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Machine Design: Different Pedagogical Approaches to Achieve Targeted Outcomes

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Abstract

Machine design is one of the core courses in any mechanical engineering program across the world. This paper presents three different approaches taken by faculty at three different regional universities in the United States with similar small class size, low student-teacher ratio, and comparable cost of attendance. We examine the pedagogical approach, course content, desired outcomes, and assessment of outcomes at three different universities to identify the desired balance between traditional, analysis-based outcomes and those targeted towards practice-based skills.

Introduction

A course in the design of machine elements has been a part of most mechanical engineering curricula since the 1950's. The content of this course has its roots in academic research in solid mechanics, mechanisms and machine elements. In most cases, this course focuses on the derivation and application of methods used to analyze individual machine elements such as shafts, bearings, and gears. Emphasis is placed on students' ability to correctly apply a specific analytical method to a particular class of machine element. Homework and assessment problems are usually focused on analyses of individual elements in isolation from the surrounding system and required input information is typically provided as part of the problem statement.

The effective practice of machine design requires different and diverse types of knowledge. Liu and Brown have made the observation that newly-graduated mechanical engineers have difficulty dealing with ambiguity and uncertainty when they are faced with real-world machine design problems.[1] The ability to move a design forward despite uncertainty is an experience-based skill. Other experience based skills that are important to the practice of machine design are the effective use of computer-aided engineering tools and the ability to extract a correct analytical model from a real-world engineering problem. Liu and Brown suggest that an effective approach to teaching these experience-based skills is through the inclusion of active, project-based learning.

Monterrubio and Sirinterlikci implement this active learning approach into the curriculum of a Machine Design course by including a semester-long laboratory in which students design and construct an injection-mold.[2] The authors found increased student engagement and high achievement of experience-based outcomes such as effective use of CAE tools. Several other authors have published results that support the idea that active, project-based learning is an effective approach to teaching experience-based skills in machine design.[3],[4],[5] The need to include experience-based outcomes in machine design courses creates a tradeoff with more traditional, analysis-based outcomes that continue to form the core of the subject. Machine Design instructors must balance class time and instructional resources between these two types of outcomes. In this paper, we consider three different approaches to teaching machine design. The authors all teach a junior-level course in machine design at one of three different universities. Each employs a different set of student outcomes and each strives for a different balance between analysis-based and practice-based outcomes. We compare pedagogical approach, course content, and desired outcomes to identify the balance between analysis and application-based skills that each instructor is trying to achieve. We then present assessment of outcomes at each university.

Background

In this work, we compare course sequences, course content, teaching style, instructor priorities, and desired outcomes for Machine Design courses taught at East Carolina University (ECU), Western Carolina University (WCU), and Penn State Berks (PSB). All three of these are regional, comprehensive universities and the student population and cost of attendance are similar. For this paper, instructors at each of the three universities have characterized their instructional methods and priorities for the course using a survey designed to identify the balance between analytical and practice-based skills that each instructor is trying to strike.

The Engineering Programs

All three of the universities at which the authors teach are public, regional universities. The programs at ECU and PSB are ABET accredited, the program at WCU is relatively new and completed its initial ABET visit in the fall of 2017. Student populations in all three programs are similar, with predominantly male students and a relatively high percentage of first-generation college students. Cost of attendance at each of the three schools is similar. The number of students in the machine design class is also similar at each school and ranges from 20-35 students. The large majority of graduates from each program take a job in industry while a much smaller percentage go to graduate school.

At ECU, the Machine Design course is taught as part of the Mechanical Engineering concentration, which is available to students pursuing a Bachelor of Science in Engineering degree. The curriculum for the Mechanical Engineering Concentration is very much a classic mechanical engineering curriculum, with required course sequences in solid mechanics, dynamics, thermodynamics, and fluid mechanics. Students are required to take two courses in mechanics of materials, however only one of these is a prerequisite to the machine design course.

