An Integrated Four-year Hands-on Design Curriculum: A Case Study

Dr. Emad W. Jassim, University of Illinois at Urbana-Champaign

Dr. Emad W. Jassim is an Assistant Dean for Undergraduate Programs in the College of Engineering at the University of Illinois at Urbana-Champaign. Prior to this position he was the Director of Undergraduate Programs at the University of Illinois at Urbana-Champaign Department of Mechanical Science and Engineering (MechSE) where he also served as Chief Advisor, Senior Design Project Coordinator, and lecturer of thermal/fluid science courses. He received his BS, MS, and PhD from the University of Illinois in Mechanical Engineering. Dr. Jassim has industry experience as a mechanical engineer working for Henneman Raufeisen and Associates Inc. Industrial Technology Group (ITG). He worked briefly for the National Center for Supercomputing Applications (NCSA) as a Visiting Research Associate where he developed the concept design for the Blue Waters supercomputer cooling system (waterside economizer) that aided in the awarding of the supercomputer to NCSA. He continues to work in industry as a consultant and he is a licensed Professional Engineer in the State of Illinois. Dr. Jassim has a passion for teaching and has received numerous teaching awards including the University of Illinois Campus Award for Excellence in Undergraduate Teaching, the College of Engineering Teaching Excellence Award, and the MechSE Five-Year Effective Teaching Award.

Dr. Blake Everett Johnson, University of Illinois at Urbana-Champaign

Dr. Blake Everett Johnson is a lecturer and instructional laboratory manager in the Department of Mechanical Science and Engineering at the University of Illinois at Urbana-Champaign. His research interests include experimental fluid mechanics, measurement science, and engineering education. He oversees undergraduate laboratories in fluid mechanics, fluid dynamics, and heat transfer. Pedagogically, Dr. Johnson employs active learning, inquiry-based laboratory instruction, and any initiative that empowers students to do hands-on learning. Additional service interests include teaching and leadership training for graduate students, enhancing communication education for undergraduate engineering students, developing evidence-based design project team formation strategies, and improving engineering design curricula.

An Integrated Four-year Hands-on Design Curriculum: A Case Study

Abstract

A review of the literature supports a hands-on curricular approach as a means to improve learning of engineering concepts and increase student retention. Many institutions incorporate hands-on design courses in their curricula, but few institutions offer an integrated hands-on design course sequence for all four undergraduate years. This paper is a case study of the development of a four-year integrated hands-on design curriculum to motivate, retain, and prepare mechanical engineering students for success in their capstone (senior) design course and future careers. Over a period of ten years, a team of faculty members have incorporated hands-on design components into a sequence of five mechanical design courses, as well as an introductory fluid mechanics laboratory course. Courses in all four years of instruction (Freshman: Computer-Aided Design; Sophomore: Design for Manufacturability; Junior: Mechanical Design I and Mechanical Design II, Fundamentals of Fluid Dynamics Laboratory; Senior: Capstone Design Project) have been revised to utilize a common design process, reporting guidelines, drawing standards, ideation methods, and Innovation Studio. This paper outlines the hands-on integrated design sequence development over time, and highlights changes made to each of the courses. Assessment of student work in the senior capstone course over the years of interest suggests that students are becoming more proficient in aspects of real-world hands-on design projects and that their ability to work effectively as a team is improving. Retention is also found to increase over the period of interest. Challenges to implementation such as financial resources to support the facilities and fabrication materials, qualified teaching assistant availability, and faculty buy-in are discussed.

Authors

1. Dr. Emad W. Jassim P.E., University of Illinois at Urbana-Champaign
2. Dr. Blake Everett Johnson, University of Illinois at Urbana-Champaign

Introduction

The University of Illinois at Urbana-Champaign (UIUC) Department of Mechanical Science and Engineering (MechSE) engages its students in approximately 50 different capstone projects (senior design projects) per year. The senior design projects can largely be classified into four categories: engineering competitions, industrial, humanitarian, and entrepreneurial. A majority of the projects are one semester long [1]. Many schools recognize the importance of preparing their students for success in their capstone design courses [2]. For example, recent work from Johns Hopkins University attests to the problem of students entering capstone design ill-prepared for hands-on work [3]. In 2007 the UIUC MechSE department established a change in the senior/capstone design program (ME 470) where students worked on only real-world projects sponsored by industry and institutions. Some of the students were able to tackle the hands-on projects that involved designing, manufacturing their design, and validating their design with testing. However, other students struggled, which was not surprising given the fact that ME 470 was the only required hands-on design course in the curriculum. Since then, there has been a push by faculty, company sponsors, alumni, and students to create a "Design Stem" that integrates the design process and hands-on design experiences into the curriculum for all four undergraduate years as a means to improve their design performance and improve retention. The literature is found to support this integrated hands-on curricular approach as a means to improve learning of engineering concepts and increase student retention. Hands-on learning experiences may promote learning at higher Bloom's Taxonomy levels [4]. Many institutions have found that the incorporation of hands-on components in courses have improved student learning [4]–[12]. Desai and Stefanek [13] performed a broad literature review of methods to improve retention of engineering students. They indicated that incorporation of hands-on experiences in the classroom is one of the five most commonly published methods to improve retention. Ten of the 26 sources that they investigated had utilized hands-on experiences in the classroom. Other studies have also found that incorporation of hands-on experiences improved retention [14], [15]. Although hands-on design experiences in courses are commonly found in engineering curricula, there are few integrated hands-on sequences found in institutions across all four years of the curriculum. Even fewer integrated hands-on sequences are found to be documented and assessed in the literature such as the sequences described in Ssemakula et al [12].

