AC 2012-5247: A NEW VISION FOR ENGINEERING DESIGN INSTRUCTION: ON THE INNOVATIVE SIX COURSE DESIGN SEQUENCE OF JAMES MADISON UNIVERSITY

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A New Vision for Undergraduate Engineering Design Education: An Innovative Design Course Sequence at James Madison University

Abstract

The rapid pace of technological progress and future challenges for globalization, sustainability, complexity, and adaptability of engineering professionals call for a paradigm shift in engineering design education. The School of Engineering at James Madison University, which is graduating its inaugural engineering class in May 2012, has been developed from the ground up to not be an engineering discipline-specific program, but to provide students training with an emphasis on engineering design, systems thinking, and sustainability. Our vision is to produce cross-disciplinary engineer versatilists. One important place in the curriculum where this is achieved is the six course (10-credit) design sequence which is the spine of the curriculum. Starting with the sophomore design courses (Engineering Design I and II), the focus is on teaching students the process of design including the phases of planning, concept development, system-level design, detail design, as well as testing and refinement. Grounded on a novel and multi-dimensional problem-based learning (PBL) pedagogy, students also learn and apply engineering design tools and methods to a two semester, real-world, problem-based, service learning project. This pedagogy continues in the capstone design experience (Engineering Design III through VI) where students are provided with important instruction concurrently with their capstone design experience, in which they work in groups with one or more faculty advisors on a four semester, two-year project. In this four-semester sequence, students start by applying the engineering design process as well as the design tools and methods learned during the sophomore design courses to their new projects, but also are exposed to a variety of advanced design topics and design challenges that aid is helping students develop their individual design process and a design process that meets the needs of the design problem.

Our vision in teaching the engineering design process is to enable *mastery learning* through directed and non-directed, group-based and independent, simple and complex, structured and unstructured, problem-based learning experiences that incrementally expose and reiterate the design process. Our goal is to teach our students to be adaptive problem solvers and have cognitive flexibility when solving problems—an essential skill for these future engineers to learn if they are going work toward developing a sustainable society. The following overarching attributes build this vision: (1) breadth and depth, (2) balance between theory and practice, (3) balance between qualitative and quantitative reasoning, (4) developmental instruction in systems thinking and sustainability, (5) integrating cross-disciplinarity perspectives, (6) process and not just content (e.g. cognitive processes), and (7) bridging engineering skills with professional skills such as communication, project management, team and collaborative work, ethics, etcetera. In this paper, we present how each course in the six-course sequence builds off the prior providing moderate instruction over a long period of time and building developmentally on prior learning outcomes, all while in the context of authentic and meaningful PBL experiences. It is such skills and attitudes that students *learn and practice* over a long period of time (with regular support from and collaboration with faculty) that are critical in students taking ownership of and tailoring to their own abilities and design habits.

Introduction

Design is widely considered to be the central or distinguishing activity of engineering. A good education in engineering design can give students the skills required to creatively solve real-world problems [1-2] and creates an opportunity for them to begin the process of becoming engineering professionals. For most engineering curricula, though, design instruction and design projects (design practice) are often limited to cornerstone and capstone design experiences. Historically, following the second World War, engineering design courses in a typical engineering curriculum were replaced with engineering science courses, where analysis and mathematics were the focus [3-4]. This pendulum swing left students without the hands-on design expertise required to be work-ready engineers [3]. Pressure from industry and direction from the Accreditation Board for Engineering and Technology (ABET), engineering design courses have slowly been reintroduced into engineering curricula.

Although it is well-known that engineering design instruction and experiences (as in the typical capstone and cornerstone courses) can provide meaningful and practical learning for students, it is important for engineering design instruction to have a strong and integrated presence in engineering curricula. Nationally, curriculum-wide integrations of engineering design instruction and project work are far from common place and vary in curricular structure. For example, there are programs, such as the Stanford University Design Program [5] and the Segal Design Institute at Northwestern [6], that focus strongly on design and enable students to receive a BS or MS degree or a minor. Although such programs are well-regarded in design instruction, they do not offer a curriculum with a strong science and engineering science to accompany the strong presence of design instruction. Engineering programs that have a strong design and engineering science presence are also not common and examples of such programs include the University of Maryland [7], Harvey Mudd College [8], Louisiana Tech University [9], Rowan University [10], Rose-Hulman Institute of Technology, East Carolina University, Smith College, and most recently James Madison University [11].

The School of Engineering at James Madison University (JMU), who is graduating the inaugural class of engineering students May 2012, has been developed from the ground up to provide an emphasis on engineering design, systems thinking, and sustainability [11]. Offering a bachelor's in engineering without discipline-specific majors or concentrations, our goal is to train and produce engineering versatilists, a term popularized by Friedman and defined as individuals who can "apply depth of skill to a progressively widening scope of situations and experiences, gaining new competencies, building relationships, and assuming new roles" (p. 291, [12]). Through an innovative curriculum and a variety of pedagogical approaches, we train students to have the cognitive flexibility to solve engineering challenges that transcend disciplinary boundaries. We provide a holistic curriculum through the integration of a campus-wide liberal arts core, several sequences of engineering courses on technology management, engineering science, sustainability, and systems analysis, and a six course design sequence that represents the spine of the engineering curriculum. ***Figure 1*** provides a general overview of the curriculum.

