineering discipline in this area could use additional scrutiny to discern what has worked for a chemical engineering population and what has not.

In this work I describe the design and impacts of a makerspace at the University of Utah, created specifically for chemical engineering curriculum. Results are compared from a first-year chemical engineering design course taught both in a traditional unit operation laboratory space and, later, in this design lab to attempt to quantify the benefits of adding such a space to a department's teaching laboratory offerings.

Methods:

The project-based design course that is used in this work as a test course to quantify the impact of the new teaching space has been described extensively in prior publications [30]–[32]. In short, the course is a required design laboratory, primarily taken by our first-year students. The lab is meant to expose students to the design process early in our curriculum and build off of our introduction to chemical engineering course, which is given the previous semester. Students are meant to learn through creation, evaluation, and analysis, using processes of cognition higher up in Bloom's Taxonomy.

The two types of lab spaces used as part of this work are shown in Figure 2. Figure 2a shows our department's long-established unit operation laboratory, which we will designate as UOL for

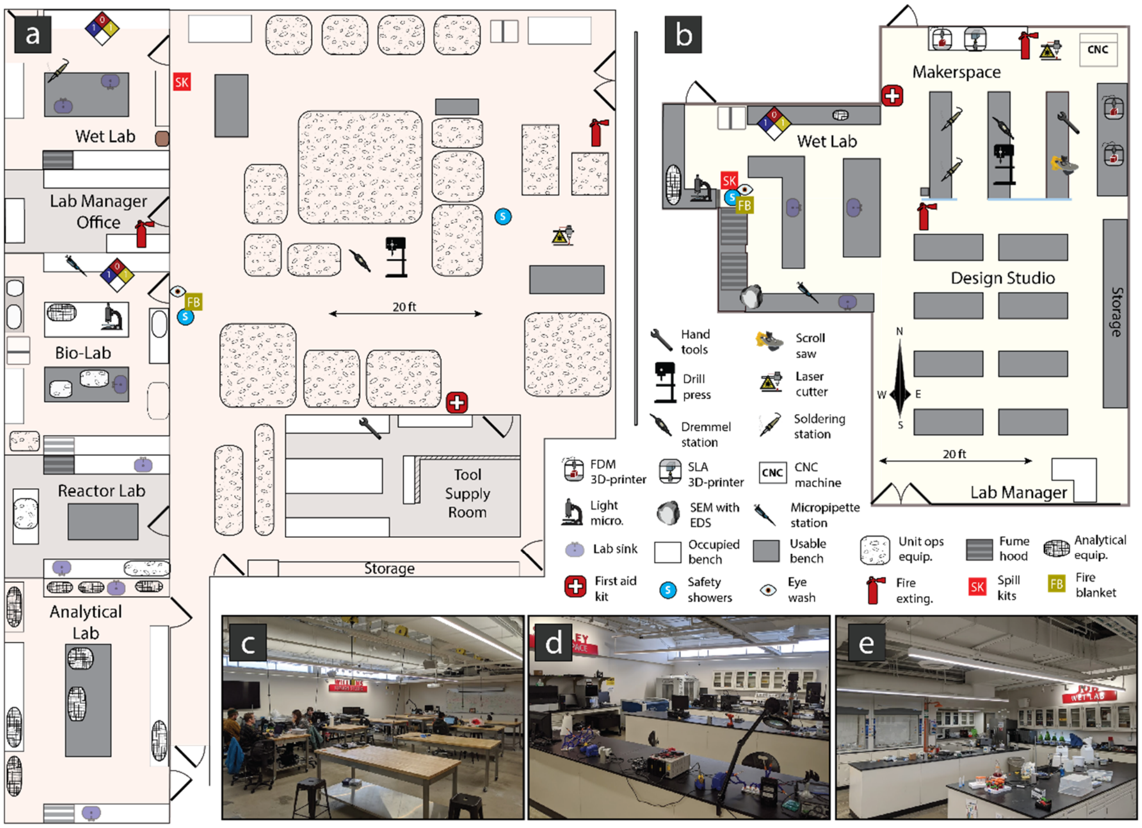

Figure 2: Laboratory Spaces Used for Chemical Engineering Curriculum. a) Unit ops space and satellite laboratories (UOL), which originally housed the design course (6,424 ft^2). b) Meldrum Innovation laboratory (MIL) designed specifically for chemical engineering curriculum design purposes (3,325 ft^2). A photograph is shown of the interior of the MIL design studio (c), makerspace (d), and wet lab (e). The illustration of the spaces in a and b are drawn to the same scale.

unit operations lab. Figure 2b shows the new teaching environment, which we will designate as MIL for the maker/innovation lab (known to our students as the Meldrum Innovation Lab).

UOL has been used for our unit ops laboratory and senior capstone labs for decades, and is likely similar to many unit ops chemical engineering laboratories across the country. It contains one large lab area which houses pilot-scale pieces of unit ops equipment. The space also includes a collection of smaller satellite laboratories: a wet lab, analytical lab, biochemical engineering lab, and reactor laboratory. Just down the hall from this space was a small room housing our 3D printers. The design course that is the test course for this paper was shoehorned into this space for four years, primarily because the space was available, until the switch to the tailored makerspace environment three years ago. The arrangement of equipment shown in Figure 2a depicts its setup during the time in which the design course was taught in UOL; some of the equipment shown has since been moved to the MIL space.