At WCU, machine design is also taught as part of the Mechanical Engineering concentration for the Bachelor of Science in Engineering. WCU uses a project-based learning curriculum in which students take a multidisciplinary, project-based, design course during each of their four years. The curriculum for the Mechanical Engineering Concentration is modeled after a classic mechanical engineering curriculum but with an emphasis on engineering practice. The machine design course at WCU is taught concurrently with a three-hour, mechanical engineering laboratory course that is tightly integrated with the machine design course.

At PSB, the machine design course is required for students pursuing the Bachelor of Science in Mechanical Engineering degree. The curriculum for this degree is a rigorous mechanical engineering curriculum with required, multi-course sequences in each of the mechanical engineering disciplines. The machine design course is preceded by two courses in mechanics of materials so that students are well-prepared for the application of engineering mechanics to machine elements. Student assessment in the machine design course is based completely on a series of engineering projects.

The Courses

The machine design courses at each of the three universities have many similarities. The course is taken by second semester juniors who have completed their math requirements. These requirements include courses in calculus, differential equations and in linear algebra. Students have also completed the physics and chemistry requirements and have had a course in materials science.

Figure 1 shows the engineering mechanics course sequence at each of the three universities. The courses have similar prerequisites, though students at ECU and PSB take Intermediate Mechanics of Materials. Students at WCU move directly from Mechanics of Materials to Machine Design, however Machine Design is supplemented with a three-hour lab course that is tightly coordinated with the lecture course.

Table 1 shows the sequence of topics covered in the machine design course at each of the three universities. One can see that there are significant differences in the courses at the three universities. Some of these are attributable to differences in the prerequisite chain while others can be attributed to differences in desired outcomes.

The course at ECU is a classic, lecture-based course in the design of machine elements. The focus is on the application of the equations of engineering mechanics to a series of individual machine elements. Students are assessed using exams in which they must identify the correct analytical method and apply it to an individual element. The ECU curriculum does not include