After ten years of effort, the MechSE department has developed an integrated hands-on mechanical engineering (ME) Design Stem consisting of five required mechanical design courses spread throughout all four years and an additional inquiry-based hands-on design experience in the junior level fluid dynamics lab [16]. This paper is a case study that outlines the current state of the MechSE department ME Design Stem, as well as changes made to ensure that the students are prepared to solve real world industry-sponsored design problems by the time they reach the senior design course. The authors have observed improvements in the students' tendency to produce a working physical prototype early in the semester. The students are improving in the frequency by which they iterate on their prototype designs. They are showing a greater capacity to produce a solution that satisfies all of their design constraints and to work effectively in a team. Senior design sponsors reported improvements to students' overall quality of proof of concept prototypes produced, ability to satisfy project design constraints, overall performance on design projects, overall design capabilities, ability to innovate, oral communication skills, and written communication skills during the period of interest. Student four-year retention was also found to increase over the period of course development, which was one of the motivations behind the development of an integrated hands-on design sequence.

History of the MechSE Design Stem

The MechSE department has undertaken significant efforts to create and integrate a Design Stem to prepare our students for their capstone design experience and their future careers. In 2008, the MechSE department began exploring ways to improve manufacturing and design courses through an ad-hoc faculty committee that conceived of the Design Stem. In 2010 a Design Stem subcommittee of the Undergraduate Programs Committee (curricular committee for the department) was formed and charged with implementing the findings of the ad-hoc faculty committee. In 2010 the Design Stem subcommittee began to implement design course changes. The department introduced an optional hands-on sophomore design pilot where students could take ME 199 Undergraduate Open Seminar and pursue an entrepreneurial project or participate in an interdisciplinary design competition such as the Formula SAE and Shell Eco-Marathon design competitions to receive technical elective credit at the completion of three semesters at one credit hour per semester. The ME 199 option was and still is very popular, with currently over 100 students (approximately half the size of the graduating class) now enrolled per semester. By 2011, a plan was formulated to create a required hands-on design experience for all four years. In that same year a hands-on design project was introduced in the freshmen level Computer Aided Design course (ME 170) where the students design and then build a product using a 3D printer. Hands-on design and build projects were subsequently introduced into the junior level Design for Manufacturability (ME 350) and two junior level Mechanical Design courses (ME 370 and ME 371). In 2013, a group of faculty involved in the Design Stem work received a University of Illinois College of Engineering Academy for Excellence in Engineering Education (AE3) Strategic Instructional Initiations Program (SIIP) grant to revise the ME junior level Mechanical Design courses (ME 370 and ME 371) to include hands-on design experiences. These changes were implemented in the Fall 2013 semester. An Innovation Studio maker space was also created that year to help students develop their prototypes.

In 2015, a broad and encompassing group of faculty involved in the Design Stem work, referred to as the iDesign team, received another College of Engineering AE3 SIIP grant to further develop the Design Stem; they created a fully integrated hands-on design curriculum across all four years of instruction. These grants not only provided much of the necessary funding for initial implementation, but the regular (typically weekly) meetings required also helped form a larger community of practice focused on improving design and manufacturing courses. Many young faculty with interests in design were drawn into this group through invitations by senior faculty. Instructors were motivated by a belief that consistency in course content from the freshman year through the capstone/senior design course would lead the students to adopt a well-defined framework for engineering design. This group shared best practices and collectively tackled issues that arose. In 2015, the junior level Design for Manufacturability course (ME 350) was moved to the sophomore year and renumbered as ME 270 to have a required hands-on design experience in all four years of the curriculum. Because of the longitudinal nature of the task, the team also decided to address other identified opportunities in the curriculum, such as improving technical writing instruction and team skills.

As a result, students began to see common graphics for the design process for each course in the sequence. The team began their development of the curriculum by formulating a unified design process flowchart for use in all courses. While students in the formative courses may not be expected to memorize the design process flowchart, by the time they have reached their capstone course, they will have worked through it in as many as four courses.

The MechSE department has developed common materials and resources throughout the ME mechanical design courses where students:

- Utilize an over 3000 SQFT Innovation Studio maker space that includes 3D printers, laser cutters, power and hand tools, wood working room, test equipment, and assembly space [17].
- Are taught a common design process.
- Are encouraged to utilize common reporting guidelines to improve their communication skills. The guidelines include report structure, formatting, and drawing standards.
- Are guided to become more creative by teaching them common ideation brainstorming techniques.

Design Course Descriptions

The following are descriptions of design courses at all levels of undergraduate instruction and the changes that have been implemented in them.

Computer Aided Design (ME 170: Freshman-level course)

In addition to CAD modeling and engineering drawings, ME 170 now contains the following introductory design content that includes:

- Ideation process including brainstorming, sketching, concept selection, and product design specification.
- Mechanical design and manufacturing introduction including 3D printing, mechanism analysis, design for manufacture, geometric dimensioning and tolerancing, ANSI/ISO limits and fits, and cost analysis.
- A design project where each student team will identify, design, develop CAD models for, and 3D print a novel consumer product of their choice.
- Guidelines for effective report writing and teamwork skills.