Due to the success of our design course, as measured by pre- and post-tests and qualitative student feedback [30], [31], and its positive reception by the department's industrial advisory board, a development push was made to build an innovation laboratory, specifically designed for chemical engineering. Not having examples at the time of tried designs of chemical-engineering-specific makerspaces, an extensive survey of existing makerspaces for other disciplines was conducted, both on campus and through existing literature [1], [7], [8], [33], [34]. A unique challenge was found in honing down equipment that may be typical to mechanical and electrical engineering makerspaces to leave what is valuable to facilitate chemical engineering students. Focus was made to assure that students could easily make their creative designs into a physical and electronic reality, without being mechanical or electrical engineers. Additionally, incorporating the wet chemistry necessary for many chemical engineering projects required unique considerations, from logistics and safety perspectives. Lastly, the new laboratory had to, of course, fit into the space allotted by the college (an old nanofabrication laboratory).

Figure 2b shows the resulting MIL layout. The original space consisted of four separate laboratories. To address a problem of student team isolation from other peers and faculty, as observed in UOL, all walls were removed, creating one contiguous, open space. This space is conceptually separated into three primary zones: the Design Studio, Makerspace, and Wet Lab, though student flow and use overlap between each space is common.

The Design Studio (Figure 2c) takes the majority of the space, 1785 ft^2. It contains an instructor's desk with connections to a projector at the front of the room, and a TV at the rear of the space and sound system, to aid students towards the back. Student teams of 3 to 4 work here at 3.3' x 9' butcher block work benches on castors, which allow rearrangement of the room. Power is provided to each workbench via retractable outlets installed on ceiling beams. Whiteboards are installed at the south and west walls of this space. The Design Studio is primarily used for instruction, team planning, assembly of designs, and design validation. Teams work at the benches, and may bring appropriate items from the other spaces into this area to be used. As can be seen comparing Figure 2a to 2b, though less floor space is used, this change increased the area of available and versatile work bench space, and consolidated student teams into one primary location, whereas in UOL they were spread across several walled-off spaces.

This organization is meant to allow students to learn from and respond to adjacent teams and remain in easy reach of faculty and TAs. The open design allows students at each bench to also maintain awareness of what other team members are doing in the two other MIL spaces. Along the east wall of the Design Studio is additional bench space and storage for backpacks, coats, and boxes containing ongoing student projects.

The Makerspace (840 ft^2) is designed after other makerspaces on our campus and described in the literature (Figure 2d). Another whiteboard is installed on the west side of this space to aid in student design discussions. The west-most bench and storage spaces are dedicated to electronics, containing two soldering stations and storage of electronic components, and microcontrollers (students typically use Arduino, CircuitPython or Raspberry Pi devices). The north wall houses the more sophisticated 3D SLA printers (uPrint, MiiCraft), and an 80 W laser cutter (Epilog). The low-cost FDM 3D printers (Flashforge) are most frequently used by first-year students; these are housed on the east side of the makerspace. Senior students are the most common users of the SLA printers, primarily for microfluidic devices. Both the laser cutter and 3D printers allow students with little machining expertise to take their technical drawing and make them into reality with minimal training. This space also houses typical makerspace hand tools as well as a drill press and scroll saw. The only piece of analytical equipment in this space, aside from multimeters, is a material tester (Instron), typically used to test fibers, recycled plastics, and such.

The Wet Lab (Figure 2e) is 700 ft^2 of space, and is meant to facilitate the other design spaces with both analysis of design products and support of the chemistry necessary to support a makerspace specifically for chemical engineering curriculum. This space contains all the typical glassware in a chemistry wet lab along the south wall. It contains two fume hoods and a complete chemical safety station along its west wall. Dry chemicals are kept on the north wall; maintenance of chemical safety under these unique circumstances is discussed below. This lab also contains an assortment of pumps—aquarium air pumps, dosing pumps, peristaltic pumps, centrifugal pumps—to aid in student designs. Analytical equipment in this space includes scales, a refractometer, a benchtop SEM with EDS capabilities, spectrophotometer, and an inverted light microscope with attached camera.

Safety Considerations:

Standard lab safety regulations and procedures are maintained in this space. However, because this space is used by students of all levels of experience, from first-year to PhD candidates, additional restrictions are placed on use. All users of the laboratory are required to pass AIChE's SAChE Laboratory safety training. Chemical hazards are limited to NFPA health and reactivity ratings of 2 or lower and flammability of 3 or lower; no chemicals that may deleteriously bio-accumulate may be brought into this space. The general rule of thumb given to users is to keep the wet lab "as safe as a kitchen, keeping in mind that kitchens can be dangerous places," and any deviations from this rule are tightly regulated. In the makerspace, each significant piece of equipment, from the CNC down to the hot glue guns, require in-person training and passing an online test particular to that equipment. Once students have passed their training, an icon appears on their lab badge to indicate their authorization to use that equipment. Lastly, the space is monitored by video to, in part, keep users from violating lab safety rules, knowing the violation could be caught.

