Senior ME Capstone Laboratory Course

Kevin Schmaltz, Chris Byrne, Robert Choate, Joel Lenoir
Western Kentucky University

Abstract

The Mechanical Engineering faculty at Western Kentucky University have developed and implemented a Design of Experiments Plan to assure that graduates of the program have acquired the skills necessary to design and conduct experiments and analyze experimental results. Instruction is integrated throughout the ME curriculum, with students finally demonstrating the ability to both define and analyze experimental problems in a capstone class. In its first offering, the capstone class required student teams to complete mechanical, materials and thermal-fluid experiences. The student teams were expected to define the requirements, determine tools and methods, execute experiment plans and report findings.

The ME faculty members have defined the components of Design of Experiments, set expected levels of student competence, and developed assessment tools to quantify student achievement. Experimental skills are developed in a variety of course structures, including stand-alone lab courses, lab experiences integrated into engineering science and design courses, and demonstration-type experiences in predominantly lecture classes.

Two phases of assessment have been implemented to improve the Design of Experiments Plan instruction. The first phase involves assessment for all courses through a collective Peer Evaluation of Course Effectiveness at the end of the semester when a class has been offered. In addition to course-level assessment, program assessment is incorporated into one or the ME Program Outcomes: Mechanical Engineering graduates can measure physical quantities and can plan, conduct, analyze and evaluate experiments. This program outcome is measured using several metrics and is reviewed on an annual basis.

The integrated structure of the Design of Experiments Plan provides a framework for building upon previous lab work, assessing student progress, and adjusting lab coverage based on prior assessments to assure that graduates of the program are capable experimental practitioners.

Introduction

The Mechanical Engineering faculty at Western Kentucky University have used the development and implementation of professional experiences to provide consistent and properly assessed instruction for students pursuing the new baccalaureate Mechanical Engineering degree at WKU.

To achieve these professional outcomes, it is necessary to provide students with the opportunity to acquire tools and skills, as well as technical competency [1].

The ME program employs an overall Professional Component Plan with the following structured sub-plans with defined measures to quantify and assess professional experiences:

1. Engineering Design Plan (teaching and practicing of design skills)
2. Professional Communications Plan (conveying designs and interacting with peers)
3. Professional Skills Plan (teaching and implementing of design tools)
4. Professional Ethics Plan (evaluating and practicing appropriate professional behavior)

The professional plans aid in the coordination efforts of multiple faculty members and multiple courses across all four years of the curriculum. The plans also facilitate the assessment of results and progress of students as they move through the curriculum, particularly since these outcomes can be difficult to precisely define and therefore assess. Finally, by assessing student progress along the students' development path, timely corrections can be made as warranted.

The implementation of a strategy to assure that students are also able to meet expectations in the area of experimental design is closely related to several of the above professional components, with similar challenges of coordinating faculty efforts across numerous lab courses, defining and assessing consistent outcomes, and being able to identify weaknesses as early as possible. The ME faculty have taken a similar approach to design of experiments by defining the components of experimentation, creating a Design of Experiments Plan, implementing a capstone experimentation course and assessing the ability of the ME graduates to successfully apply all components of experimentation. This paper will detail each of these elements and discuss the benefits and weaknesses that have been discovered in our efforts.

Design of Experiments Plan

The ability of ME graduates to successfully design, conduct and analyze experiments is integrated across the ME curriculum, and is finally demonstrated in the execution of multiple lab experiences in a capstone lab course (ME 430). Beginning in the freshman year, students are provided with opportunities to acquire experimental, analytical and modeling tools and skills, and to develop effective means of communicating the results of their work. In an analogous fashion to the capstone design project providing a measure of the students' ability to perform a design project, the capstone experimental experience requires that student teams demonstrate the application of experimental abilities to set up and analyze less-defined experimental problems. To assist in the organization of course content and its assessment, the following six components have been used to define design of experiments [2, 3]:

1. Experimental Planning
2. Methods of Measurement
3. Selection of Instrumentation
4. Analysis of Data and Results
5. Uncertainty Analysis
6. Reporting of Experimental Results

These components are described more completely in the assessment rubric, shown later in Table 3. Student work from experimentation classes in the sophomore, junior and senior years are then assessed to determine the ability of the students to successfully apply each component. The courses that provide students with instruction in these components, or the opportunity to demonstrate proficiency are offered throughout all four years of the curriculum. Table 1 summarizes the classes in the ME curriculum that encompass the Design of Experiments Plan and the components that are covered or that students are expected to demonstrate in the course. In early-level courses, students are first introduced to experimental tools, techniques and practices. Emphasis is placed on gaining experience with equipment, following stated procedures, and processing and presenting results effectively (components 2, 4 and 6).