At JMU, the vision (originally conceived and initiated by founding faculty members Pierrakos and Pappas) in teaching the engineering design process is to *instill engineering versatility* and enable *mastery learning* through directed and non-directed, group-based and independent, simple and complex, structured and unstructured, problem-based learning (PBL) experiences that incrementally expose and reiterate the design process. The PBL design experiences are developed to expose students to design theory and practice, qualitative and quantitative reasoning, sustainability, systems thinking, ethics, as well as professional skills.

YEAR 1	Calculus 1	Physics 1	Engineering Fundamentals	Liberal Arts Core	Liberal Arts Core
	Calculus 2	Physics 2	**Introduction to Engineering**	Liberal Arts Core	Liberal Arts Core
YEAR 2	Calculus 3	Chemistry 1	**Engineering Design 1**	Statics & Dynamics	Liberal Arts Core
	Linear Algebra & Different Eq.	Biology *or* Geology	**Engineering Design 2**	Management of Technology 1	Liberal Arts Core
YEAR 3	Thermal-Fluids 1	Instrumentation & Circuits	**Engineering Design 3 (Capstone)**	Management of Technology 2	Liberal Arts Core
	Thermal-Fluids 2	Technical Elective	**Engineering Design 4 (Capstone)**	Materials & Mechanics	Liberal Arts Core
YEAR 4	Sustainability Fundamentals	Technical Elective	**Engineering Design 5 (Capstone)**	Systems Analysis	Liberal Arts Core
	Sustainability & Design (LCA)	Technical Elective	**Engineering Design 6 (Capstone)**	Liberal Arts Core	Liberal Arts Core

Liberal Arts (31 Lecture Credits)
Engineering Science (18 Lecture & 5 Lab Credits)
Sustainability (6 Lecture & 1 Lab Credits)
Science (12 Lecture & 3 Lab Credits)
Engineering Design (13 Lab Credits)
Technical Elective (9 Lecture Credits)
Business (6 Lecture Credits)
Math (16 Lecture Credits)
Non-required (1 Lecture Credits)

Figure 1: The engineering curriculum places engineering design instruction at its core [13].

Much of the instruction in the School of Engineering (SoE), and certainly the design sequence of courses, has been based on a PBL foundation [14-19]. For many educators, PBL refers mainly to open-ended problems that incorporate team-based, collaborative learning. At the JMU SoE, however, we have expanded this one-dimensional PBL classification to develop a multi-dimensional PBL model that promotes diverse cognitive experiences. This model is grounded on three dimensions. These dimensions, depicted on the sides of the PBL Classification triangle in ***Figure 2***, are structuredness, complexity, and group-based collaboration. Structuredness is a dimension that measures how well a problem is defined or identified as well as how well the problem solving process is structured in terms of the methods and analysis used (i.e. a typical homework problem in engineering science courses has a well-defined problem statement and a well-structured solving process since such problems often follow specified concepts and principles) [20]. Complexity is a dimension that looks into the required domain knowledge to solve the problem, the intricacy of the solution path, and the depth of integration of varying domains. In a sense, complexity lets us gain insight into the cognitive load imposed on the problem solver [20]. Although we try to expose students to varying PBL experiences with increasing academic level, we are trying to design PBL activities that will be more complex and less structured. This is because we are trying to mimic real-world engineering practice, which itself is well-known to require engineers to solve complex and ill-structured problems.

Our PBL pedagogy is one that recognizes that not all problems are created equal, and different problems and experiences will lead to different learning outcomes. The motivation is that exposure to different types of problems will enable students to experience different modes of thinking, learning, and problem solving (leading to students that are versatile, adaptive experts, and approach problems with cognitive flexibility). For example, students will have different learning outcomes from a learning activity or project that has all the steps laid out or does not require them to integrate knowledge from various domains versus an activity or project that does not have the steps pre-defined and requires students to learn new knowledge and integrate knowledge from a variety of domains. Please refer to prior publications [19, 21-22] for more details about our PBL model.