Inclusion Considerations:

The maker movement, in its inception, seems to have been dominated primarily by able adult white men [35]. This history, fueled by cultural expectations about who a "maker" is, may lead traditionally underrepresented groups in STEM fields to feel additional layers of exclusion in makerspace environments. Furthermore, societal pressures to become familiar with tools that are common to makerspaces are not applied equally through the upbringings of all demographics. These differences can be particularly pronounced along lines of gender [36]. As such, developing an inclusive, nurturing makerspace takes consideration and intention for students who are in underrepresented groups [34], [37] and those with disabilities [38].

The old UOL lab was not designed to be approachable for all and was decidedly spartan and utilitarian for able-bodied students. The new space, MIL, is openly branded as a "Safe Space" (by use of AIChE & ASEE branded Safe Zone signs). To warrant such a claim, the MIL is supervised by faculty with extensive diversity and inclusion training, who has had years of experience addressing related issues, should they ever arise. Additionally, inclusion training and conflict resolution is part of the curriculum of the courses taught in MIL, as well as the prerequisites to these courses. Each course in this space is also guided by a class diversity and inclusion statement, in which it is made clear to the students on the first day that inclusion is a key part of professional engineering ethics and is expected in our classrooms and laboratories.

Furthermore, care is taken to signal belonging to *all* students in this space. For instance, at the entrance, recruitment and event flyers for underrepresented groups are continually posted (oSTEM, SHPE, and so on). The space is used by these same college affinity groups for meetings and makerspace projects specific to their clubs. For example, SWE has made club-branded materials for their events using the laser cutter, and oSTEM has used this space for video game nights and tie-dying parties. The space is also often used for club meetings. To initiate this use, it is our practice to invite all such groups to speak to our first year students in the fall, and make clear that the MIL exists, in part, to facilitate their activities.

Providing signals of inclusion that may even seem small can have significant meaning to those who have been historically excluded from makerspaces. For instance, several times our women engineers have commented how nice it is that this lab keeps a fresh supply of hair ties with our PPE equipment. While hair-ties do not as often impact the safety of our male-identified engineers, and male students have not once commented on their presence, having them there communicates an intent to be inclusive (and safe!). Simply, it can be remarkable how important something as small as, say, a rainbow sticker on a whiteboard can be in a space which has traditionally been exclusionary.

To attempt to include students experiencing disabilities in the MIL, lower bench space is reserved for students to complete work while seated, and magnifying tools are made available. If needed, faculty can amplify instructions through a microphone and speakers. Most frequently used materials are kept in lower drawers and cabinets, and higher cabinets are reserved for objects that are rarely accessed by students.

Community Considerations:

Makerspaces have been shown to have potential as effective social spaces [39], [40]. Care has been taken to assure this space is kept open for all students throughout the day. Students may not use the makerspace or wet lab without staff supervision, but faculty is present most of the day at the instructor's desk. When faculty must step out, the design studio may still be used for students to study and work on homework during the day. In these instances, the lab is monitored by student staff with keycard access, to assure no use of the wet lab or makerspace occurs. These spaces are also monitored by motion sensors. Given such access, the hope was that the MIL space would become a social hub of the department; whereas the UOL was primarily used at times when an official lab was underway, and was otherwise vacant.

Results:

For two years in the UOL and two years in the MIL space, we tracked several factors in an attempt to quantify the impact of this new space. Over this four-year span, two instructors remained constant for three sections of the class. The author, who created and remained the primary instructor for this lab over the last seven years, delivered all course and laboratory preparation content. This content and the assigned labs did not change significantly over the four-year span that is the focus of this work, and it has essentially remained as first described in the literature [30].

Regardless, it would be difficult to rule out all confounding factors. The third instructor, for instance, was replaced with new faculty during the first year in the MIL space. However, there was no significant impact from this switch, compared to the second year in the MIL space, in which the original instructor returned. To avoid this possible confounding factor, on instructor-specific impacts, only persistent faculty were considered in the analysis below.

Acquisition of Skills:

By consolidating students and equipment into one open space, as opposed to using multiple walled-off laboratories, it was hypothesized that students would more frequently pick up makerspace skills, due to the constant proximity of the equipment and constant and conspicuous modeling of use by peers. Whereas, in the old lab setup, to use the laser cutter, for instance, students would be well away from most lab teams. Because we require students to be certified on equipment before use and we keep records of those certifications, we are able to track student trainings before and after the move to the new lab space. No assignment details were altered that could reasonably alter student need or want for use of any particular piece of equipment in that move.

Figure 3 shows the percentage of the student body in the design course trained in makerspace skills by the end of the course. More skills are tracked than displayed here; only the skills that were available and tracked every year in both UOL and MIL were included in this analysis. The drill press, for instance, was left out because it was inoperable through spring of 2018.