Semester	Lab Course (credits)	Component Coverage
Freshman Fall	CHEM 121 Chemistry (2)	2, 4 and 6
	ME 241 Materials/Methods Mfg. Lab (1)	2, 4 and 6
Freshman Spring	PHYS 251 Physics I (1)	2, 4 and 6
Sophomore Fall	PHYS 261 Physics II (1)	2, 4 and 6
Sophomore Spring	ME 200 Sophomore Design*	1, 2, 3 and 5
	ME 331 Strength of Materials (1)	1, 2, 4 and 6
Junior Fall	STAT 301 Applied Statistics*	4 and 5
Junior Spring	ME 310 Engineering Instrumentation and Experimentation (3)	2, 3, 4, 5 and 6
Senior Fall	ME 411 Vibrations/Controls Lab (1)	2, 3, 4 and 6
	ME 420 Senior ME Lab I (3)	1, 2, 3, 4, 5 and 6
Senior Spring	ME 430 Senior ME Lab II (3)	1, 2, 3, 4, 5 and 6
	ME 412 Senior Project*	1, 2, 3 and 4

*Experimentation is a component of the course

Table 1: Design of Experiments Curriculum

Upper-level students are expected to synthesize and incorporate experiences into determining proper lab procedures and techniques. Greater emphasis is placed on analyzing the data and results, and performing uncertainty analysis. The three key upper-level lab courses for ME students are Engineering Instrumentation and Experimentation (ME 310), and the two Senior ME Lab courses (ME 420 and ME 430).

ME 310 reinforces mechanical system experiments, while introducing junior students to the issues of equipment selection and more advanced analysis of results (components 3 and 5), within the context of clearly defined experimental problems. In the senior year, ME 420 provides coverage of thermal-fluids laboratory experiences, but also begins to require the students to demonstrate their abilities to define problems that they are unfamiliar with. By the time students take the capstone lab course, ME 430, they are expected to be able to completely specify, plan, conduct, and analyze experimental situations. ME 430 student teams must completely perform all of the components of design of experiments, from the definition of a problem, to the set-up and execution of procedures, and the communication of properly analyzed results.

Capstone Design Course

The senior capstone experimentation class requires student teams to each complete three different experiences – mechanical, materials and thermal-fluid [4]. Based on their earlier experiences, projects are introduced in an appropriately imprecise fashion, and student teams are expected to define the problem, determine appropriate tools and methods, and execute experiment plans and report their findings.

The stated goal of the course is to equip students to design, plan, conduct, evaluate, and document major experiments. They are expected to develop the capability to produce professional engineering reports and the ability to utilize mathematics and the physical sciences to characterize physical systems. The focus is on the prediction and measurement of system performance, with the following topics being covered:

1. Lab specifications and customer needs
2. Laboratory Project Planning
3. Planning Reviews
4. Professional Documentation and Engineering Drawings

This is similar to the instrumentation objective categories of Instrumentation, Experiment, Data Analysis, and Learn from Failure, from other institutions stated as follows [5]:

1. "the student will be able to apply appropriate sensors, instrumentation, and software tools to measure physical quantities." (Instrumentation)
2. "the student will be able to devise an experiment, specify equipment and procedures, implement the procedure, and interpret the resulting data to characterize an engineering material, component, or system." (Experiment)
3. "the student will be able to collect, analyze and interpret data, form and support conclusions, make order-of-magnitude judgments, and know measurement unit systems and conversions." (Data Analysis)
4. "the student will be able to recognize unsuccessful outcomes due to faulty equipment, parts, code, construction, process or design, and develop effective solutions." (Learn from Failure)

Through the execution of the three different lab experiences, the following WKU course outcomes are to be achieved:

1. Students will be able to design, plan, and conduct experiments to predict system performance.
2. Students will be able to evaluate and apply various methods of experimental measurement for physical phenomena.