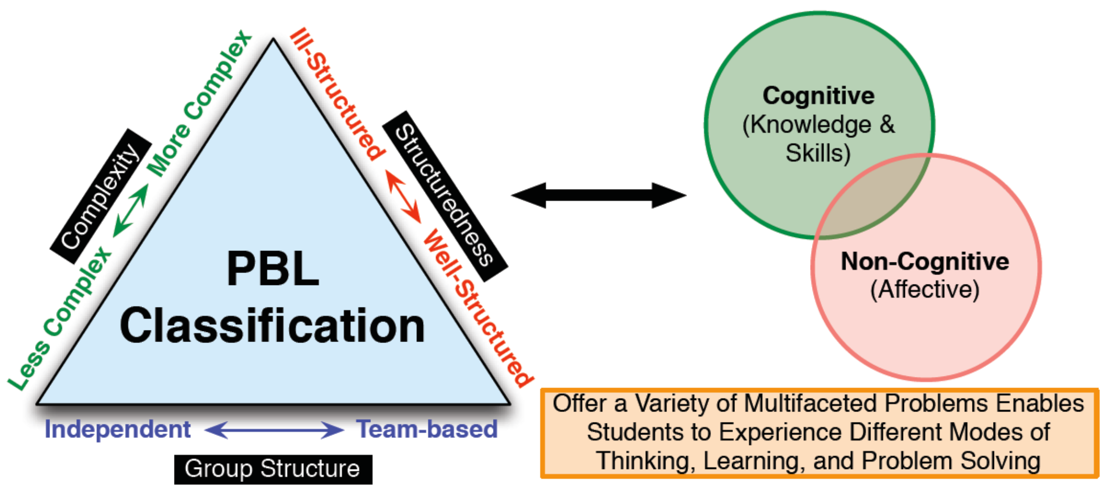

Figure 2: Schematic illustrating the James Madison University School of Engineering Problem-Based Learning model [13].

Attributes and Vision for Design Sequence

Our goal is to teach our students to be adaptive problem solvers and have cognitive flexibility when solving problems—an essential skill for these future engineers to learn if they are going work toward developing a sustainable society. Our vision in teaching the design process is to enable *mastery* through directed and non-directed, group-based and independent, structured and unstructured, problem-based learning experiences that incrementally expose and reiterate the design process. The following overarching attributes build this vision:

Balance between Theory and Practice. An education in engineering design must blend design theory and methodology with practice. This is achieved by following a project-based learning (PBL) approach and pedagogy that recognizes that not all problems are created equal, and different problems and experiences will lead to different learning outcomes. We strive to incorporate multiple pedagogical methods into our instruction such as case-based instruction, inquiry-based learning, and active learning. Consequently, students receive a combination of directed, in-class instruction covering topics such as design theory, professional skills, systems thinking, ethics, et cetera and out-of-class, non-directed application and practice. Further, to reinforce the in-class instruction, we strive to provide meaningful experiences that tie classroom learning to real projects, real problems, and real applications. This can be achieved by having real customers with real needs. Our goal is to teach our students to be adaptive problem solvers and have cognitive flexibility when solving problems—an essential skill for these future engineers to learn if they are going to work toward developing a sustainable society.

<u>Balance between Qualitative and Quantitative Reasoning.</u> A complete education in engineering design must not only focus on the quantitative reasoning taught in engineering science classes, but must also incorporate instruction in the fuzzy front end of the engineering design process. Instruction during the sophomore year, before the students complete any engineering science courses, focuses on using qualitative and quantitative reasoning stemming from both design theory and methodology to plan, define, and develop prototype designs. Instruction also must iterate how quantitative reasoning links to their forthcoming engineering science education demonstrating different approaches to solving design problems encountered. During the capstone experience, projects should follow the same engineering design process—planning, conceptual design, system-level design, detailed design, testing and refinement, product ramp-up—and, therefore, build on the qualitative and quantitative reasoning skills developed during Design I and II, but also through the guidance of faculty advisors (due to the varied nature of the projects), integrate the quantitative reasoning taught during our engineering science courses.

<u>Developmental Instruction in (a) Design Knowledge, Skills, and Thinking; (b) Systems Thinking; (c) Sustainability Contexts; (d) Sustainable Design; (e) Cognitive Processes; (f) Ethics, et cetera.</u> Each course in the six-course sequence should build off the prior providing moderate instruction over a long period of time and building developmentally on prior learning outcomes [23-24]. Skills and attitudes students learn and practice over a long period of time (with regular support from and collaboration with faculty) are the skills and attitudes that they will take ownership of and tailor to their own abilities and design habits. This includes not only personal attitudes such as practicing ethical behaviors but also following engineering best practices. Students need to understand clearly that learning by experience and collaboration is a lifelong endeavor, and the instruction (or practice in the studio) they receive in the design sequence is specifically meant to model long-term professional practice.

<u>Application of Project Management Skills.</u> The two Management of Technology (MOT) required engineering courses complement the engineering design courses. Students consider and apply the tools learned in their MOT courses in their capstone courses. Having the opportunity to work with business students on the same project should continue to build, strengthen, and reinforce communication, team, and professional skills during the capstone project. This experience provides our engineering students with an opportunity to work

across disciplinary boundaries with business students who ideally have a vested interest in the successful organization of the project, but due to their different backgrounds, take a different interest in each project.