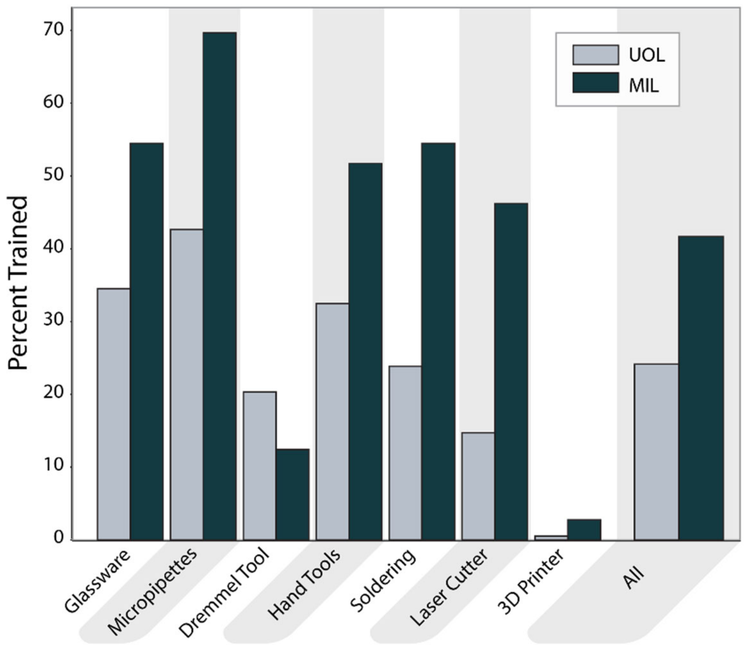

Figure 3: Percentage of Students Trained in Makerspace Skills in Both Lab Space Designs. Nearly all trainings have increased in the new makerspace.

On average, trainings approximately doubled within the new space. In fact, trainings on each item increased in MIL, except for the use of the Dremel$^{\text{TM}}$ tool. This particular tool was commonly used by students to alter existing materials (such as Altoid containers and pipes) to build photometers in one of their first projects [41]. As can be seen in Figure 3, the use of the laser cutter went up dramatically in MIL and may have taken the place of the Dremel$^{\text{TM}}$ tool. Students now commonly use the laser cutter and 3D printers to make custom sensor housings for their photometers and flow cells, and have less need for altering existing containers, which could explain the Dremel's decline.

Low adoption of the 3D printers may be striking in Figure 3. While the lab now has five printers and they are frequently in use, most of their use during this time period was by students further along in our program. In the test course for this work, primarily first year students are considered, and the laser cutter has a significantly lower activation barrier for the students (in that they only have to make 2D drawings, avoiding the complications of 3D modeling). The numbers may also be deceptively low for first year student *teams*. Typically, a couple students get immersed in the 3D printers and then they become the "3D printer expert" for each team they join; thereby more teams use the printers than Figure 3 may suggest. Furthermore, while this 2020 spring semester is not yet over and its data are not included in this analysis, we now have just below 20% of first-year students trained on 3D printers. As such, it seems 3D printing adoption in the first year is increasing significantly.

Diminishing class size could be a suspected confounding factor at play here, as class sizes around the country (and in our department) have been dropping [29] in the same years we switched lab designs. However, our class size has only dropped over these four years from 78 down to 72 students, and, with the same number of instructors, trainings have still doubled in the new space. The correlation of trainings per student with the number of students is extant at -0.44 but this is most likely due to coincident factors. For instance, each year each section has a very different number of students. Section 2 repeatedly had the least number of students, at around 10; Section 3 had more; and Section 4 had the most, over 30. The correlation of the number of students with their section number (2,3, or 4) is positive at 0.49, but the correlation for trainings per student with section number is nearly zero, at -0.03. Within the same year, class size does not seem to impact the percentage trained in sections with very different sizes. In all, it seems the slight correlation of percent students trained with class size is not causal, and is only due to the fact that the positive effect of the new space was coincidentally occurring during national declines in chemical engineering student populations.

Another interesting finding that supports the hypothesis that one shared open space encourages student skill acquisition is seen Figure 4. Figure 4a contains box plots of training timings and it is clear that, on average, trainings occur earlier in the MIL space (p = 1.7e-10), meaning that students are more quickly picking up skills. Furthermore, looking at the box plot of all skills averaged, it is clear that there are many outliers later into the semester. Figure 4b shows the dot plot of all trainings and it is apparent that, not only are trainings occurring earlier and more frequently in MIL, they occur in a more distributed manner throughout the semester. In the UOL (Figure 4b) most all the trainings occur on during the lab period, which is why they more often clump into certain periods. These data support the instructor's observation that, in the MIL space, trainings have been more likely to occur by impulse, during a convenient time, rather than to meet a specific project goal. Also, trainings in the new space are not only occurring during