3. Students will be able to document experimental results through comprehensive reports.
4. Students will be able to provide an appropriate evaluation of the uncertainty of experimental results.
5. Students will be able to prepare an oral/graphical/written presentation suitable for delivery at a professional function.

The course activities listed in Table 2 are performed to achieve the intended course outcomes. A strong emphasis is placed on student-led design reviews; reviews have been used repeatedly in the design component of the curriculum, so students are already proficient in this concept. The preliminary design review in week 2 is intended to be a milestone activity that assures the faculty that the team understands the problem and is headed in the right direction. The detailed design review in week 3 provides a forum for in-depth discussion of the planned activities, and then allows students to proceed with their plans over the final two weeks of the lab. This sequence is repeated for weeks 6 - 10 and for weeks 11 - 15 for each of the three lab activities.

Week	Topics	Deliverables
1	Lab Introduction; Discussion, Lab Concept Statement	
2	Conceptual Design Review	Design Review documents; Plan to order materials
3	Detailed Design Review	Design Review documents
4	Assistance with lab	
5	Lab Completion	Report/Demonstration

Table 2: Capstone Design of Experiments Course Outline

Student teams were required to complete three different types of experimental projects: a thermal project, a mechanical vibration project and a materials project. Each team completed their three projects in a different sequence so that all types of projects were taking place continually during the semester. Students interacted with a different faculty member for each type of project, while a faculty of record coordinated the overall course and was involved in all graded activities to provide consistency across the course.

A thermal project was implemented that supported an actual construction issue involving structural steel protruding through an exterior wall. The effect of outside temperature changes on the heat gain or loss of the overall structure and the more important issue of internal moisture formation were to be determined. The overall capstone course project consisted of designing and constructing a wall cross-section to model the steel beam, testing the thermal performance, analyzing and validating the experimental results, and creating a parametric computational model for future modifications and recommendations. Given the scope of the project, it was divided into three phases: test bed construction; instrumentation and data collection; numerical model creation and validation. Three different student teams handled each phase and provided information to the team that followed.

A mechanical vibration project involved the creation, simulation, and verification of the mathematical model for the vibration of a continuous system and a 3-DOF lumped-parameter system. All teams devised a method of determining the mass, stiffness, and damping properties, and then verified their model by running the physical system to find both its step and harmonic responses. A finite element analysis (FEA) was performed, and the resulting dynamic model was verified with the actual physical system.

There were three different materials projects. The first project was to provide information that can aid the manufacturer of hydraulic motors in improving fatigue resistance and surface durability of the materials used. The student team determined and implemented a method for analyzing properties and developed a plan to evaluate fatigue failure initiating at the root of the gear teeth.

The second materials project analyzed ultrasonic wave propagation and reflection at boundaries in solid materials. The goal was to compare theoretical and experimental results for reflection or transmission from an interface between two media including those with imperfect contact. The team devised a method to analyze reflection phenomena using standard ultrasonic equipment, and assessed the validity of the results obtained.

The third materials project involved the analysis of liquid infiltration of porous materials using ultrasonic methods. The team created and implemented a method for the analysis of ultrasonic wave propagation through a porous carbon material that is being filled with a catalyst-cured resin in order to develop a method for determining the efficiency of infiltration.

The individual faculty members leading each session drove the types of lab experiences and project outcomes. The vibration lab material was most familiar to the students, but a strong component of the lab was numerical simulations that they were not as familiar with. Although modified slightly, this lab was substantially the same for all student teams. The thermal lab was externally industry provided, and was the most open ended. The concept of the lab results of prior teams being used by subsequent teams was moderately successful, although the combined outcomes of the three student teams did not meet our expectations. Different materials lab experiences were provided for each student team, and these labs were the most academically oriented. The students had little familiarity with most of the concepts initially, and the major component being demonstrated was proper experimental implementation and evaluation of results.