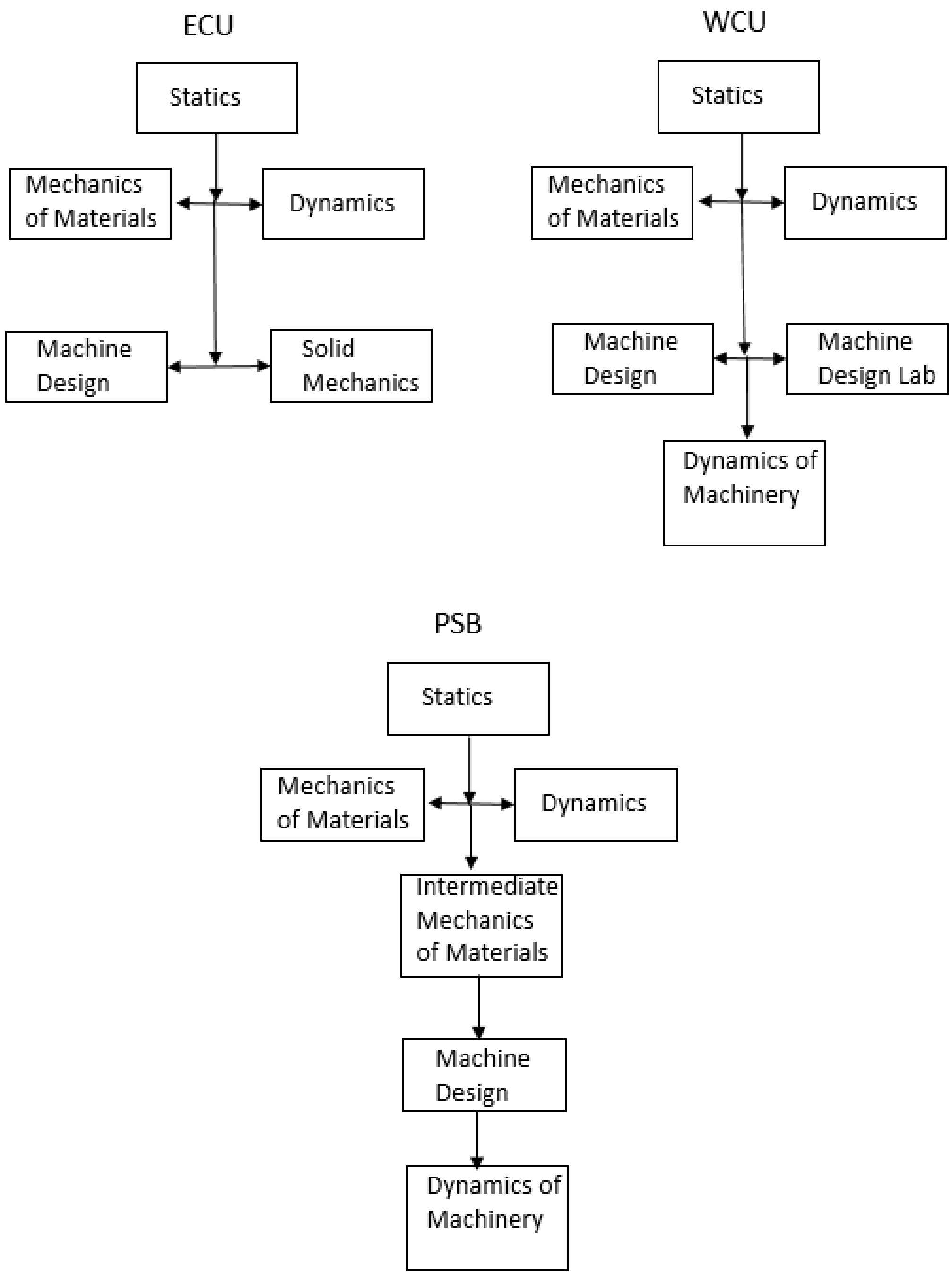

Figure 1. Course sequence in mechanics at the three universities

	ECU	WCU		PSB
		Lecture	Lab	
Week 1	Factor of Safety, Principal Stresses, Ductile Failure	Review of mixed loading	Factors of Safety, Engineering Estimates, Performing Technical Research	Design of Shafts
Week 2	Fatigue Failure, Gears	Static failure of ductile materials	Centrically-Loaded Column Buckling	Design of Shafts
Week 3	Gears	Static failure of ductile materials	Eccentrically-Loaded Column Buckling	Gear Analysis and Design
Week 4	Gears	Static failure of brittle materials	Roller Bearings	Gear Analysis and Design
Week 5	Shafts	Fatigue Failure	Finite Element Analysis	Final Project Assignment
Week 6	Review, Exam	Review, Exam	Finite Element Analysis	Roller Bearings
Week 7	Roller Bearings	Fatigue Failure	Finite Element Analysis	Clutches and Brakes
Week 8	Journal Bearings, Bolts	Shafts	Finite Element Analysis	Clutches and Brakes
Week 9	Bolts, Springs	Gears	Electric Motor Selection	Flat and V-Belts
Week 10	Springs	Gears	Gear Reducer Selection	Roller Chains
Week 11	Review, Exam	Gears	Design of Electromechanical Drive Systems	Fasteners and Power Screws
Week 12	Linkage Kinematics	Review, Exam	Design of Electromechanical Drive Systems	Fastener Analysis
Week 13	Velocity and Acceleration Analysis	Fastening and Joining	Design of Electromechanical Drive Systems	Helical Springs
Week 14	Cams	Fastening and Joining	Semester Project Presentation	Compression Springs

Table 1: Sequence of topics covered at each of the three universities.

a course in the dynamics of machinery so the last few weeks of Machine Design are devoted to this topic.

At WCU, students taking Machine Design have taken only one course in mechanics of materials, however their machine design class is supplemented with a three-hour lab course. The lecture class starts with a review of mixed loading, followed by development and application of static failure criteria. This is followed by several classes dedicated to analyzing fatigue failure. The course then moves into the application of engineering mechanics to individual machine elements such as gears and fasteners. Students are assessed using exams in which they must identify the correct analytical method and apply it to an individual machine element.