Design for Manufacturability (ME 270: Sophomore-level course)

Design for Manufacturability, now ME 270, was moved from the junior year (formerly ME 350) to the sophomore year to ensure continuity in the design curriculum and provide the students with the design and manufacturing background required in subsequent design courses. Fall 2015 was the first term to offer ME 270. This project-based course emphasizes product design and manufacturing through:

- Investigation of current manufacturing processes, including rapid prototyping, injection molding, casting, machining, sheet metal work, composite construction, forming, and forging. Hands-on labs are incorporated to reinforce the concepts.
- Product ideation including brainstorming and refinement of ideas as well as the complete design process, which was not included in the previous junior level manufacturing course.
- Optimization of designs including design for manufacture, design for assembly, design of experiments, quality control, and evolutionary design.
- A new project where each student team implements concepts learned in the course to identify, design, manufacture and test a novel commercial product.

Mechanical Design I (ME 370: Junior-level course)

Mechanical Design I is a machine design course that focuses on kinematics and dynamics of machinery. This course previously contained only theoretical design projects; it now incorporates:

- Kinematics and dynamics of machinery to understand the forces generated in mechanisms.
- Design of rotating machinery including gears, cams and balancing.
- A hands-on lab where the students design and analyze walking mechanisms.
- A team design project provided by the faculty where the students design and build machines. The faculty formulate common design projects with constraints for all student teams to complete. Examples of these projects include the design of a walking machine, or a climbing

machine. The student teams engage in a competition at the completion of their design projects. Videos of examples of these competitions can be viewed at the following links:
https://www.youtube.com/watch?v=MLjtLh5qCuo
https://www.youtube.com/watch?v=pgtKwCLNf2Y

Mechanical Design II (ME 371: Junior-level course)

Mechanical Design II is a machine design course aimed at designing and analyzing machinery and components to prevent failure in load bearing and power transmission applications. The course contains new hands-on labs and design projects to reinforce the material:

- Investigation of failure modes such as yielding, fracture, and fatigue.
- Design and optimization of machine components such as springs, threaded fasteners, bearings, and gears.
- Introduction to finite element analysis and modern software packages.
- Hands-on group project that involves designing, manufacturing, and testing power transmitting or load bearing machinery utilizing the concepts and skills gained in the course. The instructors formulate common design projects with constraints that all the student teams must satisfy. An example project is the design of a mechanical battery as shown in the following video: https://www.youtube.com/watch?v=ZRIEp-06wIc. Similar to ME 370, the student teams engage in a competition at the completion of their design projects.

Senior Design (ME 470: Senior-level course)

This capstone design course is a one or two-semester course where students work on a project that may be industry sponsored (about 80% of projects), national competitions (15%), or other projects (5%) such as entrepreneurial and humanitarian[1]. All projects are now required to have a hands-on component where a majority of the projects involve building and validating a proof-of-concept prototype or a test rig. Recent changes to the course emphasize improving technical communication skills:

- Partnership with graduate students in Library Science to assist with literature searching.
- Using outlines to prepare logical narratives in technical communications.
- Advanced improvement of writing mechanics.
- Presentation skills, with workshop led by graduate students in Communication.
- Production of marketing videos, with instruction from a professor in the College of Media.

Results

Longitudinal data gathered in ME 470 indicates that the integrated hands-on design curriculum has made a positive impact on the ability of the students to produce a design solution within sponsors' design constraints. Graduate teaching assistants (TAs) evaluated past ME 470 student reports from the Spring 2012 and the Spring 2018 semesters, which exemplify the student learning outcomes before and after major Design Stem changes, respectively. For the duration of this section, these semesters will simply be referred to as "2012" and "2018." In particular, the longitudinal study focused on three student learning outcomes: (1) students produce a proof-of-concept prototype that satisfies stated design constraints, (2) students use an iterative design process to refine an engineering design, (3) students consider multiple design concepts that they produced during the ideation phase of the process. Only projects sponsored by industry partners were evaluated in order to ensure that they all had similar deliverable objectives and semester timelines. The TAs were given evaluation rubrics and a mixture of projects from 2012 and 2018. Student identifying information was removed from the project reports in an attempt to remove personal familiarity bias from the TAs' analysis. The TAs were not informed of the motivation behind the work.

The analysis focused on three reports that the students are required to produce during the course. The first report is termed the "Proposal." The Proposal is due early in the 16-week semester, at the start of week 4. It is supposed to include the complete Ideation Phase of the Design Stem design process, which includes complete background research, concept generation (brainstorming), and a formal decision process whereby students propose the design idea that will be developed into a proof-of-concept prototype to address their engineering problem. The rubric for the proposal required the TAs to count the number of unique potential design solutions (concepts) that the students conceived.

The second report is the "Mid-Semester" status report, which is due during week 10. Students are encouraged to have made significant progress in their project at this point in the semester, but no specific benchmarks in the design process are required. The rubric for the longitudinal study involved the TAs counting the number of unique potential design solutions (concepts) that the students conceived, as well as identifying if the "Team developed early physical prototype," for which a simple yes/no response was expected.