Changes to course content are in progress for the next offering. Some of these are discussed in the Lessons Learned and Conclusions section below. However, the overall concept of a variety of lab experiences and implementation methods has provided value and will be continued.

An Example

It is intended that the students demonstrate the six Design of Experiments components:

1. Experimental Planning
2. Methods of Measurement
3. Selection of Instrumentation
4. Analysis of Data and Results
5. Uncertainty Analysis
6. Reporting of Experimental Results

These components are to be accomplished in one experiment, or over the multiple experiment projects. To use the thermal experiment project as an example, students were given the task of determining thermal issues involving structural steel protruding through an exterior wall. The effect of cold outside temperatures causing heat loss from the overall structure and allowing internal moisture formation was to be determined. Figure 2 showing this arrangement was provided to the students.

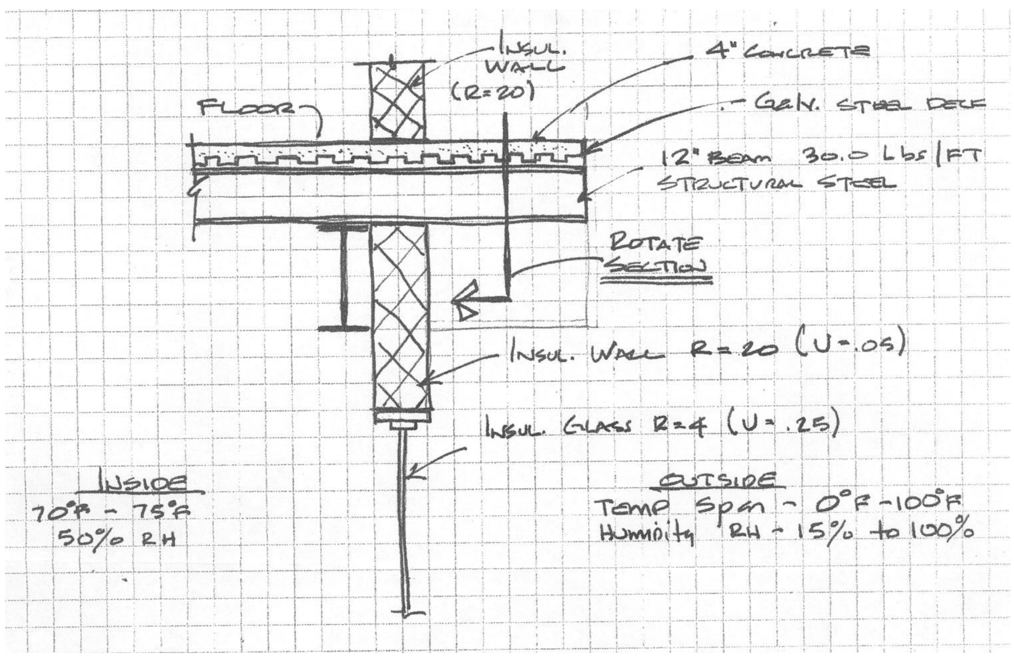

Figure 1: Cross-section view of the building wall system

Over the course of the entire semester, three teams implemented phases I through III. The overall project consisted of designing and constructing a wall cross-section to model the steel beam, testing the thermal performance, analyzing and validating the experimental results, and creating a parametric computational model for future modifications and recommendations. The first team set the entire semester sequence and constructed the test bed (1. Experimental Planning), and investigated potential instruments (2. Methods of Measurement); the second team finalized instrumentation and proposed data collection methods (3. Selection of Instrumentation); the final team partially created a numerical model to validate results (4. Analysis of Data and Results) and attempt to characterize the level of confidence in the results (5. Uncertainty

Analysis). All three student teams provided documentation that was ultimately combined into the final experimental report (6. Reporting of Experimental Results).

The project turned out to be too ambitious, and while the students made a decent effort toward executing the project, they were unable to provide definitive conclusions. This is discussed more completely in the Conclusions section.

