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Stimulating Interest in First-Year Mechanical Engineering Students through Design Modeling/Analysis and CNC Manufacturing

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Abstract

Before a recent curriculum change for 1st and 2nd year students, Mechanical Engineering students at South Dakota State University did not see Mechanical Engineering faculty and did not necessarily attend courses with only mechanical engineering students until their 4th semester. Most courses taken during this time fulfilled either general science and mathematics course requirements for engineering students or general university requirements. Problems with retention and gaining student interest early in the program led to the creation of three new courses for 1st and 2nd year Mechanical Engineering students. In the first semester, students take the course "Production and Manufacturing Processes". The goal of this course is to teach the basics of manual milling and turning, CNC milling and turning, welding, and injection molding/casting. Each student gets hands-on experience working with shop/lab equipment. In the 2nd semester, students enroll in "Mechanical Engineering Design Technologies". This course focuses on developing skills in 3d CAD modeling (Solidworks), spreadsheet calculations (Excel), and scientific computations (Matlab). The last new course, "Engineering Design Methods", taken in the 4th semester, focuses on design projects specifically formulated to allow the students to practice new skills gained in courses from the first three semesters. While enough data is not yet available to quantify changes in retention rates, anecdotal evidence shows that the students retained to the 3rd year are more engaged in coursework and extracurricular activities, more knowledgeable, and, most importantly, have good attitudes and are ready to learn in future courses.

Introduction

Three years ago, the Mechanical Engineering Department at South Dakota State University developed a new strategy for improving student retention and overall student quality based on a new first-year engineering experience. The older curriculum had become outdated, was not teaching our students what we thought they needed, and was not preparing the students for the rest of the mechanical engineering program and beyond.

As our graduating students completed exit surveys, common criticisms of the program included a perceived lack of software availability and a deep knowledge of how to use the software, lack of preparation for constructing prototypes (mechanical and/or electrical), and lack of product design instruction and practice. In an effort to address these problems, two new courses were developed for 1st year students [1] and a 2nd year course was significantly redesigned [2]. As these courses were developed, a strong emphasis was placed on adding hands-on authentic experiences that are specific to mechanical engineering as a way to improve retention [3, 4] and student performance for future courses and future employment [5, 6].

Concurrent with the curriculum redesign, the department was experiencing significant growth, both in terms of number of students starting the program and number of faculty members teaching courses. From the year the curriculum redesign was initiated until present, the department has seen a sustained increase of about 25% for incoming 1st year students. In the same period, the overall undergraduate enrollment has also grown by about 25%. To accommodate these larger than normal (and larger than expected) classes, new techniques [7] were employed, such as creating lab sections to allow students more individual instructor time for questions and additional help sessions.

As we have an entire cohort of students graduate with the new curriculum, we will look to further quantify the effects of these changes.

Previous Curriculum

Before our most recent curriculum changes, students enrolled in three separate 1-credit courses classified as "General Engineering (GE)" courses and one Mechanical Engineering 3-credit design course for a total of 6 credits. The GE courses were developed to give a broad engineering perspective, and, when introduced many years ago, were intended to be broad enough to allow students to change engineering degrees in the first year of coursework without much penalty. All GE courses were intended for students in semesters 1 through 3, with ME 240, the mechanical design course, taken in semester 4. However, due to limited section sizes in the GE courses, some students were not able to take GE courses until they were nearly ready to graduate.

The course catalog description for each of the courses is listed below, along with the common descriptions by students after taking the course:

GE 121 - Engineering Design Graphics (1 credit)
Course Description: A course in graphical communication, expression and interpretation. The ability to visualize in three dimensions is developed through shape description, sketching and multi-view projection exercises. The emphasis is on visualization and free hand sketching. Also includes Engineering, Mechanical, and Architectural scales, geometric constructions, use of instruments, dimensioning, and sectional views.

Student Interpretation: Hand drawing skills, 2d drawings, projections, section views, and drawing tools

GE 123 - Computer Aided Drawing (1 credit)
Course Description: A course with major emphasis on 2-dimensional drafting skills and 3-dimensional solid modeling utilizing microcomputer software. All work requires a "hands-on" approach.

Student Interpretation: 2d AutoCAD for half of the course, introduction to Solidworks basics for the other half of the course

GE 225 - Survey of Machine Tool Applications (1 credit)
A survey course introducing machine tools and their applications. Automation in machining and CNC programming and operations are also topics addressed in this course.