The "Final" report is due during week 15. Students are expected to have developed a physical proof-of-concept prototype that satisfies all of the final design constraints. Design constraints were first identified in the Proposal but teams were allowed to reevaluate and modify the design constraints during the Mid-Semester report, which become the final design constraints. The rubric for the study asks the TAs to reevaluate items from the Proposal and Mid-Semester reports. It also asks them to rank how well the prototype satisfied the final stated design constraints. In addition, the TAs evaluated how many iterative steps the students used in the design process. These items were scored according to the rubric shown in Table 1.

Table 1. Final report evaluation of iterative process and design constraint satisfaction.

	Unsatisfactory (0)	Marginal (1)	Satisfactory (2)	Outstanding (3)
Team performed iterative design process (count number of iterations of the design)	No evidence of iteration in design process	Team made 1 or 2 iterations throughout the process	Team made 3 to 4 iterations throughout the process	Team iterated extensively, more than 5 iterations throughout the process
Design meets final stated design constraints	Meets none of the constraints	Design meets up to 50% of the constraints	Design Meets up to 75% of the constraints	Design meets 100% of the constraints

There were 16 and 22 projects that met the stated requirements for the analysis in 2012 and 2018, respectively. Table 2 shows the median number of unique design alternatives produced for each of the three reports in each semester. The data show a decreasing trend in the number of alternative concepts that students are producing during the initial brainstorming process, as well as in subsequent iterations of ideation. Since the curricular changes were implemented, the students have been focusing their efforts on fewer viable design concepts, rather than a large number of less-feasible concepts. In a sense, they are brainstorming lower quantities of higher quality design ideas.

Table 2. Median number of unique design concepts conceived per project

Semester	Proposal	Mid-Semester	Final
Spring 2012	3.5	7.5	9
Spring 2018	3	4.5	5.5

The percentage of projects in each semester for which a physical prototype has been produced is shown in Figure 1. It is evident that a nearly-identical majority of projects in both 2012 and 2018 feature a physical prototype at the end of the semester. But there is fourfold improvement for 2018 over 2012 at the Mid-Semester point. Students are making greater progress on their prototype development during the first half of the semester than they had prior to the curricular changes.

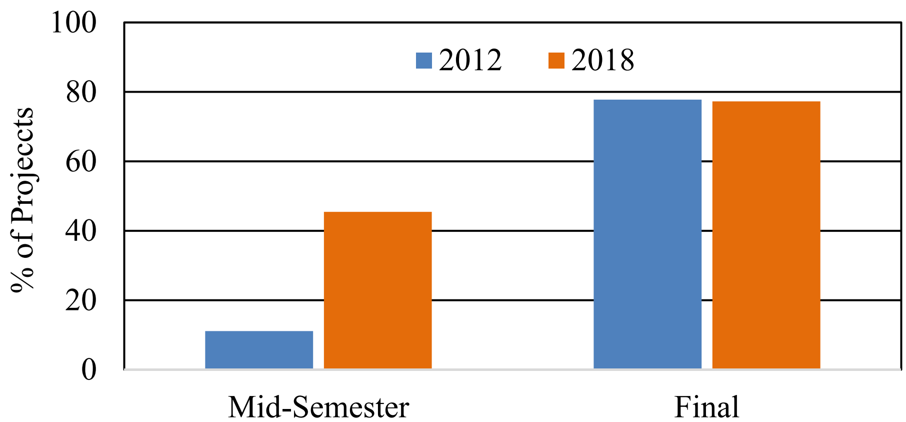

Figure 1. Percentage of projects with a physical prototype at the Mid-Semester and Final report milestones.

Figure 2 shows the results of the Final report assessment of the iterative design process. The distribution shifts markedly in 2018 toward outstanding usage of iteration in comparison to 2012, according to the criteria given in Table 1. Numerically, the mean shifted from 1.71 in 2012 to 2.00 in 2018, with the same median ranking of 2.0 in both semesters.

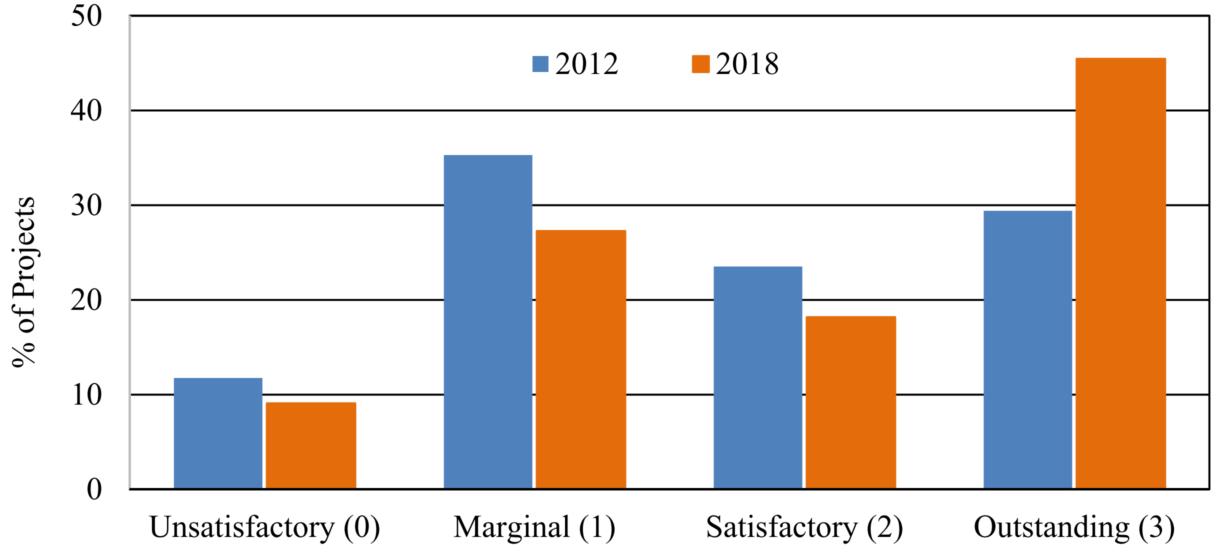

Figure 2. Amount of iteration used in the design process. Criteria follow the descriptions in Table 1.