The laboratory course at WCU is based on a semester-long project in which students design a ski lift to run over a specified route in the mountains surrounding the campus. The course uses a pedagogical approach in which projects are orchestrated by the instructor but in which students have considerable autonomy in choosing tasks.[6] The first few weeks of the course are spent designing the cable support poles, which facilitates a study of column buckling, beam analysis, and the selection and mounting of rolling-element bearings. Several weeks are then spent on an application-oriented study of finite-element methods, which are applied to the analysis of ski lift components. The lab then moves to the design of the ski lift drive system. This facilitates the study of commercially-available electric motors, selection of gears and gear reducers, design of drive shafts, and structural analysis of the loading station. Student learning is assessed using a series of engineering reports and oral presentations.

At PSB, students taking Machine Design have already completed a two-course sequence in mechanics of materials This allows the instructor to focus most of the course on the application of engineering mechanics to individual machine elements. The class is primarily lecture-based, however student learning is assessed through a series of projects that give students the opportunity to apply the principles of engineering mechanics to the design and analysis of real mechanical systems. Deliverables for these projects are a series of engineering reports that contain an executive summary for top level management, a design report for a middle level engineering manager and a detailed analysis report and drawings for an engineer.

Figure 2 provides a visual representation of the instructors' views of their courses. Instructors at each university were asked to complete a series of questions designed to uncover the nature of the pedagogy in each course. From the responses, one can see that the class at ECU is a classic, lecture-oriented course with a strong focus on the ability to perform by-hand analyses of machine elements. At WCU and PSB there is more of a focus on combining analytical skills with practice-oriented skills such as the use of computer-based tools and engineering communications.