Student Interpretation: The "tap wrench" class, mostly working on a lathe to manufacture a tap wrench

ME 240 - Introduction to Mechanical Design (3 credits)
Introduction to the design process, statement of problem, modeling, research, interaction of system components. Economic, social, environmental and manufacturing constraints. Factors of safety, reliability. Utilization of graphics and vector methods in mechanical design. Design project.

Student Interpretation: Matlab class, 3d printing design project

Over the years, the goals of these GE courses and the goals of the ME Department diverged, leading to mismatches in expectations. Because of these mismatches, the ME Department developed two new courses and significantly modified an existing course to provide our students with a first-year engineering experience directed towards providing new Mechanical Engineering students a broad overview of the Mechanical Engineering degree.

Curriculum Changes Implemented

Any changes made to the curriculum were required to be credit neutral. Therefore, three credits from the GE courses and thee credits from the ME 240 course were removed and six credits were available to develop the new courses. The number of credits and the general topics of the new courses are not greatly different from the previous courses; however, a greater emphasis was placed on modern techniques and modern skills necessary for practicing mechanical engineers.

ME 121 - Production and Manufacturing Processes (2 credits)
Previously, a one credit (mostly lab course) was the only experience many students had working in a machine shop and getting hands-on practice with real manufacturing equipment. ME 121, a new two-credit course, was developed as a modernized "shop" class for mechanical engineering students. This class is designed to be taken by new students in their first college semester with no prerequisites. This allows all students, including those with a weaker mathematical background (the students required to start with math courses before Calculus 1), to participate in the mechanical engineering program and get early experiences to determine if mechanical engineering is the correct major for them. The course is a combination of introductory lectures (one per week) and small sections of hands-on lab activities to practice the techniques learned in lecture Each week students complete a pre-lab, which is required to start manufacturing in the

lab that week, and a post-lab assignment, which requires quality inspection of the manufactured part.

The course starts with manual machining via mills, lathes, drill press, and hand tapping. This allows the students to (at their own pace) see how the machines function with cranks and experience how the machine moves and feels as it cuts through material. For their first project, each student manufactures an all-aluminum meat tenderizer. This project involves using a lathe to make cut-down diameters, along with knurling a grip, on the handle. One end of the handle is threaded with a die. The head of the tenderizer is faced flat on a mill and the teeth are cut using a chamfer tool, giving the students an opportunity to change tooling. A hole is drilled in the center of the head and threaded using a tap. This simple two-week project allows the students to quickly have a positive experience in the shop, and they hopefully go home with a sense of pride in their new souvenir from the course.

The next section of the course focuses on CNC manufacturing methods. The students are still learning the basics and often make mistakes. With this is mind, a machinable wax is the material being cut each week. When students make mistakes, they can get a new block and recycle the block with their mistakes. Students start learning G-code and learn how to set up the machines by writing a short code to cut their initials into a block. This process gives students some knowledge of G-code and the background to understand what CAM software does behind the scenes. During the next several weeks, students learn the basics of a CAM software called HSMWorks. HSMWorks is an add-on to Solidworks and is freely available from Autodesk for educational purposes. After four weeks of CNC mill practice, the course transitions to the CNC lathe for one week. The students realize that many of the techniques and knowledge gained from the CNC milling experience transition to the CNC lathe. In one week, students learn new lathe techniques and complete two projects in lab, cutting aluminum because our CNC lathes do not have a tailstock and do not allow for cutting soft materials.

Next, the students spend two weeks learning the basics of welding. In the first lecture, the instructor introduces types of welds and the science behind welding. In the two weeks of lab, students learn the basics of setting up a welder and practice a variety of weld types. During the second week of welding labs, the lecture focuses on injection molding, which helps lead into the final course project.

Finally, the course ends in a mold development project. The students choose from several projects available and complete the CAM work before lab to cut both halves of a mold. The wax mold is not suitable for injection molding; instead, a quick-cure casting resin is poured into the mold and allowed to harden. Students are able to take their projects home as a source of pride and a final souvenir from the course.

Course Catalog Description: Overview of manufacturing production and fabrication processes from an engineering design viewpoint. Topics include: cutting, forming, shaping and finishing raw materials; fastening and joining techniques; advanced manufacturing methods; precision measurement and layout.