The assessment includes an analysis of how well the student projects are satisfying all of the final stated design constraints for their projects. According to the rubric presented in Table 1, students in 2018 are outperforming the students from 2012 in terms of their ability to achieve outstanding measures of compliance with project constraints, as shown in Figure 3, and a smaller portion of them are performing in the Marginal category. Numerically, the 2012 data produces a mean score of 2.25 while the 2018 data has a mean of 2.36.

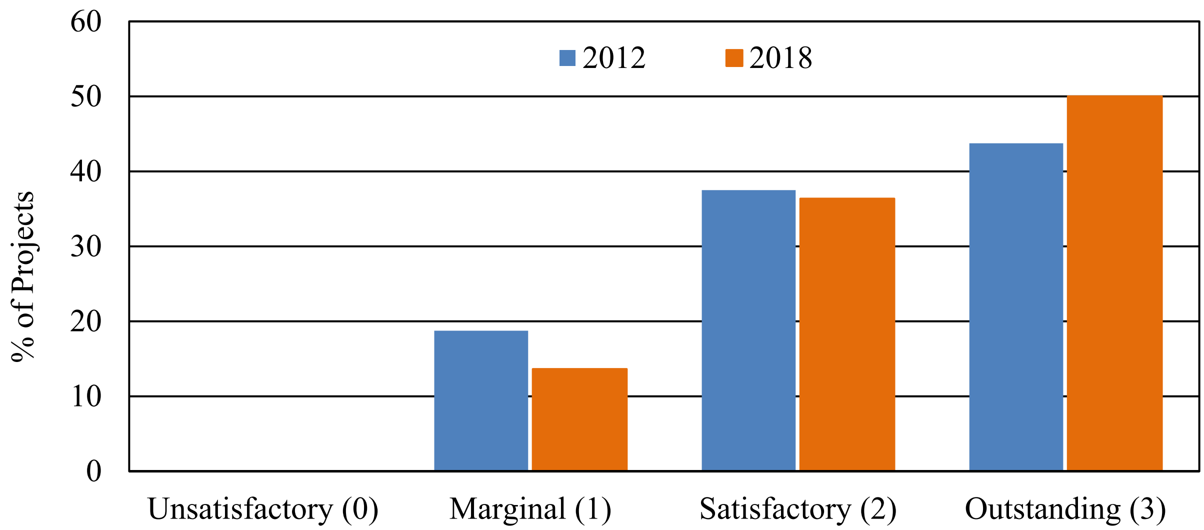

Figure 3. Assessment of how well the final prototypes meet the final stated design constraints in 2012 and 2018. Criteria follow the descriptions in Table 1.

Additionally, ME 470 sponsors who sponsored projects in or before 2013 and continued sponsoring projects through 2017 or later were identified. This time period was chosen as the major Design Stem changes were not seen by seniors before 2013 and were seen by seniors in 2017 and beyond. The time period used in this survey is narrower than that of the assessment of student reports by the TAs because the pool of sponsors that met these criteria is small. All nine sponsors who met these criteria were emailed an anonymous survey that asks the participants to "compare the students' performance in the Senior Design Course (ME 470) in 2013 and prior to students' performance in the Senior Design Course in 2017 and later." Five of these senior design sponsors completed the survey. The results can be seen in Figure 4.