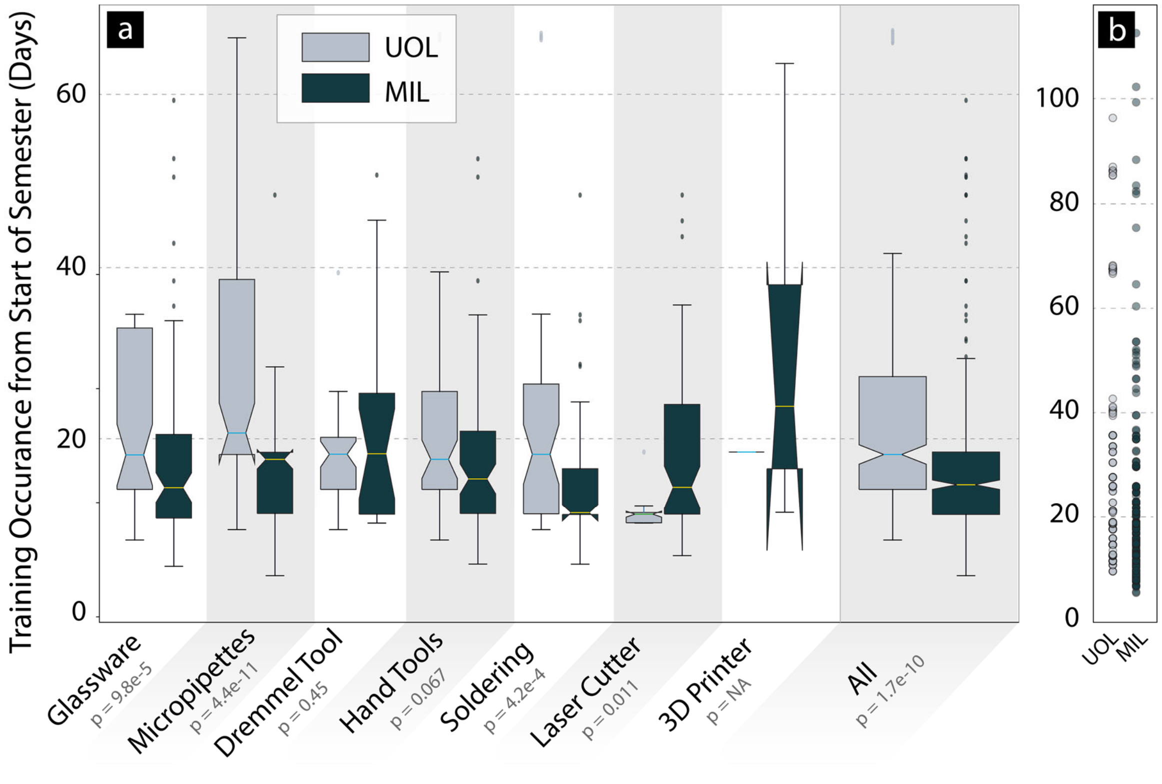

Figure 4: Training timings. a) Boxplots for various skills. b) Dot plot of all training timings in both spaces. In general student trainings happened, on average, both earlier and with greater dispersion in the new MIL lab design.

official lab time; because the MIL has been made to also act as a social hub for students, trainings occur throughout the week, outside of class time.

It has also been anecdotally noted that labs are ending earlier in the MIL space as compared to the UOL space, possibly due to the efficiency of the lab design. Around 20% of the student teams would need to return and complete a lab the following week in the UOL. In the MIL space that percentage seems to be around 10%, which could also account for the extra time available for trainings.

Student Project & Team Scores:

Projects in this test course involve technical communication, team writing, and analysis of the data collected in lab. While creation of devices and collection of data occurred in the lab spaces, the rest of this work typically occurred outside of lab. As such, it is perhaps no surprise that moving from UOL to MIL had no statistically significant impact on student project scores. While team projects were scored higher on average in MIL than in UOL, the p value was only 0.088.

Furthermore, it may be worth noting that the same observations could be made for student peer evaluations of their team members. In the test course, students switch teams for each of their six projects and they tend to work with almost every peer in their section. Part of the score for their team assignments are peer team working assessments. Given the focus of this space on community and inclusion, it was hypothesized that these assessments would be higher in MIL, and they were, on average (93.7% in UOL and 94.6% in MIL). However, students tend to give most all peers scores of 100% in this course, unless there were significant problems; as such averages are bunched near the top and this difference was not statistically significant.

Course & Instructor Evaluations:

Figure 5 shows average student evaluations of the lab course and instructor (only the lead instructor who was persistent all four years), as taught in UOL and in MIL. The college average student evaluation for each question is also shown. In each year and measure, this course was ranked significantly above the college average, as it was when first reported [31], [42]. However, each evaluation in the new MIL space was significantly higher than it was in the UOL space. Again, no significant portion of the course projects or lecture material changed over this four-year period, save for moving into the new space.

The greatest gains in student evaluations were seen in the general regard for the lab course. Students in the new space generally felt the objectives were better met, in a more organized fashion, and that they learned more than the students in the UOL space. The reason for such increases in regard for the course could certainly be related to the increase in trainings (Figure 3); students feel they have learned more skills from the course because they objectively have. Also, the fact that the maker space is specifically organized for hands-on design projects for chemical engineering could have increased the perception of the course as being “well-organized” and that it contained “helpful” materials. In fact, the perceptions that the course materials were helpful and presented efficiently most significantly surpassed the college averages.