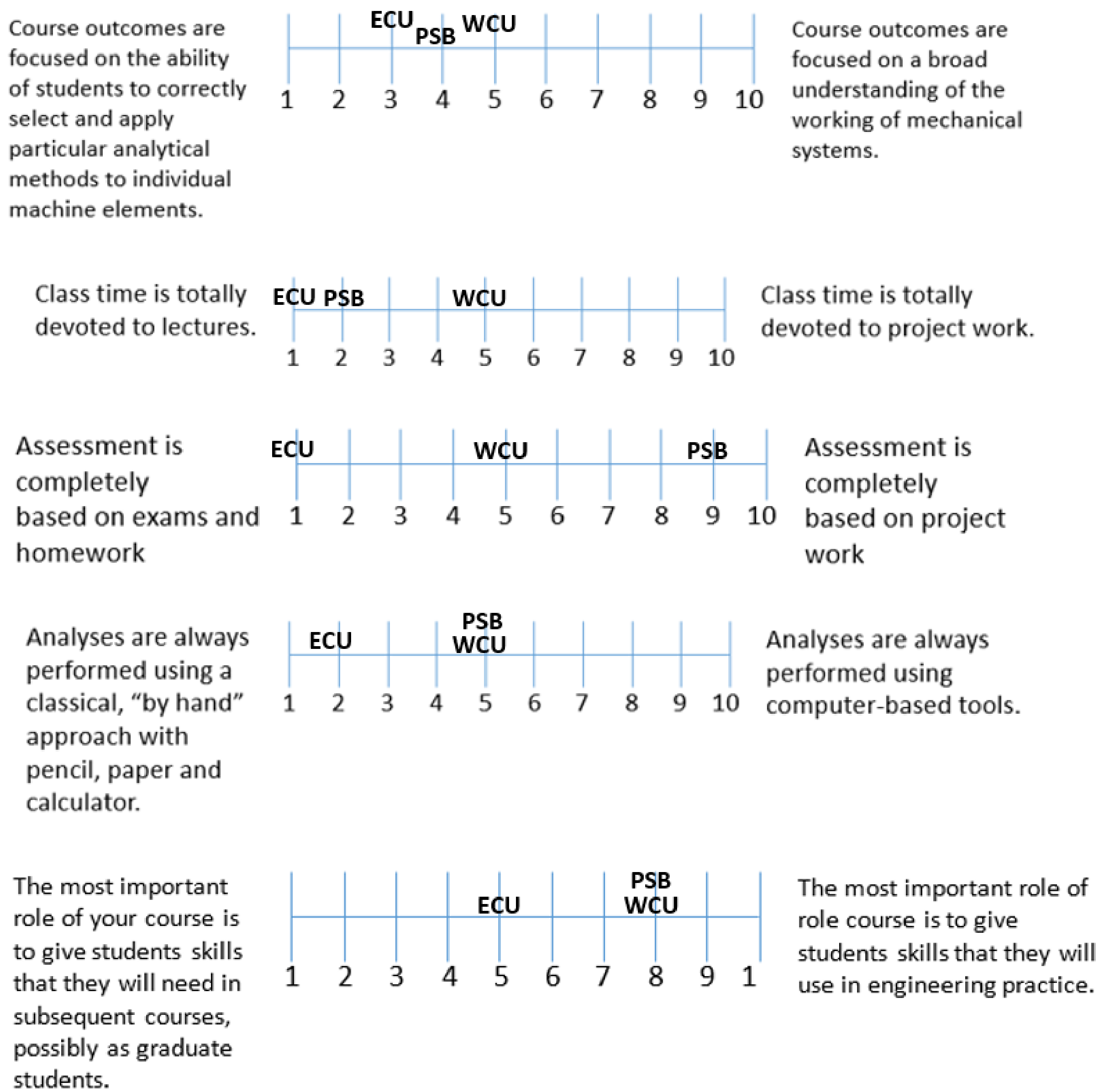

Figure 2: Instructor responses to questions regarding course pedagogy.

Outcomes Assessed for ABET

In order to explore the relationships between course content, structure, and desired outcomes we break desired student outcomes into two categories:

a) The "official" student outcomes that are formulated and tracked as part of the formal, ABET assessment process and which tie directly to the ABET a-k student outcomes, and

b) Outcomes based on the instructor's personal views as to the most important student outcomes for the course.

While there is overlap between these two categories they are not always the same.

Table 2 lists the ABET a-k outcomes and shows which of these outcomes are assessed at each university. As one might expect, assessment is performed on a wider range of outcomes at WCU and PSB, the two schools that use large projects. These projects offer an opportunity to assess outcomes that are difficult to assess in a traditional lecture course. At WCU, the top-level ABET outcomes are broken down into "performance indicators." For example, ABET outcome c is broken into performance indicators that include the ability, "to formulate ideas to develop the design," and the ability, "to reiterate/optimize design solutions." The laboratory course offers an ideal setting to assess several of these performance indicators.

ECU has added an extra outcome to the list, *"(l) Graduates of the Engineering program will demonstrate an ability to apply engineering concepts to an area of concentrated study, chosen from biomedical engineering, bioprocess engineering, electrical engineering, environmental engineering industrial and systems engineering, or mechanical engineering."* This outcome is heavily assessed in Machine Design using the final exam as the assessment instrument. ECU also assesses outcomes f and h using reflective writings on readings and research.

Outcomes Most Important to the Instructors

In the survey, instructors were asked to list the five student outcomes that they considered most important. The responses to this question are shown in Table 3. These responses provide a somewhat different picture of course priorities than the course coverage shown in Table 1. At ECU, it is clear that the goal is to produce students who can correctly analyze machine elements. In their comments, instructors from ECU referred to the need for students to take strong analysis skills into their senior capstone course.

Outcomes that instructors at WCU and PSB found important were a mix of analytical skills and "engineering practice" skills. At WCU, the laboratory course is the principle vehicle for teaching finite element methods and a high value is placed on these skills. The responses from the instructor at PSB reflect the role this course plays in the solid mechanics sequence. PSB students have already learned analytical methods in solid mechanics and the machine design course is more about applying these skills in practice.