Assessment of Experiments Plan

Two phases of assessment are implemented to monitor student outcomes and to improve the design of experiments instruction. The first phase of the process involves overall course assessment that is common for all ME courses. The ME Faculty performs a collective Peer Evaluation of Course Effectiveness at the end of the semester when a class has been offered. The purpose of this structured activity is to ensure that the curriculum of each program is integrated and consistent throughout the course of study. The peer review system reviews such issues as course content, student expectations, grade distribution, and prerequisite requirements so that they are adequately understood and achieved by all program faculty members. These activities are also in place at other institutions [6].

Peer Evaluation reports for each course contain a portfolio typically containing the following information: a current syllabus including student-based outcomes, copies of materials provided to students and examinations, selected examples of graded student work and the student grade distribution, as well as other material or discussion deemed important by the instructor. In addition, student self-evaluation and faculty evaluation of achieving course outcomes are presented.

This initial offering of the design of experiments course required significant modifications during the semester. While student work was used to assess the five course outcomes listed earlier (shown as "Instructor" in Figure 2), the students did not self assess the course outcomes. The results of course grade based assessment by the Instructors of the course outcomes are shown below with a 0 indicating no mastery and 10 very proficient.

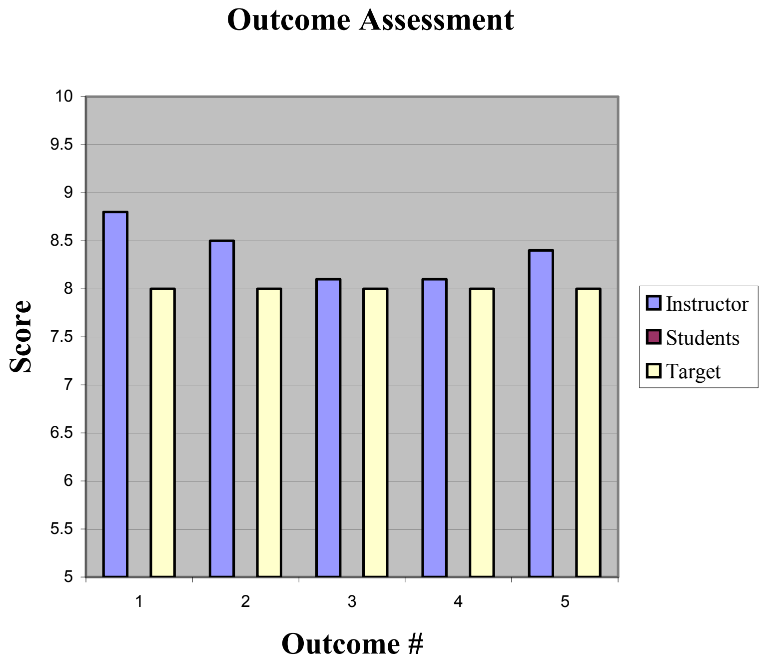

Figure 2: Course Assessment from Peer Evaluation

Student comments during the course indicated frustration at the expectations of the course and a lack of appreciation for the professional outcomes expected. The disconnect between student and faculty expectations has resulted in the modifications discussed in the Lessons Learned and Conclusions section.

Assessment specific to design of experiments is incorporated into ME Program Outcome 3: Mechanical Engineering graduates can measure physical quantities and can plan, conduct, analyze and evaluate experiments. This program outcome supports ABET Outcome (b) directly, as well as ABET (a) and (c) to a lesser extent. The Program Outcomes are measured using several methods and are reviewed on an annual basis. The primary means of assessment is ME faculty evaluations of selected student work in several of the courses listed in Table 1.
The assessment rubric shown in Table 3 is used for all evaluation of student work, and courses are selected to capture the evolution of student progress from sophomore through senior years. Secondary methods of assessing student competency are average grades of ME graduates in the design of experiments courses, and student self-evaluation through surveys of exiting seniors and 1st year alumni.

The assessment of individual program outcomes is condensed into a report for several outcomes. The design of experiments outcome is one of three outcomes in the Fundamental Skills group. Overall, the thirteen program outcomes are collected into five groups: Fundamental Skills, Professional Skills, Engineering Professionalism, Life-Long Learning, and Societal Awareness. These collective evaluations of program outcomes are reviewed by the ME faculty members annually.