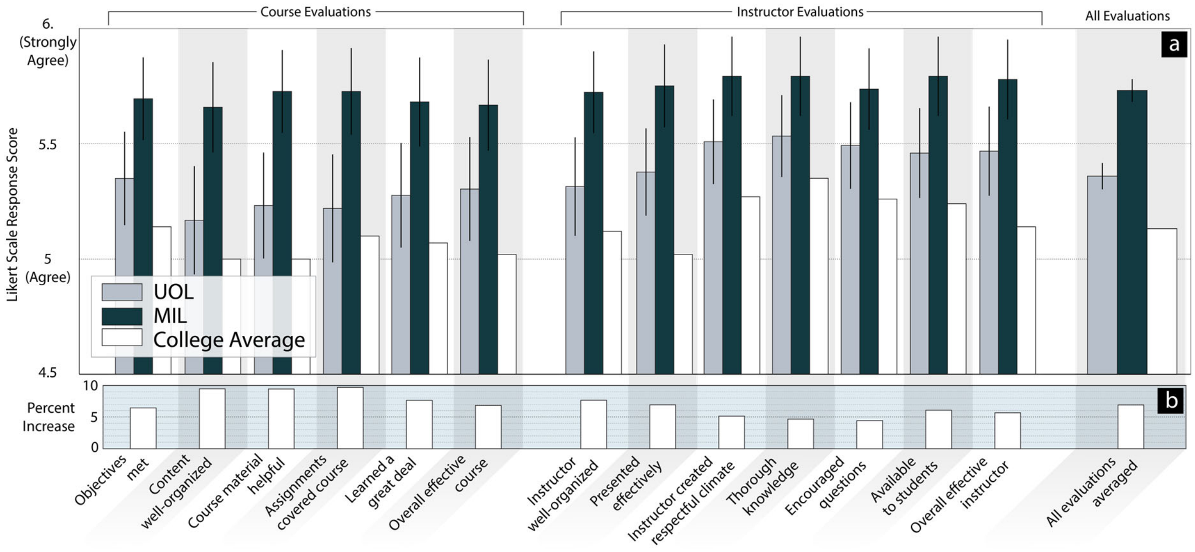

Figure 5: Student Course Evaluations. Course and instructor evaluations are consistently higher on each question in the MIL verses the UOL space.

The evaluations of the instructor did not increase as much as they did for the course, but they did start nearer to the maximum in the UOL space. The two most positively ranked questions in all were regarding the perception that the instructor "created a respectful climate" and that the instructor was "available to students." The MIL's focus on inclusion and nurturing a healthy social environment seems to be successfully noticed and appreciated by students. Furthermore, the fact that the instructor works frequently in that same space, side-by-side with the students during non-class times likely strengthened the mentoring opportunities and led to increased student regard.

While the exact mechanisms remain somewhat vague, the positive impact of this new space is apparent in both course and instructor evaluations.

Conclusions:

It is nearly impossible to perform a rigorous double blind study when the intervention is an expensive remodel of undergraduate teaching laboratories; not to mention the fact that students would revolt, being in a control group and kept out of the sparkling new lab which their peers were using. However, this transition to a makerspace designed specifically for chemical engineering curriculum gave us a rare opportunity to attempt to quantify some of the benefits that such an investment might engender, if being considered by other departments.

Our findings suggest we have developed a space that is effective for the purposes of creating a chemical engineering maker environment and fostering active and collaborative hands-on learning. Compared to attempts to fit such learning into an existing unit operation laboratory's geography, we witnessed:

- An increase in student trainings on equipment
- Earlier average student trainings

- Greater dispersion in trainings throughout the semester and outside of class
- A substantial increase in student evaluations of both the courses taught in this space and the instructor teaching them.

Anecdotally, we see far more efficient use of the space, as it now doubles as a social space for students all day long. On top of the other benefits, this space has become the home for many student clubs (e.g. ChemE Car Team and oSTEM), and our K-12 outreach efforts.

For future work, we plan to move more mid-curriculum activities into this space and expand on our experience with intra-cohort teaching/mentoring. Starting next year, we will begin including half of a semester of junior laboratories in this space and will continue to study its impact on our curriculum.

As the discipline of chemical engineering evolves and as more departments look to bolster evidence-based pedagogy in their curriculum, we anticipate such spaces to become more and more common in departments across the country. It is our hope this work may help ease that transition for those looking to offer such spaces to their student body.

Maker Spaces under Quarantine:

Lastly, it seems appropriate, in the midst of the coronavirus pandemic, to address how a quarantine has impacted this work and how it is being managed. Of course, hands-on team-based learning faces significant hurdles when students cannot physically enter lab spaces and cannot even be in the same room as their team members.

At the time quarantine was initiated at our university, students in the test course for this work had finished all but their final projects. These projects are greatly open-ended, as long as the team addresses the department mission of research, service, or education, using design principles, experimentation, and analysis of data. To allow this lab to conclude offsite, all proposed projects needed to literally be “kitchen safe” and executable by people alone at multiple sites. Students have stepped up to this challenge and are now working on very interesting projects, many of them related to the current crisis (e.g. assessing the efficacy of homemade hand sanitizer, turning newspaper to toilet paper, assessing pre- and post-quarantine air quality…). The MIL space has facilitated these projects by sterilizing and then renting out materials, such as fountain pumps, multimeters, thermoresistors and the like. Students still meet at lab times and work in teams in teleconferencing breakout rooms.

The physical space of MIL is in the process of accumulating 3D printers from across the campus to be used to make PPE for our local hospital. The MIL was chosen because the workbenches in the design lab provided the greatest area of versatile space in the college, with good ventilation. The faculty allowed into the space (the author) is also faculty for these MIL courses, and they will keep the printers operating. Being onsite, the faculty will also be able to aid students, should they need to obtain data or rent out additional materials (students are not allowed to come into the building to pick up materials and so materials are sterilized and exchanged at a distance outdoors).

Finally, our outreach program has been a core student group for our department [43] and had operated from this space. We have begun conducting virtual outreach visits to K-12 teacher's online classrooms. As part of these visits, and because faculty will already be maintaining 3D printers in the MIL, we use the lab space to conduct live STEM demonstrations via webcam.