ABET Outcome	ECU	WCU		PSB
		Lecture	Lab	
(a)		Mid-term exam questions.		Project reports
(b)				
(c)		Final exam questions.	Selections from lab reports.	Project reports
(d)				
(e)		Final exam questions.	Selections from lab reports.	Project reports
(f)	Reflective paper on a reading of case studies.			Project reports
(g)			Research report on the operating principles of ski lifts, final project presentations.	Project reports
(h)	Reflective paper on reading about a disruptive technology.			Project reports
(i)				Project reports
(j)				Project reports
(k)		Final exam questions.		Project reports
(l)*	Final exam questions.			

(a) an ability to apply knowledge of mathematics, science, and engineering

(b) an ability to design and conduct experiments, as well as to analyze and interpret data

(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability

(d) an ability to function on multidisciplinary teams

(e) an ability to identify, formulate, and solve engineering problems

(f) an understanding of professional and ethical responsibility

(g) an ability to communicate effectively

(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context

(i) a recognition of the need for, and an ability to engage in life-long learning

(j) a knowledge of contemporary issues

(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

ECU incorporates an extra, internally-generated outcome in their assessment: "(l) Graduates of the Engineering program will demonstrate an ability to apply engineering concepts to an area of concentrated study, chosen from biomedical engineering, bioprocess engineering, electrical engineering, environmental engineering industrial and systems engineering, or mechanical engineering."*

Table 2: ABET Outcomes assessed in each course [2].

ECU	WCU	PSB
Demonstrate the ability to design and analyze gears.	Correctly identify loading conditions in a machine.	Demonstrate the ability to perform basic failure analyses.
Demonstrate the ability to design and analyze shafts	Apply finite-element analysis effectively and safely.	Demonstrate the ability to search and use design standards.
Explain how various types of bearings work	Predict failure due to static loading.	Generate a design report that can be used by various levels of industry personnel.
Demonstrate the ability to select and analyze threaded fasteners	Predict failure due to fatigue.	Demonstrate the ability to use CAD and CAE tools in machine design.
Demonstrate the ability to analyze compression springs	Demonstrate confidence in their ability to work as a Machine Design Engineer.	Demonstrate the ability to reverse engineer a product.

Table 3: Instructor responses to the question, "What five outcomes are most important to you?"

Results

Tables 4a – 4c give assessment results for each of the three Machine Design courses. Since the assessment process and the role of the course in that process vary between schools the level of assessment and outcomes assessed are different, however each of the three schools assesses a combination of "hard" analytical skills along with practice-based skills. It is interesting to note that even ECU, with its strong emphasis on analysis skills uses the machine design course to assess ABET outcomes f and h which are not analytical in nature.

Student achievement of outcomes at each university were measured differently, however it is interesting to note that there is no obvious correlation between an emphasis on analytical or practice-based skills and achievement of outcomes related to those skills. Students at both ECU and WCU scored lower on outcomes related to their ability to perform engineering analysis than they did on the less technical outcomes. At PSB students scored lower on the less technical outcomes despite the inclusion of several projects and reports in their course.

Outcome	Percentage of students rated satisfactory or superior	Comments
(f) an understanding of professional and ethical responsibility	85%	Students have a strong understanding of ethical responsibilities.
(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context	81%	Students have a strong understanding of the broader context of their profession.
(l) Graduates of the Engineering program will demonstrate an ability to apply engineering concepts to an area of concentrated study, chosen from biomedical engineering, bioprocess engineering, electrical engineering, environmental engineering industrial and systems engineering, or mechanical engineering.	65%	Evaluated using four final exam problems. Superior: All four problems worked correctly Satisfactory: Minor errors on one or more of the problems, but no major errors. Currently re-evaluating the rubrics for this outcome. Student performance as a whole was good.

Table 4a: Results of assessment in the Machine Deign Course at ECU for Spring semester 2017.