Instruction and Practice of Professional Skills. In order for our graduated engineers to function as successful members of society, they must understand the material individually but also know how to work as a member of a team, be able to communicate effectively, and recognize and practice professional behavior. Students receive initial instruction and feedback in these areas, allowing them to hone their skills through the design sequence. Students learn to work and communicate in both small (2-4), medium (5-7), and large (10+) engineering teams, as an effective member of these design teams, and to work on the process as a team as well as learn to develop and execute a design plan. Individually, students should begin to understand their strengths and weaknesses, be able to reflect on the process and grow. Communication is emphasized and practiced throughout the design sequence through regular submission of memos and technical reports, and frequent technical presentations. Students learn how to compose a proposal, memo, report, technical paper, and technical presentation as well as how to project their professional image through a resume. Our goal through the design sequence is to provide the students with multiple opportunities to develop and practice professional skills as they work with their faculty advisors, peers, and clients.

Overarching Goals and Objectives for Design Courses

Engineering design instruction in the form of modules begins in our first engineering course, Introduction to Engineering. In this course, we introduce students to engineering design through both reverse engineering exercises and a variety of design activities that span engineering disciplines. Some examples of these design activities in the past have included the design of solar tower, design of a water filter, design of a dorm room, et cetera. This is meant to provide students with basic knowledge and comprehension of the engineering design process as well as introductory engineering design tools and methodologies. Through reverse engineering and redesign activities, students should begin to develop early application skills, recognizing how to apply the design process to solve engineering problems.

During the ***Engineering Design I and II*** course sequence, respectively in the fall and spring semesters of the sophomore year, students continue to gain knowledge and comprehension of the engineering design field as well as begin to develop the application, analysis, and synthesis skills necessary to begin their capstone projects. The sequence follows Ulrich and Eppinger's *Product Design and Development* through the first five phases (planning, concept development, system-level design, detail design, and testing and refinement) of their six phase design process [25]. To achieve this goal, a year-long design project is woven into instruction in the area of design theory and methodology. ***Table 1*** details the course learning outcomes and topics covered in the sophomore design courses. At the core, these courses were designed to teach students design theory and methods as well as enable them to practice applying the design process and methods learned in a two-semester project. Students learn and apply engineering design tools and methods to a real-world, problem-based, service learning project [26].

Table 1: Learning outcomes and topics covered in the two sophomore design courses.

Course Learning Outcomes	Course Topic Coverage
ENGR 231 – Design I - Fall Semester Sophomore Year	
1) Identify and describe the stages of the design process 2) Identify, describe, and discuss the customer needs which inform an engineered product 3) Research and establish target specifications to describe customer needs 4) Describe and discuss creative engineering design practices 5) Identify and analyze sustainability in contexts from case studies 6) Analyze simple products and elementary processes for basic sustainability and ethical issues 7) Demonstrate basic cognitive processes and problem solving skills for decision making 8) Construct and assess designs using elementary physical prototypes 9) Demonstrate basic computer aided design skills 10) Complete a semester-long engineering design group project 11) Demonstrate basic project management skills	• What is design? Who does design? What is engineering design? • Design in Different Contexts • Design and systems thinking • Design Process • Customer needs • Team and Collaborative Skills • Functional Analysis • Target Specifications • Intro to Ethics and Values • Concept Generation Methods • Design and Creativity • Design Evaluation • Design Failures • Sustainable Design • Concept selection methods • Technical writing and technical presentations
ENGR 232 – Design II - Spring Semester Sophomore Year	
1) Identify and describe the stages of the design process 2) Establish a detailed design for an engineered product 3) Establish a bill of materials and procure materials for a engineering design project 4) Describe and discuss creative engineering design practices 5) Identify and analyze sustainability in contexts from case studies 6) Analyze simple products and elementary processes for basic sustainability and ethical issues 7) Demonstrate basic cognitive processes and problem solving skills for decision making 8) Construct and assess designs using elementary physical prototypes 9) Demonstrate basic computer aided design skills 10) Demonstrate basic Matlab skills 11) Complete a semester-long engineering design group project 12) Demonstrate basic project management skills	• Design Process • Principles of Redesign • Reflection • Creative Design Techniques • Prototyping • Bill of Materials • Engineering Drawings • SolidWorks Modules • Matlab Modules (Syntax Basics and Programming Basics) • Team and Collaborative Skills • Sustainable Design • Cognitive Processes • Testing and Prototyping • Technical writing and technical presentations

The project for the sophomore design sequence, described in great detail in ***Table 2***, is currently in its third offering and involves the design of a human-powered, pedaled vehicle for a client with cerebral palsy. During the first run of this course sequence, students designed their vehicle for a professor on the JMU campus, and in the second and third runs for a local high school student that varied each year. Throughout the project, students interact with an actual client to design and prototype an actual product. Having a client and working on a tangible, real-world problem helps motivate students—including those who tend to not be mastery driven—to learn the design process and complete the project with a working prototype. Other specific goals include: functioning as a member of a design team; communication (to team members, clients, and peers); professionalism; project management; and understanding how engineering science, engineering design, product testing, and manufacturing come together in real problems.

Table 2: Description and learning outcomes for the two-semester sophomore design project.