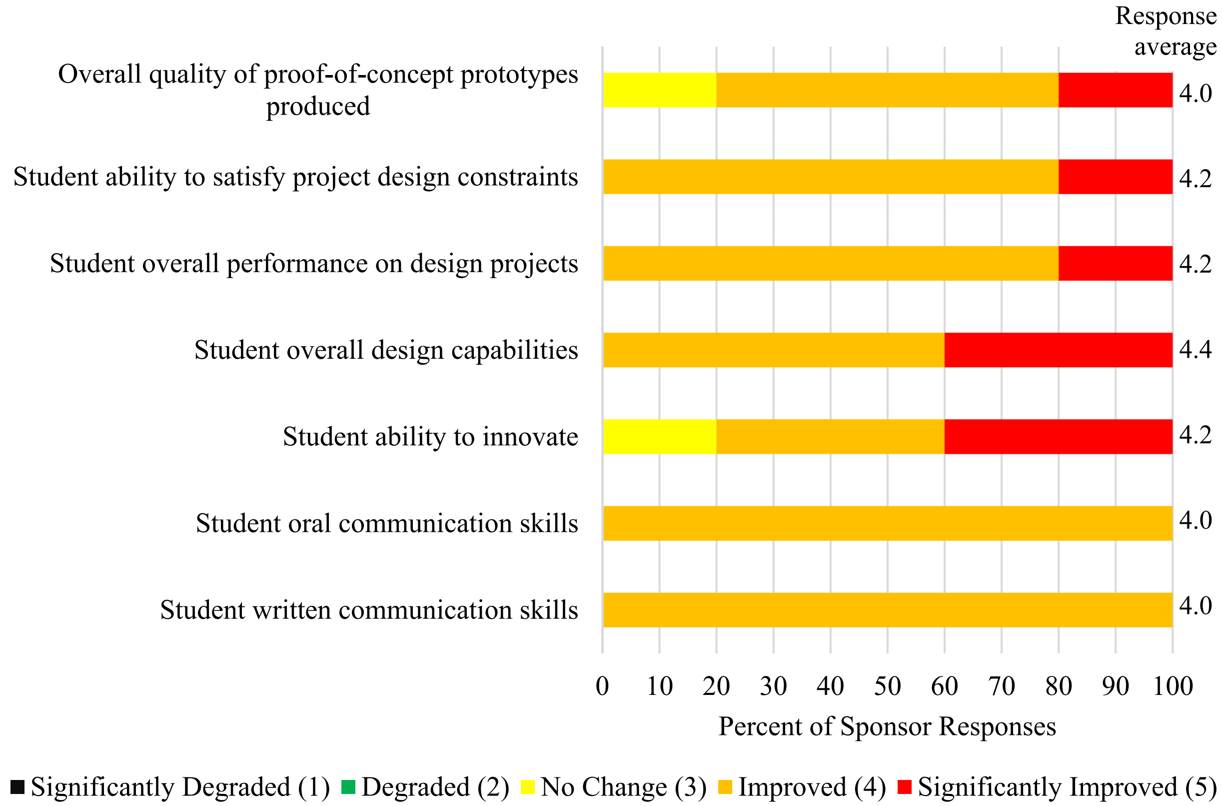

Figure 4. Senior Design (ME 470) Sponsor Reported Change in Student Performance from 2013 and prior to 2017 and subsequent

From Figure 4 it can be seen that all the sponsors who completed the survey indicated that the student ability to satisfy project design constraints, overall performance on design projects, and overall design capabilities either improved or significantly improved. All of the sponsors reported that students' written and oral communication skills improved. The sponsors had more varied responses for the students' overall quality of proof of concept prototypes produced and ability to innovate with one sponsor indicating no change and the rest indicating that it improved or significantly improved. The average response for each of the seven criteria is found to be 4.0 (improved) or above with the highest response average of 4.4 (between improved and significantly improved) for student overall design capabilities.

The sponsors were also asked in the same survey to "Please provide any additional comments on trends in student performance over time in the Senior Design (ME 470) course". Three sponsors who completed the survey also provided the following comments:
1) "The teams seem to understand the concept and flow of innovation better than previous years. It's been much easier to work with them to evaluate ideas and their initial concepts are better."
2) "Company A has participated in a number of design projects over consecutive years and has found the students to be very capable, articulate, communicative and innovative in addressing our project needs. While we have no complaints, we have seen an improvement in the program's focus and the ability of the students to grasp the objectives of the projects and apply their education and knowledge in innovative ways to analyze our issues and develop designs based on these objectives."
3) "The teams with regular communication and collaboration with their project sponsors perform significantly better than teams which 'go it alone.'"
The first two comments point to improvements in the students' abilities. It should be noted that the sponsor who provided the third comment indicated the highest levels of student improvement with student ability to innovate, overall design capabilities, and overall quality of proof of concept prototypes produced marked as "significantly improved (5)" and the rest of the categories listed as "improved (4)."

CATME peer-evaluations at the midpoint of the semester reveal improving student perceptions of team contributions and interactions since the major integration of the design curriculum, as shown in Figure 5.

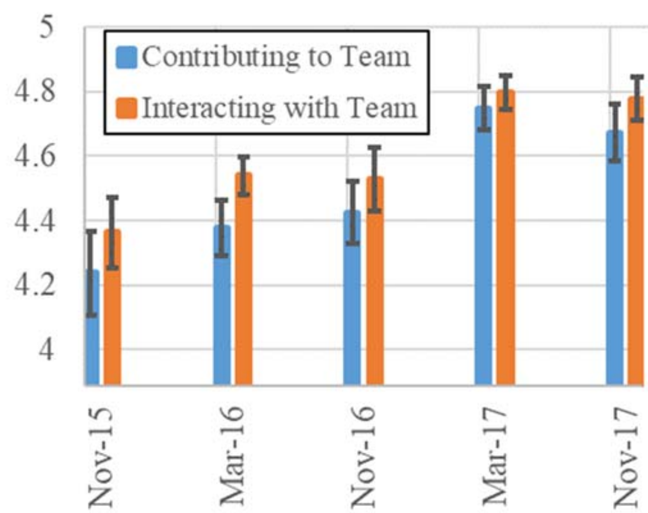

Figure 5. CATME-based trends in teamwork since integration of design curriculum

Student four-year retention (mechanical engineering students entering as freshmen and graduating within four years in mechanical engineering) was found to increase 14.8% over the period of minor and major Design Stem development of required courses as seen in Figure 6. Freshmen starting in Fall 2011 were the first to see the Computer Aided Design, Mechanical Design I, and Mechanical Design II (ME 170, ME 370 and ME 371, respectively) improvements. The freshmen starting in Fall 2014 were the first class to see an integrated hands-on design sequence in all four years since Design for Manufacturability (ME 270) was first introduced to sophomores in Fall 2015. It should be noted that the four-year retention does not include students who transferred to other majors, and students who took longer than four years to graduate. While many factors influence student retention, the increase in retention is nonetheless positive and reflects one of the goals of the present curricular development. Further investigation must be performed to identify what role the present curricular changes played in improving student retention.