ABET OUTCOME	WCU SUB-OUTCOME	Percentage of students rated satisfactory or superior	
(a)		Lecture	Lab
	The student shall be able to apply fundamental engineering principles to solution of advanced engineering problems.	84%	
(c)			
	The student shall be able to properly define a problem.	84%	
	The student shall be able to formulate ideas to develop the design.		100%
	The student shall be able to develop models that incorporate the design components.		100%
	The student shall be able to evaluate the model.		84%
	The student shall demonstrate the ability to develop a design that meets specifications by internal or external customer.		100%
	The student shall be able to demonstrate the ability to reiterate/optimize design solutions.		88%
(e)			
	The student will be able to identify an engineering problem through a preliminary investigation.	64%	
	The student will be able to analyze related and supporting information.	60%	
	The student will be able to generate a problem statement for an engineering problem.	100%	
	The student shall be able to identify constraints within an engineering problem.		
	The student shall be able to list necessary equipment and resources.		100%
(g)			
	The student shall be able to compose a well-structured and organized technical written report.		100%
	The student shall be able to compose a grammatically correct, well written report, with adequate citations.		100%
	The student shall be able to adhere to an accepted technical format, per course requirements.		88%
	The student shall be able to present technical information in a logical manner.		100%
	The student shall be able to speak clearly in information presentation and answering audience questions.		100%
	The student shall be able to present technical material consistent with intended audience.		88%
	The student shall be able to convey technical data in an appropriate graphical format.		88%
	The student shall be able to apply engineering graphical standards, within an engineering profession.		80%
(k)			
	The student shall be able to select and apply appropriate techniques to solve engineering problems within their discipline.	88%	

Table 4b: Results of assessment in the Machine Design course at WCU for Spring semester 2017.

Outcome	Percentage of students rated satisfactory or superior	Comments
(a) an ability to apply knowledge of mathematics, science, and engineering	100%	
(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability	95%	
(e) an ability to identify, formulate, and solve engineering problems	92%	
(f) an understanding of professional and ethical responsibility	93%	Students have a strong understanding of ethical responsibilities.
(g) an ability to communicate effectively	77%	
(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context	60%	Students have a strong understanding of the broader context of their profession.
(i) a recognition of the need for, and an ability to engage in life-long learning	70%	
(j) a knowledge of contemporary issues	70%	
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.	95%	

Table 4c: Results of assessment in the Machine Design course at PSB for Spring semester 2016.

Discussion:

In 1996, ABET adopted the current a-k outcomes as part of the *Engineering Criteria 2000* standards.[8] In addition to traditional outcomes such as an ability to apply mathematics, the a-k included outcomes that focused on engineering practice. During this same period of time there was a growing recognition that engineering curricula had become too large and that they often contained overly specialized topics outside of the core body of discipline knowledge. [9] These large, technically-deep curricula meant that many students took more than four years to graduate. It was suggested that this extra time to graduation acts as a barrier to entry and that the profession would be best-served by curricula that could be completed in four years.

The curricula of all three of the universities that we have studied reflect these changes. To differing degrees, all three have molded their curriculum to include practice-based skills. At WCU this has resulted in the adoption of a project-based learning curriculum and a strong focus on engineering practice. Both ECU and WCU offer the Bachelor of Science in Engineering degree. Curricula of these programs were designed so that students could realistically expect to graduate in four years.

At all three universities, room in the curriculum for practice-based skills has been created by reducing the number of highly-specialized, technical skills. We have shown how instructors at each university view this balance between analysis and how they implement this balance in their courses.

Future Work:

This paper is part of an ongoing project to examine the content, assessment, and outcomes of machine design courses across multiple universities. In the future, we intend to focus on the achievement of specific student learning outcomes and on student self-assessment of learning. Our immediate goal is to correlate content and pedagogy with achievement of both traditional and practice-based outcomes. In the longer term, we are interested in identifying teaching practices that are most effective in disciplines like machine design that are a mix of theory, analysis, application of tools, and experience-based skills.

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