Course Delivery (each week): 1 Lecture (50 minutes), 1 Lab (2 hours)

Course Topics:

Week	Lecture Topic	Lab Project
1	Shop Safety	Shop introduction and tours
2-3	Manual Machining (Lathe, Mill, Drill/Tap)	Aluminum Meat Tenderizer Lab
4	Intro to G code	Manual G code to spell and cut initials in block
5	Intro to CNC Milling with CAM (Facing, Pockets, Post-processing)	CNC Mill Lab 1 - Block with several pockets at a variety of depths (2.5D Milling)
6	Mill CAM 2 (Rest Machining, Bores/Drills)	CNC Mill Lab 2 - Pockets requiring several sizes of tooling, boring and drilling
7	Mill CAM 3 (3d features, roughing/finishing), types of tooling	CNC Mill Lab 3 - Fully 3d features using a variety of techniques
8	Mill CAM 4 (Multi-surface Machining)	CNC Mill Lab 4 - Machining on 3 sides of the block
9	CNC Lathe	CNC Lathe Lab – Chess Pieces
10	Welding	Welding Lab 1 - Practice with a variety of weld types
11	Injection Molding	Welding Lab 2
12	Final Project Introduction	Final Project - Cutting Molds
13	Review for Final Exam	Final Project – Resin is cast in molds

ME 212 - Mechanical Engineering Design Technologies (2 credits)

ME 212 was designed to be taken by 1st year students in their 2nd semester. It introduces the students to modern software packages and to the rigor and work ethic required to continue in the major. It prepares the students to use these software packages in future courses and may be of some help to them getting summer internships. The course is divided into three parts: Engineering Drawings and 3D CAD modeling (1/4 of the course), Computational Analysis through Matlab (1/2 of the course), and Computational Analysis through Excel (1/4 of the course). The students all have access to university licenses to install the required software on their own personal computers. Parts of this course do require some mathematical background and all students must be enrolled in Calculus 1 or higher. The course is team taught with one instructor focusing on Matlab and the other instructor focusing on Solidworks/Excel. From experience with teaching Matlab in ME 240, students need to time to practice and think about coding homework assignments. With that in mind, the course alternates topics (and instructors) every day. Tuesdays are always Matlab instruction, while during the first half of the semester, Thursdays are Solidworks instruction and during the second half of the semester, Thursdays are Excel instruction.

The course begins with understanding mechanical drawings and projecting 3d objects into 2d views. Since most students completed ME 121 in the previous semester, they do have some familiarity with reading mechanical drawings and some familiarity working within Solidworks (mostly using the HSMWorks module). Generally, the students are excited to start learning how to create their own CAD models. The Solidworks portion of the course focuses on sketching, extruding, revolving, lofting, linear/circular patterns, assembling, and creating mechanical drawings from CAD models. Students are required to attend a 50-minute lab in a computer lab where a graduate teaching assistant shows several more examples using any new features learned in lecture, but at a slower pace than in the lecture. Each week, students are given a homework assignment that typically includes practicing new techniques to model 3-4 objects from engineering drawings/dimensions. This section of the course ends with a culminating project were students are given a broad prompt and allowed to figure out how to model the project. While the object to be modeled changes every semester, the same broad rules apply each semester – the project must be an assembly of at least five parts, drawings must be created to manufacture each individual part, and a general assembly drawing must be supplied. Typical projects have included objects to force the students to stretch their minds into topics that they may have never seen before, such as designing a heat exchanger or a turbomachine. Students must first do some preliminary research to learn about the topic and then determine the best way to model the object.

While the students are learning CAD modeling, they are also introduced to computational analysis and computer science through Matlab. Most students coming into this course have no experience using Matlab, very little experience writing any computer code, and very little experience typing equations and seeing fractions written horizontally. This portion of the course starts by using Matlab as a calculator, forcing the students to type equations and see fractions written horizontally. This also helps students start to learn how to debug their code while it is still relatively simple. Next, the course moves into using Matlab vectors/arrays to do many calculations in one line. This also shows the students how information is stored/retrieved from memory in Matlab. Naturally, 2d plots are studied next allowing the students to visualize the data created from the large vectors they have learned to create. Throughout these first weeks, homework problems are intentionally designed to be somewhat tedious and repetitive so students appreciate using functions. After learning to write functions, the course moves into 3d plotting followed by "if" statements.

At this point, it is approximately mid-semester and the Solidworks portion of the class is complete. This is the natural time to have a mid-term exam and allow the students some extra time to work on their Solidworks project. The midterm exam consists of an in-class exam (multiple choice, read code and write the output, write simple 2-3 lines of code to solve a problem, etc.) and an out-of-class exam that forces the students to solve several longer problems requiring 20-30 lines of code each.