Project Based Learning in Sophomore Design Courses **"Design of a Human-Powered Vehicle for a User with Cerebral Palsy"** **PROJECT DESCPRIPTION AND PROJECT OBJECTIVES**
The goal of this project is for you to design and prototype a unique **pedaled cycling vehicle** for an individual with cerebral palsy. The customer (changes every year) would like to expand upon his fitness activities to include outdoor activities such as the utilization of a cycling vehicle, which can also be used for training for cycling events and muscle strengthening. Despite extensive research of the adaptive bicycle market, there is currently no pedaled vehicle to suit the specific needs of the customer. Prohibitive cost of custom design work, ineffectual designs for training and racing, and designs incompatible for his stature are primary difficulties encountered by the customer. This is a two-semester project. Your overarching task this semester (Design I) is to apply the design process and to generate numerous pedaled vehicle designs that are viable to meet the specific user needs. Ideally, these cycling vehicle designs should provide sufficient adaptability to accommodate others with some similar and some different needs and requirements. Your overarching task next semester (Design II) is to reiterate on the design process and prototype one concept for the client.
1) Identify, describe and discuss the needs of the customer to inform the design process 2) Understand, research, and establish design specifications to meet the needs of the customer 3) Generate multiple conceptual designs using by sketching and with Solid Works 4) Explore and evaluate the multiple conceptual designs using a number of methods (performance testing, decision-making strategies, sustainability principles) 5) Work effectively in a team setting 6) Develop a framework in selecting the conceptual design that is to be presented to the customer 7) Address and analyze the conceptual designs for basic sustainability characteristics 8) Effectively document and present the process of this design project 9) Construct a working prototype demonstrating designs 10) Test and iterate to demonstrate achievement of target specifications

The ***Engineering Design III, IV, V, and VI*** course sequence, respectively in the four semesters of the junior and senior years, is meant to provide students with important instruction and also a capstone design experience. Although many instructional topics are directly related and developed to assist students with the concurrent capstone design experience, there are also several instructional topics that are not directly related to the capstone design experience but are topics critical to advancing design knowledge and further meeting ABET learning outcomes. ***Table 3***and ***Table 4***detail the course learning outcomes and topics covered in the junior and senior design courses. Considering the allotted instructional time is one hour per week, the goal for these topics is to provide students a good exposure and some practice (either in the context of their capstone design project or a small PBL assignment such as a design challenge). During these full-class instruction periods, students consider and solve unstructured problems related to design and sustainability through cases studies using visualization, writing, and personal reflection [27]. Students explore reciprocal effects of their potential decisions and the related ethical dilemmas inherent in environmental, social, and professional contexts.

Outside of class time for the Engineering Design III, IV, V, and VI course sequence, teams meet on a weekly basis with their faculty advisor and/or project sponsors. During these weekly meetings, teams focus on the technical aspects of their projects by meeting with their faculty advisors, who help to guide students through the engineering design process and technical details of the project. Also critical during these four semester junior and senior design courses is a common and consistent schedule of key deadlines and deliverables (reports and presentations) for all capstone projects. Both capstone project advisors and design course instructors evaluate these deliverables and provide students feedback. For the capstone project experience, the capstone project advisors serve the role of technical advisors and provide their capstone teams with feedback in that capacity, whereas the course instructors serve the role of coordinators in setting common deliverables for all capstone teams, in evaluating and providing all capstone teams feedback, and in facilitating capstone teams and advisors when/if needed.

In the **capstone projects**, which are part of Engineering Design III, IV, V, and VI course, students work in groups with one or more faculty advisors on a four semester, two-year project. In this four-semester sequence, students apply the engineering design process and design tools and methods learned during the sophomore design sequence to their new projects. The capstone experience is currently in its first two runs. Projects range from biology-inspired designs, to robotic systems, to a sustainability-themed solar-hydrogen energy system, to electric motorcycles, to the design of a clinic for Sub-Saharan Africa, to wind harvesting systems, to a campus dining hall composting reactor design, to a stormwater filtration system, et cetera. Faculty members propose projects, and students bid into teams. Ultimately, each student is placed in either his or her first, second, or third choice project. ***Table 5*** illustrates the vision of the JMU engineering capstone project experience in terms of project attributes and deliverables semester-by-semester. This capstone project vision is inspired by an industry design model that can be summarized in terms of five design reviews: systems requirement review, preliminary design review, critical design review, testing readiness review, and production readiness review. Overall, the first semester of the project is focused on problem formulation, research, and planning with some teams being able to start on the concept development design phase. At the core, for most capstone teams, the second semester is all about concept development and initial efforts towards prototyping and modeling, both of which continue in the third semester. Detailed designs are the culmination of efforts in the third semester and accompany testing and evaluation efforts. For several teams, the fourth semester continues to focus on testing and evaluation as well as redesign processes.

Table 3: Learning outcomes and topics covered in the two junior design courses.