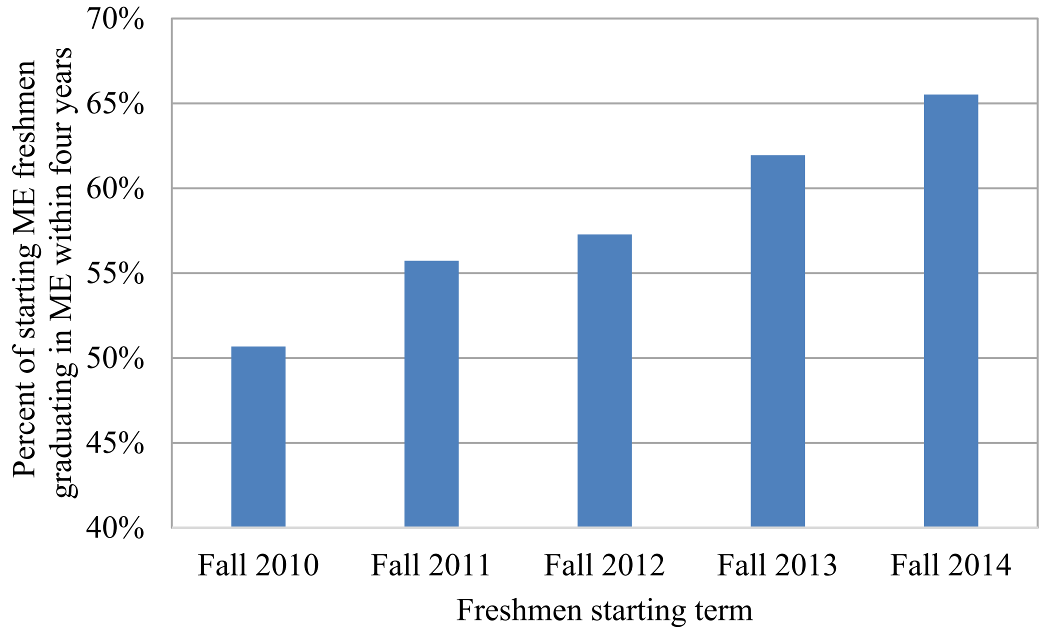

Figure 6. Percent of starting UIUC MechSE mechanical engineering freshmen graduating in mechanical engineering within four years (four-year retention) versus their freshman starting term.

Challenges to implementation

Creating an integrated hands-on design curriculum poses many challenges to implementation:

- It is paramount to have faculty buy-in to implement such a sweeping change in the design curriculum. The UIUC MechSE department leadership and design faculty were keen on developing and implementing an integrated hands-on design curriculum. The faculty involved in this effort hold weekly meetings to address challenges and discuss improvements to the design curriculum.
- Significant financial resources were required to support the design curriculum.
    - Student design teams are given a budget of approximately $200 per team per course, except for ME 470, for which $1,500 is allocated per team.
    - UIUC College of Engineering AE3 SIIP grants were obtained to pay for extra graduate teaching assistant support and basic materials in the development phase.
    - The MechSE Department now pays for all student material expenses, apart from the senior design course ME 470, where the industry sponsors cover expenses.
    - UIUC College of Engineering provided funds for Senior Design lab and Innovation Studio equipment. In addition, the MechSE department obtained equipment and monetary donations from industry to help support the Innovation Studio.

- Qualified graduate and undergraduate teaching assistants who understand the design process were challenging to find prior to implementation of the hands-on design curriculum.
- Design is an iterative process and so have been the changes to our design curriculum.

Conclusions

The UIUC Mechanical Engineering program has implemented an integrated hands-on Design Stem that spans all four years of the curriculum, which is not commonly found and assessed in the literature. Senior Design course sponsors reported improvements in student abilities, which suggest that the Design Stem improved student preparation for their senior design course. Senior design sponsors, on average, reported improvements to students' overall quality of proof of concept prototypes produced, ability to satisfy project design constraints, overall performance on design projects, overall design capabilities, ability to innovate, oral communication skills, and written communication skills during the period of interest. This integrated approach allows our students to build and practice an array of skills in a deliberate and systematic manner. A comparative review of archived projects from 2012 (before integration of the curriculum) and 2018 (after integration) shows that students are more consistently meeting their design project constraints. We see positive indications in student performance as they start prototyping earlier in the semester, allowing more time for design iterations, of which they are taking advantage. CATME evaluation results show improving team dynamics since 2015, when the full design curriculum integration began. Student four-year retention was also found to increase by 14.8% over the period of minor and major Design Stem changes of required courses, which was one of the motivations behind the development of an integrated hands-on design sequence. While this is a positive retention trend, the specific role of the present curricular changes made in improving student retention must be investigated further. Implementing the present hands-on curriculum changes has required significant financial resources, as well as a dedicated group of faculty and teaching assistants to develop and sustain the integrated design sequence. We hope to further benchmark our learning outcomes over time to continuously refine our design curriculum and improve the preparation of our students for their capstone design course and future careers.