The second half of ME 212 transitions into Matlab and Excel instruction. To finish the Matlab portion of the course, emphasis is placed on learning "for" and "while" loops – key concepts learned in computer science courses. The last few sections of Matlab focus on the power of the built-in functions in Matlab, such as curve fitting, interpolating and extrapolating, simple numerical analysis for calculus and differential equations, and finally, the Matlab Symbolic engine. The last week is meant to be a fun week to inspire the students to want to learn more about Matlab on their own, by showing how Matlab will be used in a future course (animations in a course related to kinematics and dynamics of machinery) and how complex problems can be solved using image and sound processing and analysis.

During the second half of ME 212, students are also introduced to Excel. Many of the concepts learned in the Matlab portion of the course are again studied, but this time using Excel. Typical topics include writing equations in cells, using built-in functions, nesting and logic, iterating, and formatting as tables.

The final exam follows a similar format to the mid-term exam. There is an out-of-class portion and an in-class portion of the exam. On the final exam, about 2/3 of the points are focused on the 2^{nd} half of the Matlab portion of the course and about 1/3 of the points are related to Excel.

Course Catalog Description: This course provides an introduction to several mechanical engineering design technologies and computer-aided tools that ME students will use throughout their coursework. Students will be introduced to engineering graphics, including freehand sketching, 2D/3D computer aided drafting (CAD) and graphical presentations of designs (views, sections, dimensioning, and tolerancing). Computer-aided engineering tools for solving complex mathematical systems will also be presented.

Course Delivery: Two 50 minute lectures per week, Two 50 minute computer lab sessions per week

Course Topics:

Week	Tuesday (Matlab)	Thursday (Solidworks/Excel)
1	Course Intro	Mechanical Drawings
2	Matlab 1 - Use Matlab as a calculator	Solidworks - sketching and linear extruding
3	Matlab 2 - 2d vectors and 3d matrix	Solidworks - Revolve
4	Matlab 3 - 2d plots	Solidworks - Patterning, Sketch plane creations
5	Matlab 4 - Functions	Solidworks - Mirror, Advanced Sketching
6	Matlab 5 - 3d plots	Solidworks - Assemblies
7	Matlab 6 - If statements	Solidworks - Engineering Drawings
8	Solidworks Project Introduction/Matlab Out-of-Class Exam	Matlab In-Class Exam
9	Matlab 7 - For Loops	Excel - Terminology, Using Simple Functions, Writing Simple Equations
10	Matlab 8 - While Loops	Excel - If Statements, Tables
11	Matlab 9 - Polynomials, Curve Fits, Interpolations/Extrapolations	Excel - Plotting, Curve Fitting
12	Matlab 10 - Numerical Analysis, ODE Solving	Excel - Pivot Tables
13	Matlab 11 - Symbolics	Arduino Preview
14	Matlab 12 - Animations, Image Processing, Sound Processing	Course Review

ME 230 - Engineering Design Methods (2 credits)

ME 230 is designed to be the final part of the early engineering experience for our students and is typically taken in the 4th semester. The class brings together many of the concepts learned in the previous two courses in a final design project. The previous version of this course (ME 240) used about 1/3 of the time and credits to teach the basics of Matlab and left the final 2/3 of the time and credits to teaching design methods. Besides removing the Matlab portion of the course, the rest of the course was modified to focus on design methods and prototyping skills for developing new products.

The course begins with a short two-week project that begins on the first day of the class. In this project, students design a solution to a real-world problem (typically related to a research project that the instructor is working on) in small, randomly assigned groups. Students are assessed on likelihood of success of their design solution, the quality of a representative CAD model, and their ability to communicate the results through a short presentation and a short design report. This project is meant to excite the students for the rest of the course and to help them understand why learning design methods, team-working skills, and prototyping skills are important.

The next section of the course shows students the design process through a series of interactive class discussions and in-class exercises ending with a unit on 3d printing as a way of physically prototyping critical parts. This leads into the discussion of advanced manufacturing processes and the first large project, the ASME IAM3D competition.

The ASME IAM3D competition focuses on developing a new product or redesigning an existing product while taking advantage of unique capabilities of additive manufacturing (3d printing). This is the first chance that the students have to practice the design process in a continuous project. While the students first see 3d printing as a method for rapid prototyping, the goal of the project is to use 3d printing for end use manufacturing. Problems and needs are identified through small group brainstorming sessions, followed by the students choosing project topics and not group members, with the goal being that everyone is excited to work on the project selected. Groups design solutions and 3d print the parts necessary to demonstrate that the idea is feasible. Groups must clearly communicate the results of the project through a five-page design report and a 3-minute video.