Course Learning Outcomes	Course Topic Coverage
ENGR 331 – Design III - Fall Semester Junior Year	
1) Apply design and systems thinking, principles, and process to formulate the two-year capstone design project. 2) Prepare a systems requirement review in the form of a proposal. 3) Work effectively in a team setting. 4) Illustrate basic competency in technical and scientific writing. 5) Illustrate basic competency in technical and scientific presentations. 6) Analyze case studies and describe the ethical dilemmas inherent in each (environmental, social, and professional contexts). 7) Evaluate sustainability (environmental, social, economic, technical) of given designed products. 8) Identify and describe a variety of professional tracks in engineering and develop a preliminary career plan. 9) Apply a variety of strategies in facilitating a creative team environment and a healthy team dynamics. 10) Examine human interface analysis of given products.	• Vision for capstone projects • Systems Requirement Review • Team Building Knowledge and Practices • Facilitating Creative Team Environments • Managing Diverse Teams and Measuring Team Performance • Technical Writing Modules (Cover letters, audience analysis; proposal writing) • Professional Prep – Resume Skills, Internships, REUs, grad school, etc. • Technical Presentation Modules (from slide design to delivery) • Individual and collaborative design process
ENGR 332 – Design IV - Spring Semester Junior Year	
1) Apply design and systems thinking, principles, and process to formulate and conduct the two-year capstone design project. 2) Conduct a preliminary design review. 3) Work effectively in a team setting and in working independently. 4) Illustrate competency in technical and scientific writing. 5) Illustrate competency in technical and scientific presentations. 6) Communicate effectively in team and professional settings. 7) Analyze case studies and describe the ethical dilemmas inherent in environmental, social, and professional contexts. 8) Evaluate sustainability (environmental, social, economic, and technical) of products. 9) Analyze designs for failure (and design weakness) and suggest improvements for technical sustainability. 10) Analyze designed products / processes according to human interface and aesthetic principles. 11) Apply a variety of advanced design tools. 12) Articulate basic knowledge about intellectual property and patents. 13) Formulate and apply modeling and analytical prototyping. 14) Understand a variety of professional tracks in engineering and develop a career plan. 15) Apply a variety of strategies in facilitating a creative design process and creativity in design.	• User-Centered Design and Human-Centered Design • Creative Design Process & Creativity in Design • Innovation and Creative Product Development • Ethics (personal, professional, design, research) • Human Interface in Design • Modeling (mathematical vs physical prototyping) • Professionalism • Conflict Resolution • Intellectual Property and Patents • Design Aesthetics Principles • Advanced Design Tools (Robust design, TRIZ, Design for X) • Product Design Evaluation • Values and Sustainability

Table 4: Learning outcomes and topics covered in the two senior design courses.

Course Learning Outcomes	Course Topic Coverage
ENGR 431 – Design V - Fall Semester Senior Year	
1) Apply design thinking, principles, and tools. 2) Demonstrate competence in evaluating holistic design for sustainability (includes ethics and aesthetics). 3) Evaluate community sustainability principles in case studies and local communities. 4) Explain the basic principles of accounting and manufacturing. 5) Demonstrate individual and group cognitive processes and problem solving analyses. 6) Work effectively on a collaborative design project. 7) Demonstrate competence in individual and collaborative technical and scientific writing and presentation skills. 8) Explain the principles of design marketing and testing of assigned products and capstone project. 9) Explain the principles of the psychology of design. 10) Demonstrate modeling and analytical prototyping. 11) Test and analyze prototypes. 12) Apply a variety of advanced design tools.	• Holistic Design • Psychology of Design • Design Marketing • Design Aesthetics • Connection among Function, Human Interface, and Aesthetics • Product Testing • Community Sustainability • Advanced Design Tools (Design for Six Sigma, Quality Function Deployment (QFD) • Sustainable Design Evaluation • Failure Modes and Effects Analysis (FMEA)
ENGR 432 – Design VI - Spring Semester Senior Year	
1) Apply design thinking, principles, and tools 2) Demonstrate competence in evaluating holistic design for sustainability (includes ethics and aesthetics) 3) Work effectively on a collaborative design project 4) Demonstrate competence in individual and collaborative technical and scientific writing and presentation skills 5) Evaluate products for failure and human interface 6) Justify varying cognitive process and problem solving analyses in a variety of applications 7) Justify an individual and collaborative design process for a variety of applications 8) Conduct an analysis of accounting and manufacturing profile of capstone project 9) Demonstrate product testing procedures and completed analysis 10) Apply and justify a variety of advanced design tools for use a variety of applications 11) Describe basic knowledge of engineering practice in a variety of cultural settings 12) Interpret technological implications and impacts to society	• Design Accounting and Manufacturing • Cognitive Processes / Decision Making • Sustainable Business Processes and Practices • Ethics (business) Modules and Case Studies • Commercialization • Engineering Cultures • Society and Technology • Evaluation of technical design for human interface and failure • Advanced Design Tools (DOE, Simulation/Optimization, Reliability-based Design)

Table 5: Attributes and deliverables for the two-year capstone design projects.