Acknowledgements:

I would like to sincerely thank the gracious and generous donors who made this space possible for our students: Peter and Catherine Meldrum, Jason Job, Gregory Starley, John and Amy Williams, and the many others. I would like to thank and acknowledge our department chair at the time who spearheaded the MIL development effort, Milind Deo, and those who have taught sections of the lab used as the test case for this paper: Swomitra Mohanty, Kyle Branch, and Geoff Silcox. I would also like to thank my son, Lucas Butterfield, for being my copy editor on this paper. Finally, I would like to thank all our students who bring life, excitement, and potential energy to the spaces in which we teach. I will be thrilled to see them all again in person, once the current crisis ends.

References Cited:

[1] V. Wilczynski, "Academic Makerspaces and Engineering Design," in *ASEE Annual Conference and Exposition*, 2015.

[2] E. R. Halverson and K. M. Sheridan, "The maker movement in education," *Harvard Educational Review*, vol. 84, no. 4. pp. 495–504, 2014, doi: 10.17763/haer.84.4.34j1g68140382063.

[3] M. Lande and J. Nelson, "Defining Makers Making: Emergent Practice and Emergent Meanings," in *ASEE Annual Conference*, 2013.

[4] P. Johnson and H. Jack, "The impact of makerspaces on engineering education," *Proc. Can. Eng. Educ. Assoc.*, 2016, doi: 10.1109/ISTAS.1998.688139.

[5] S. Farritor, "University-Based Makerspaces: A Source of Innovation," *Technol. Innov.*, vol. 19, no. 1, pp. 389–395, 2017, doi: 10.21300/19.1.2017.389.

[6] B. K. Litts, "Resources, facilitation, and partnerships: Three design considerations for youth makerspaces," *Proc. IDC 2015 14th Int. Conf. Interact. Des. Child.*, pp. 347–350, 2015, doi: 10.1145/2771839.2771913.

[7] M. Hlubinka *et al.*, "Makerspace Playbook," p. 78, 2013.

[8] C. McKay, T. D. Banks, and S. Wallace, "Makerspace Classrooms: Where Technology Intersects With Problem, Project, and Place-Based Design in Classroom Curriculum," *Int. J. Des. Learn.*, vol. 7, no. 2, pp. 11–16, 2016, doi: 10.14434/ijdl.v7i2.20267.

[9] S. Freeman *et al.*, "Active learning increases student performance in science, engineering, and mathematics.," *Proc. Natl. Acad. Sci. U. S. A.*, vol. 111, no. 23, pp. 8410–5, 2014, doi: 10.1073/pnas.1319030111.

[10] R. Beichner, "The SCALE-UP Project: A Student-Centered Active learning Environment for undergraduate Programs," National Academy of Sciences, 2008.

[11] R. J. Beichner *et al.*, “The Student-Centered Activities for Large Enrollment Undergraduate Programs (SCALE-UP) Project,” *Res. Reform Univ. Phys.*, vol. 1, no. 1, pp. 2–39, 2007.

[12] Y. J. Dori and J. Belcher, “How Does Technology-Enabled Active Learning Affect Undergraduate Students’ Understanding of Electromagnetism Concepts?,” *J. Leaning Sci.*, vol. 14, no. 2, pp. 234–279, 2005.

[13] Y. J. Dori, E. Hult, L. Breslow, and J. W. Belcher, “How Much Have They Retained? Making Unseen Concepts Seen in a Freshman Electromagnetism Course at MIT,” *J. Sci. Educ. Technol.*, vol. 16, no. 4, pp. 299–323, 2007.

[14] M. T. Oliver-Hoyo and D. Allen, “Effects of an Active Learning Environment: Teaching Innovations at a Research I Institution,” *J. Chem. Educ.*, vol. 81, no. 3, pp. 441–448, 2004.

[15] E. Fredericksen, “Minority Students and the Learning Community Experience: A Cluster Experiment,” in *Annual Meeting of the Conference on College Composition and Communication*, 1998.

[16] L. Berry, “Collaborative Learning: A Program for Improving the Retention of Minority Students.” ED384323, 1991.

[17] R. Marra, K. Rodgers, and B. Bogue, “Leaving Engineering: A Multi-Year Single Institution Study,” *J. Eng. Educ.*, vol. 101, no. 1, pp. 6–27, 2012.

[18] A. Hira, C. H. Joslyn, and M. M. Hynes, “Classroom makerspaces: Identifying the opportunities and challenges,” *Proc. - Front. Educ. Conf. FIE*, vol. 2015-Febru, no. February, pp. 1–5, 2015, doi: 10.1109/FIE.2014.7044263.

[19] D. Chachra, “Why I Am Not a Maker - The Atlantic,” *The Atlantic*, 2015. [Online]. Available: http://www.theatlantic.com/technology/archive/2015/01/why-i-am-not-a-maker/384767/. [Accessed: 05-Jan-2017].

[20] O. G. McGrath, “Making a makerspace: Designing user services to serve designing users,” *Proc. ACM SIGUCCS User Serv. Conf.*, vol. 06-09-Nove, pp. 95–98, 2016, doi: 10.1145/2974927.2974949.

[21] R. Steven Kurti, Deborah Kurti, and Laura Fleming, “The Environment and Tools of Great Educational Makerspaces,” *Teach. Libr.*, pp. 8–12, 2014.