Before the final project for the course begins, the class shifts to prototyping and simulating skills. Students purchase an inexpensive Arduino Uno kit for about $35, which comes with sensors and all other necessary equipment to prototype several simple scenarios. Each segment of the Arduino tutorials used in class ends with a culminating experience that forces the students to combine everything learned that week. In the end, students spend about 4 weeks learning simple Arduino coding and simple circuit development and analysis and then demonstrate these concepts through simple projects.

At the same time, students use ANSYS Workbench to simulate mechanical scenarios. Similar to the Arduino tutorials, students learn several new concepts each week and combine the concepts into one final project. By the end, students have learned the basics of ANSYS Workbench and can modify or add engineering data to materials, simulate static structural scenarios, complete a modal analysis, simulate heat transfer, and simulate simple fluid flow. Although most of the students have not taken the advanced courses required to fully understand these concepts, they leave the course with a general understanding of what is required to simulate each of the scenarios.

Finally, a traditional manufacturing project is assigned that requires students to combine most of the knowledge from ME 121, ME 212 and ME 230. Students are required to integrate the use of Arduino microcontrollers into the project for simple controls and must simulate something using ANSYS Workbench. The project concept changes every semester to encourage creativity. An example of a project prompt is an Internet of Things (IoT)-connected piece of dorm furniture that a typical college student would want to purchase.

Course Description: Introduction to the engineering design process, including development of the problem statement, modeling, research, cost/benefit analysis, and interaction of system components. Design optimization techniques will be used to drive design decisions. The course will incorporate consideration of economic, social, environmental and manufacturing constraints within the engineering design process. Design projects will be used to instill these concepts.

Course Delivery: Two 75 minute sessions per week which are a combination of lecture, lab, and interactive work sessions

Couse Topics: Introduction to the design process, simple mathematical design optimization algorithms implemented via Matlab, introduction to advanced manufacturing techniques (3d printing) with the ASME IAM3D Challenge, introduction to Arduino microprocessors, introduction to ANSYS Workbench simulations, and a traditional manufacturing project

Results

This curriculum change is currently in its 3rd year, meaning the first cohort to enroll in ME 121, ME 212, and ME 230 are currently in their 3rd year in our department. The goals of the curriculum changes were to better prepare our students for future courses, better prepare our students to obtain summer internships and coops, and increase retention.

Because this is only the 3rd year of the curriculum change, there is not enough data available to draw statistical conclusions from these changes. Starting with the year before the curriculum change (students starting in Fall 2014), our retention is almost identical (see Figure 1) to the retention after the curriculum change. Therefore, we cannot say that we have increased overall retention yet. However, we believe that as the implementation and the teaching execution of the courses continues to improve, we will see improvement in overall retention.