Ideal Attributes and Deliverables for the Capstone Design Projects		
Capstone Projects Should:	**Typical Project Focus and Deliverables Each Semester**	**Each Team Will Focus on Conducting:**
(1) Be designed to span a **two-year duration** and meet the deliverables described (to the right). (2) Address a **real-world** need or problem (and ideally have a specific client in mind). (3) Involve the **design of a specific system or technology** (whether that system is a product, a process, etc.) (4) Apply **design thinking, principles, and process.** (5) Incorporate a **balance between theory and practice.** (6) Incorporate **modeling**, which may include physical, theoretical, computational, experimental, etc. (7) Integrate **engineering science** content. (8) Apply systems thinking and systems analysis to evaluate designs from a **sustainability perspective** to assure a sustainable design. (9) Encourage and seek **cross-disciplinary** collaborations or consultants (within and outside of engineering). (10) Be conducted in a **team setting** where both individual and group contributions are critical.	**Design III-ENGR 331** **Planning and Conceptualization** **Deliverables** **Midterm and End-of-Semester Reports and Presentations**	***System Requirement Review (SRR)*** will focus on addressing: problem identification and statement, project goals, literature review, market analysis, stakeholder analysis, analysis of available resources, feasibility study, project management plan (budget, timeline, team member roles and responsibilities), list of consultants, etc.
	Design IV-ENGR 332 **Conceptualization, Modeling, and Prototyping** **Deliverables** **End-of-Semester Report and Presentation**	***Preliminary Design Review (PDR)*** will focus on the evaluation of the conceptual design and planning of the project to ensure that teams are meeting the necessary requirements.
	Design V-ENGR 431 **Prototyping, Testing and Evaluation** **Deliverables** **End-of-Semester Report and Presentation**	***Critical Design Review (CDR)*** will focus on the evaluation of the detailed designs, prototyping models, and planning of the project to ensure the design implementation plan. ***Testing Readiness Review (TRR)*** will focus on the evaluation of testing preparations, readiness, and procedures.
	Design VI-ENGR 432 **Evaluation, Redesign, and Production** **Deliverables** **End-of-Semester Report and Presentation**	***Production Readiness Review (PRR)*** will focus on the evaluation of the design to ensure that it is completely and accurately documented and ready for formal release to manufacturing. Marketability and commercialization of the design could also be evaluated.

Assessment

To accompany a strong pedagogical tradition, the School of Engineering has also set forth a detailed assessment plan that continues to improve annually. In fact, embedded in a strong culture of assessment, JMU requires all academic programs to develop an extensive assessment plan and submit annual reports providing evidence of how well students are meeting the program goals (in our case ABET outcomes "a-k"). In addition to the JMU assessment culture, two NSF-funded projects (included in the acknowledgements) have also helped shape the assessment practices of the School of Engineering.

The JMU School of Engineering assessment plan includes numerous measures, direct and indirect, to evaluate the extent to which program outcomes are met. The measures that are of particular importance to the design courses include the National Engineering Students' Learning Outcomes Survey (NESLOS), a project evaluation survey, achievement goal orientation, creativity scales, etc. In this paper, we focus on NESLOS results. NESLOS measures students' perceptions of ABET-based learning outcome gains. Students' learning outcome ratings correspond to students' self-assessments on their abilities to achieve the specific learning outcome as a result of completing design projects [28-31]. NESLOS, a widely-used and reliable instrument, has been administered to freshman and junior students but not yet administered to our senior engineering students. Thus, only data from freshman and junior design projects are presented herein. The NESLOS item prompts ask students to rate their ability on a set of ABET-based learning outcomes (knowledge, skills, attitudes) from 1 (low ability or no experience) to 5 (high ability). The learning outcomes survey comprises twelve subscales (corresponding to fifty items), nine of which (corresponding to thirty-one items) are relevant to the SoE program goals, which are the ABET learning outcomes 'a-k'.

Table 6 provides descriptive statistics for these nine subscales comparing the two groups (freshman and juniors). Overall, we see that juniors have significantly higher ratings in comparison to the freshman on all nine subscales. The overall average response for all items was 3.37 for freshmen and 4.03 for juniors (~20% gain overall). In fact, the last column shows the mean effect sizes, and it is evident that the differences between junior and freshman ratings are mostly large to very large. This certainly suggests that going through the first three years of engineering design projects, students perceive significant learning gains and abilities on identifying and solving engineering problems, analytical skills, experimentation skills, project management, communication skills, ethical and societal awareness, team skills, as well as an appreciation and understanding of being lifelong learners.

Further, in comparing freshman versus junior students' NESLOS ratings, ***Table 7*** shows the learning outcomes that revealed the biggest differences in terms of effect size. Some of the largest learning gains from freshman to junior year in the engineering design projects appear to be skills such as communication, research and lit review skills, operating in the unknown, critical self-assessment, problem solving skills (e.g. problem identification and formulation, understanding assumptions to a problem, and formulating a range of solutions), project management, design, and valuing diverse perspectives to solving problems. These results indicate that students' perceptions of their learning gains are good and align very well with our program goals and ABET.

Table 6: Engineering freshmen and junior design students' mean ratings on NESLOS subscales.