Lessons Learned and Conclusions

The Design of Experiments Plan together with the capstone experiments course provides a framework for coordinating the efforts of many lab courses, building upon previous lab work, assessing student progress, and adjusting lab coverage based on prior assessments to assure that graduates of the program are capable experimental practitioners upon graduation. The system is in place and is guiding the efforts of the entire ME faculty to create and modify lab courses. Assessment of student outcomes is ongoing and taking place at the course level and the program level, with a common experiments rubric being used to quantify the performance of students over several years.

Because the Design of Experiments Plan has only been in place for the past year, student performance varies along the stages of implementation. There are evident differences between the performances of juniors, compared to seniors, since the younger students have benefited from greater exposure the Design of Experiments Plan. By contrasting the demonstrated abilities of subsequent senior classes, we will have another means of assessing the benefits of this structured plan.

It has become clear to the ME faculty that the current organization of the capstone design of experiments course contains too many lab experiences. Next year, we plan to reduce the number of labs from three to two (a thermal-fluids and a mechanics-materials), increasing the time student teams have for each experiment, as well as increase the amount of lecture setup time for the course. However, we will keep the variety of lab types, including industry/academic-driven, and stand-alone or collaborative. The delivery method involving multiple student design reviews was assessed as effective.

Currently, the Design of Experiments Plan is only implemented within ME lab courses, although activities in non-ME courses contribute to student learning. It is our intention to use this assessment plan as a forum to help introduce outcomes assessment to non-engineering groups. By providing non-ME faculty with specific examples of evaluating the effectiveness of lab activities, we will endeavor to expand the overall scope of outcomes assessment for ME students [7].

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CHRIS BYRNE
Chris Byrne teaches mechanical systems courses in Mechanical Engineering at WKU. This includes engineering science courses from the freshman to senior year of the program. He is active in research and industry outreach, with specialization in materials science, friction and wear mechanisms, and non-destructive evaluation. Prior to teaching at WKU, he was a faculty member of Southern Illinois University.

ROBERT CHOATE
Robert Choate teaches thermo-fluid and professional component courses in Mechanical Engineering, including the Sophomore Design, Junior Design, the Senior ME Lab I and the ME Senior Project Design course sequence. Prior to teaching at WKU, he was a principal engineer for CMAC Design Corporation, designing and verifying thermal management solutions for telecommunication, data communication and information technology equipment.

JOEL LENOIR
Joel Lenoir is the Layne Professor of Mechanical Engineering at WKU, and primarily teaches in the dynamic systems and instrumentation areas of the curriculum. His industrial experience includes positions at Michelin Research and Oak Ridge National Laboratory, as well as extensive professional practice in regional design and manufacturing firms.

KEVIN SCHMALTZ
Kevin Schmaltz teaches thermo-fluid and professional component courses in Mechanical Engineering, including the Freshman Experience course, Sophomore Design, Junior Design and the Senior Project Design course sequence. Prior to teaching at WKU, he was a project engineer for Shell Oil, designing and building oil and gas production facilities for offshore platforms in the Gulf of Mexico.

Attributes	**Absent (0)**	**Novice (1):** Use material or instructions provided	**Intermediate (2):** Implement from moderately complete instructions	**Proficient (3):** Implement on own with minimal instruction.
Experimental Planning: Be able to define problem, evaluate measurement needs, and organize execution of project.				
Method of Measurement: Be able to investigate, justify and select measurement approach.				
Selection of Instrumentation: Be able to specify, acquire and use measurement tools.				
Analysis of Data and Results: Be able to organize, synthesize, and present data. Infer meaningful conclusions from results.				
Uncertainty Analysis: Be able to assess the proper level of confidence in results and recommend modifications to change uncertainty.				
Reporting of Experimental Results: Be able to professionally document results, evaluate audience, and accurately convey process and product of experiment.				
Total Score: (Expect 6 for Sophomores, 12 for Juniors and 15 for Seniors)				

Table 3: Assessment Rubric for Design of Experiments