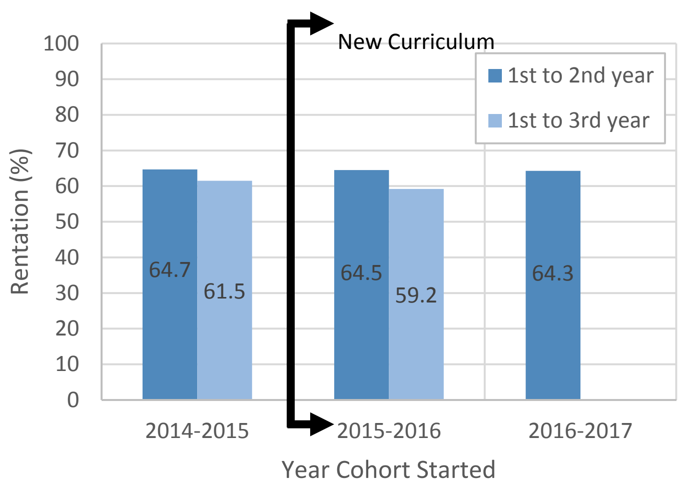

Figure 1. Retention rate data 2014-2017

Although overall retention rates have not increased, we believe that we have made two improvements that have ultimately caused a neutral retention trend. In the new curriculum, students are exposed to and understand what mechanical engineering is sooner than in the old curriculum. In the old curriculum, we lost high achieving students that likely would have become excellent engineers because they did not get a chance to do “real engineering” until their 4th semester. By moving some of these course topics to the first year and by having our mechanical engineering faculty teach these courses, we are retaining some of these students who become engaged and excited about engineering. On the other hand, ME 121 and 212 introduce more rigor and more difficult concepts into the first two semesters, similar to what the students would have seen in semester 4 in the old curriculum. Some of the students that may have normally dropped mechanical engineering after semester 4 now drop mechanical engineering sooner. Other students realize earlier in their studies that they are not interested in mechanical engineering. We consider both of these changes to be important. We want to retain the potentially high achievers and help the students that are not interested in mechanical engineering find their true passions quicker. Therefore, the net retention rate seems to be unchanged; however, we see evidence that the students we are retaining are more interested in mechanical engineering and are better prepared for the more difficult courses in years 3 and 4.

To attempt to quantify this result, we have calculated the cumulative GPA for all students entering the senior design capstone experience this year. All of these students were part of the old curriculum and have not taken any of the new courses. Because we do not have enough data to compare the students at equivalent points in the curriculum, we will compare this GPA to the cumulative GPA of students currently enrolled in Thermodynamics 1 and 2 because these courses are typically taken by students in semesters 4-6 and include only students that are part of the new curriculum. The cumulative GPA of the students in the new curriculum is 0.15 grade points higher than the previous cohort from the older curriculum (***Note – this comparison is not entirely fair. Most of our course instructors have stayed the same over this period, but some courses have changed instructors. In addition, our students’ GPAs are typically lowest at the beginning of the program and end higher at graduation. With this in mind, when we are able to compare Senior Design Capstone GPAs for both the new and old curriculum, we expect this GPA increase to be higher yet). Along with this quantitative data, the instructors of Thermodynamics comment that the students are more open to class participation, are more comfortable asking the instructor for help when needed, and in general are not afraid of tackling difficult assignments and have almost come to expect difficult assignments.

The students took a survey related to the new courses they have taken to help us learn about their experiences in the new sequences of courses. The following are a few questions and typical responses:

How well do you feel you can use the concepts from ME 121, 212 and 230 to develop innovative solutions to problems to design problems?

- “All of the software packages we learned have already helped me design solutions to my own real-world problems”
- “I feel like I have a broader/improved tool-set to apply to real world engineering problems as a result of taking these courses”

As a result of taking these courses, do you have a better understanding for the use of software in engineering design?

- 100% answered yes

Are you more comfortable with the idea of learning new and unfamiliar software after these courses?

- 93% answered yes

Has learning the software packages in these courses helped you in any other courses?

- 93% answered yes
- “I am much more confident on a computer now in many ways, not just (the software we learned)”
- Much more willing to use Matlab now – it’s much more powerful than other software

The last goal of the new curriculum was to help the students obtain internships and coops sooner in their college careers and to be better prepared for these opportunities. This is perhaps the most difficult goal to quantify because we do not hear from all (or even many) of the students’ internship or coop employers. However, on our final class surveys we have asked the students themselves if they feel prepared to work at an internship/coop:

Do you feel these courses have helped you feel more prepared for working at an internship/coop?

- 96% answered yes

Finally, to attempt to gather the general sentiment and overall feelings from the students about these three courses, the last question on the survey simply asked the students for any other general comments. The responses were mostly positive with many students also leaving suggestions for the instructors to help improve the classes. Below is a sample of responses:

Do you have any general comments?

- “Overall, I complained a lot throughout the semester, but I have to admit that I learned a lot and have taken a lot away from this course”
- “I truly enjoyed the content of this class and believe that it will help me in future courses”
- “I really enjoy this course. Not only did it expose me to a lot of situations in which computer programs can help in class, but also how they (Matlab, Solidworks, Excel) can benefit my future career.”

Conclusions and Next Steps

The curriculum change implemented three years ago has provided many positive outcomes for our department. Our students are now more engaged in the classroom, are achieving higher GPAs, report feeling prepared to take on internships and coops and, in general, have a better attitude about working hard in every course. While we have not seen the retention improvements that we originally expected, we have seen evidence that we are retaining more of the people that we want to retain and are helping others find their non-mechanical engineering passions faster, resulting in a flat retention rate but more focused students in the department.

The next steps in this curriculum change project are to continue to collect data from the students to understand more fully the long-term effects of the curriculum changes. We plan to begin addressing some of the changes requested by the students, such as more online video tutorials and online written notes and perhaps a course manual/textbook as a reference for the entire set of courses.

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