NESLOS Subscale	No. of Items	Reliability	Mapping ABET Outcomes A-K	Freshmen Mean (N~80)	Junior Mean (N~40)	Diff.	Pooled SD Mean	Cohen's d Mean
Problem Identification	3	0.82	A and E	3.48	4.15	0.67	0.73	0.91
Engineering Problem Solving	4	0.67	A, B, C, E, K	3.15	3.86	0.71	0.93	0.79
Analytical and Evaluation Skills	3	0.84	B, C, E, H, K	3.55	3.91	0.36	0.80	0.45
Experimentation Skills	3	0.80	B, C, K	3.40	3.76	0.36	0.92	0.40
Project Management	5	0.77	D, F, G	3.48	4.11	0.63	0.86	0.74
Ethical and Societal Awareness	4	0.95	F and H	3.25	3.64	0.39	0.94	0.42
Communication Skills	3	0.85	D and G	3.08	4.38	1.30	0.93	1.40
Team Skills	3	0.81	D	3.64	4.29	0.65	0.85	0.77
Lifelong Learning	3	0.86	I and J	3.27	4.18	0.91	0.86	1.05

Table 7: Summary of learning outcomes showing the highest effect sizes in comparing freshman and junior engineering students' self-assessment of their abilities.

Learning Outcome	Cohen's d
Convey ideas verbally and in formal presentations	1.53
Locate and reference scientific/engineering textbooks, journal papers, and other documents to understand and solve problems	1.28
Convey technical ideas in formal writing and other documentation	1.27
Operate in the unknown (open-ended problems)	1.23
Engage in critical, reliable, and valid self-assessment	1.12
Identify and define problems	0.93
Formulate and justify the need and relevance of a problem or project	0.93
Understand assumptions needed to solve a problem	0.90
Take new opportunities for intellectual growth or professional development	0.87
Create and follow a timeline when managing projects	0.85
Work in a team setting during engineering/scientific projects and problem solving	0.85
Formulate a range of solutions to a problem	0.84
Recognize the need for diverse perspectives in solving problems	0.84
Understand the impact of engineering solutions in societal and global contexts	0.84
Apply interpersonal skills when working with others	0.83
Recognize connections between and within different disciplines	0.81
Reach beyond myself (challenge myself to new limits)	0.79
Design a product, process, or system to meet desired needs	0.75

Discussion

Our vision in this design sequence of courses is to not only teach students developmental and advanced knowledge of engineering design theory, methods, and tools, but also enable students to practice what they are learning in the classroom through project work. Our PBL model, grounded on characterizing problems across dimensions of structuredness, complexity, and group structure, enables us to expose our students to authentic experiences. It in itself is a design to meet curricular and professional demands. Our PBL framework enables to "design" problems and projects for our students taking into account their academic and developmental needs. For example, we can provide our students with the same real-world and complex problem as freshman or sophomores (when they are in the midst of science and mathematics coursework and just starting their engineering science and design courses), and then again as juniors or seniors (when they are in the midst of their fundamental engineering science coursework, the upper-class design courses, and technical electives). The major difference across these two cases (lower-class vs upper-class PBL design activity) would be the structuredness of the learning experience and the expectations (technical and non-technical) we would have for them. In other words, the complexity of the design problems can be similar across a freshman or sophomore and junior or senior design course, but the degree of guidance and direction given to students will vary greatly. This is exactly the situation for the sophomore design project - bike project – described previously. The project itself is quite complex for students, but most of the learning experience is either highly or somewhat directed by the design course instructors. If this same project were given to juniors or seniors, the design project would be less structured and more self-directed by the students. Also, the expectations for our students would differ greatly between a lower-class vs upper-class PBL design activity. For the latter, we would expect not only a more thorough and well-justified design process to meet the needs of the project, but also a more thorough integration of their knowledge and thus coursework (science, mathematics, engineering science, sustainability, systems, project management) in carrying out the design project from the planning and research phases to the modeling, testing, and analyses phases. Assessment efforts to measure all this is ongoing and will be the focus of future publications.

Conclusion

The School of Engineering at James Madison University is, quite clearly, a significant effort, especially for a new program. Our initial successes— numerous publications, strong and consistent University support, substantial grant awards, and more applicants than we can teach— have allowed us to take chances and innovate freely, but not without great regard for traditional engineering content and culture. We are not trying to *change* engineering. We are, however, *expanding* it. This is certainly the case for our innovative engineering design instruction, both in terms of pedagogy and content. We feel our innovative efforts are a reasonable response to the changes occurring in society and in the engineering workplace. Students need to understand, for example, how and why systems theory applies to all their work, and why design, sustainability and problem solving are central skills in the profession.

With our program still growing, we anticipate less rapid change than what we have experienced in the first four years. We recognize that some of the content and instructional methodologies we embrace are not yet accepted in more traditional engineering programs. We will continue, however, to innovate and take reasonable risks in order to offer a continually innovative engineering education that is timely, relevant, and stimulating.

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