Acknowledgements

The authors wish to thank the present and past UIUC MechSE faculty and staff involved in formulating the Design Stem and compilation of data, including Stephanie Ott-Monsivais, Ralf Moller, Drs. Steve Downing (junior level mechanical design course SIIP principal investigator), Bruce Flachsbart, Itay Grinberg, Leon Liebenberg, Brian Mercer, and Profs. Armand Beaudoin, Alison Dunn, Placid Ferreira, Liz Hsiao-Wecksler (iDesign SIIP principal investigator), Seok Kim, Hae Won Park, Mike Philpott, Andreas Polycarpou, Darrell Socie, Sameh Tawfick, Arend van der Zande, and Aimy Wissa. The authors would like to thank Chris Marry, Nicholas Thompson, and Nathaniel Speidel, graduate students who evaluated past project reports for the longitudinal study. Finally, the authors would like to thank the UIUC College of Engineering Academy for Excellence in Engineering Education for their financial support and guidance.

References

[1] E.W. Jassim, "Formulation of Capstone Design Projects for Experiential Learning," 2014 Capstone Design Conference, Columbus, OH, USA, June 2-4, 2014, paper 74.
[2] E.E. McEwen, "Integrated Capstone Design Experience," Journal of Professional Issues in Engineering Education and Practice, Vol. 120, No. 2, pp. 212–220, 1994.

[3] N. Scott, "Two Innovations in JHU's Two Semester ME Capstone Course," 2014 Capstone Design Conference, Columbus, OH, USA, June 2-4, 2014, paper 58.
[4] L.E. Carlson and J.F. Sullivan, "Hands-on Engineering: Learning by Doing in the Integrated Teaching and Learning Program," Int. Journal of Engineering Education, Vol. 15, No. 1, pp. 20–31, 1999.
[5] G.S.A. Kumar, R. Mercado, G. Manimaran, D.T. Rover, "Enhancing student learning with hands-on RTOS development in real-time systems course" 2008 IEEE Frontiers in Education Conference, Saratoga Springs, NY, October 22-25, 2008, pp. 6.
[6] R.J. Bowman, "Inspiring electrical engineering students through fully-engaged hands-on learning" 2013 IEEE 56th International Midwest Symposium on Circuits and Systems (MWSCAS), Columbus, OH, August 4-7, 2013 pp. 574-577.
[7] C. H. Ramming and J. J. Phillips, "Improving Retention of Student Understanding by Use of Hands-on Experiments in Statics," 2014 ASEE Annual Conference & Exposition, Indianapolis, Indiana. June 2014. https://peer.asee.org/20610
[8] L. Albers, and L. Bottomley, "Six Hands-on Activities Designed to Improve Student Achievement in and Attitude Towards Learning Fluid Mechanics," 2012 ASEE Annual Conference & Exposition, San Antonio, Texas, June 2012. https://peer.asee.org/21916
[9] S. Das, "Development of a Low-cost, Portable, and Programmable Solar Module to Facilitate Hands-on Experiments and Improve Student Learning," 2016 ASEE Annual Conference & Exposition, New Orleans, Louisiana, June 2016, 10.18260/p.26800.
[10] J.R. Goldberg and D.B. Rank, "A Hands-On, Active Learning Approach to Increasing Manufacturing Knowledge in Engineering Students," 2013 ASEE Annual Conference & Exposition, Atlanta, Georgia, June 2013. https://peer.asee.org/19066
[12] M.E. Ssemakula, G.Y. Liao, and S.S. Sawilowsky, "Assessing the Learning Gains of Manufacturing Students in an Integrated Hands-on Curriculum," 2015 ASEE Annual Conference & Exposition, Seattle, Washington, June 2015. 10.18260/p.23592.
[13] Desai, N. H., & Stefanek, G. (2017, June), An Introductory Overview of Strategies used to Reduce Attrition in Engineering Programs Paper presented at 2017 ASEE Annual Conference & Exposition, Columbus, Ohio. https://peer.asee.org/27584
[14] D. Knight, J. Sullivan, and L. Carlson, "Staying In Engineering: Effects Of A Hands On, Team Based, First Year Projects Course On Student Retention," 2003 Annual Conference, Nashville, Tennessee, June 2003. https://peer.asee.org/11855
[15] B. Tiwari, P. Nair, and S. Barua, "Effectiveness of Freshman Level Multi-disciplinary Hands-on Projects in Increasing Student Retention Rate and Reducing Graduation Time for Engineering Students in a Public Comprehensive University," 2018 ASEE Annual Conference & Exposition, Salt Lake City, Utah, June 2018. https://peer.asee.org/30360
[16] B.E. Johnson and J.W. Morphew, "An Analysis of Recipe-Based Instruction in an Introductory Fluid Mechanics Laboratory", 123rd Annual ASEE Conference and Exposition, New Orleans, LA, USA, June 26–29, 2016.
[17] E.W. Jassim, "An Entrepreneurial Capstone Design Option: U of I MechSE Innovation Trophy Competition," 2016 Capstone Design Conference, Columbus, OH, June 6-8, 2016, paper 61.