[22] A. Wong and H. Partridge, “Making as Learning: Makerspaces in Universities,” *Aust. Acad. Res. Libr.*, vol. 47, no. 3, pp. 143–159, 2016, doi: 10.1080/00048623.2016.1228163.

[23] R. Morocz *et al.*, “University Maker Spaces: Discovery, Optimization and Measurement of Impacts,” in *Proceedings of ASEE Annual Conference & Exposition*, 2015, pp. 26.1631.1-26.1631.10, doi: 10.18260/p.24967.

[24] M. Vigeant *et al.*, “BFab for Faculty: Using Making to Empower Entrepreneurially-Minded Learning,” *Proc. - Front. Educ. Conf. FIE*, vol. 2018-Octob, pp. 1–5, 2019, doi: 10.1109/FIE.2018.8659034.

[25] N. B. Pour, D. B. Thiessen, R. F. Richards, and B. J. Van Wie, “Ultra low-cost vacuum

formed shell and tube heat exchanger learning module," *Int. J. Eng. Educ.*, vol. 33, no. 2, pp. 723–740, 2017.

[26] J. Darwin, J. P. Kale, M. S. Thompson, M. A. Vigeant, and A. Cheville, "MAKER: A maker space smart badging system," *ASEE Annu. Conf. Expo. Conf. Proc.*, vol. 2016-June, 2016, doi: 10.18260/p.25600.

[27] M. A. Vigeant, "Maker : # BucknellMakers," in *ASEE Annual Conference and Exposition*, 2015, p. 13120.

[28] S. Perri, "Lifelong Learning: New Model Frameworks for University and Industrial Partnerships," *2018 Winter Chem. Eng. Educ. J.*, vol. 52, no. 1, pp. 38–43, 2018, doi: 10.18260/2-1-370.660-29393.

[29] J. Roy, "Engineering by the Numbers," *Am. Soc. Eng. Educ.*, pp. 11–47, 2019.

[30] A. E. Butterfield, K. Branch, and E. Trujillo, "First-Year Hands-On Design Course: Implementation & Reception," *Chem. Eng. Educ.*, vol. 49, no. 1, pp. 19–26, 2014.

[31] A. Butterfield and K. J. Branch, "Results & Lessons Learned from a Chemical Engineering Freshman Design Laboratory," *2015 ASEE Annu. Conf. Expo.*, 2015, doi: 10.18260/p.24674.

[32] A. Butterfiled and K. J. Branch, "Collaboration between Seniors and Freshmen on Senior Capstone Projects Collaboration between Seniors and Freshmen on Senior Capstone Projects," *2016 ASEE Annu. Conf. Expo.*, 2016, doi: 10.18260/p.26506.

[33] T. W. Barrett, M. C. Pizzico, B. Levy, and R. L. Nagel, "A Review of University Maker Spaces," *ASEE Annu. Conf. Expo.*, vol. #13209, 2015.

[34] A. C. Barton, E. Tan, and D. Greenberg, "The makerspace movement: Sites of possibilities for equitable opportunities to engage underrepresented youth in STEM," *Teach. Coll. Rec.*, vol. in press, 2016.

[35] "Libraries & makerspaces: A revolution? | Technology & Social Change Group." [Online]. Available: https://tascha.uw.edu/2014/06/libraries-makerspaces-a-revolution/. [Accessed: 03-Feb-2020].

[36] S. L. Mann, D. L. Peters, and R. Reck, "Society of women engineers (SWE) welding and machining day: Women's confidence with individual hands-on manufacturing," *ASEE Annu. Conf. Expo. Conf. Proc.*, vol. 2017-June, no. April, 2017, doi: 10.18260/1-2--28830.

[37] W. Roldan, J. Hui, and E. M. Gerber, "Opportunities to Support Equitable Participation for Women in Engineering," *Int. J. Eng. Educ.*, vol. 34, no. 2, pp. 751–768, 2018.

[38] K. M. Steele, B. Blaser, and M. Cakmak, "Accessible Making: Designing Makerspaces for Accessibility," *Int. J. Des. Learn.*, vol. 9, no. 1, pp. 114–121, 2018, doi: 10.14434/ijdl.v9i1.22648.

[39] N. Taylor, U. Hurley, and P. Connolly, "Making Community: The Wider Role of Makerspaces in Public Life," in *Proceedings of the 2016 CHI Conference on Human*

Factors in Computing Systems., 2016, doi: 10.1145/2858036.2858073.

[40] A. Toombs, S. Bardzell, and J. Bardzell, "Becoming makers: hackerspace member habits, values, and identities," *J. Peer Prod.*, vol. 5, pp. 1–8, 2014.

[41] A. Butterfield and C. Young, "An Effective and Economical Photometer for Classroom Demonstrations and Laboratory Use," *Chem. Eng. Educ.*, vol. 46, no. 3, pp. 152–156, 2012.

[42] A. E. Butterfield and K. Branch, "Building Chemical Engineering Students from Miscellaneous Parts & Vague Instructions: A Hands-on First-Year Design Laboratory," in *AICHE Annual Meeting*, 2014, p. 686e.

[43] C. Young and A. Butterfield, "Effective Engineering Outreach through an Undergraduate Mentoring Team and Module Database," *Chem. Eng. Educ.*, vol. 48, no. 1, pp. 31–36, 2014.