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Engaging Undergraduate Students in Experimental Learning in Materials Science through a Hybrid Project-Based Learning

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Dr. AbdelGawad's interests are centered around materials and manufacturing, with a strong focus on corrosion of advanced materials, and the study of statics and mechanics. With an extensive teaching background, she has developed a keen interest in advancing innovation in engineering education. At present, she actively explores various methods to enhance student engagement and optimize their learning experiences through curriculum and course design.

ENGAGING UNDERGRADUATE STUDENTS IN EXPERIMENTAL LEARNING IN MATERIAL SCIENCE THROUGH A HYBRID PROJECT-BASED LEARNING

Abstract

This paper introduces a transformative approach to engineering education, specifically targeting the materials and manufacturing laboratory curriculum. As traditional laboratory experiments tend to limit student engagement and creativity, a Work-in-progress (WIP) has been initiated to transform the conventional laboratory into a dynamic project-based learning (PBL) environment. Emphasizing critical thinking and mental flexibility, the methodology integrates materials science and manufacturing knowledge, guiding students through open-ended experiments. The project's objective is to enhance problem-solving skills and apply theoretical concepts to real-life design challenges. The initiative has gained positive feedback from students, emphasizing the demand for more hands-on experiences. The paper details the methodology, expected outcomes, connection to ABET student learning outcomes, and assessment strategies. This WIP reflects a commitment to advancing engineering education in response to the evolving demands of the profession.

Introduction

Experimental curriculum in engineering has witnessed a decreasing involvement. Laboratory courses are simply used to support and demonstrate theoretical aspects of core engineering classes [1]. Traditionally laboratory experiments involve a step-by-step procedure with a known outcome. However, this method has proven to be effective in demonstrating a concept, it limits the student's engagement in learning and doesn't enhance their problem-solving skills or creativity and imagination [2], [3].

Studies of workforce requirements reveal the emphasis on foundational skills needed in the workplace for graduates to thrive [4]. These skills were identified as critical thinking, planning, ways of working, communication, mental flexibility, mobilizing systems, developing relationships, teamwork effectiveness, self-awareness and self-management, entrepreneurship, goals achievement, digital fluency, software use, and digital systems. Aligning with the Accreditation Board for Engineering and Technology (ABET) outcomes in engineering with market changes presents a need for more critical thinking and mental flexibility in teaching methods. Moving from well-defined experiments to more open-ended experiments that encourage the students to translate knowledge to different contexts, adapt, and improve their ability to learn has become a necessity for laboratory courses [5]–[7].

Experimental application of materials science concepts has been well established in engineering curriculums, the current Work-in-progress (WIP), advances student engagement in materials science by transforming laboratory learning into project-based learning (PBL). The presented methodology establishes guidelines for transforming a one-credit-hour mandatory undergraduate materials and manufacturing laboratory into a series of experimental laboratories with the notion of engaging students in critical thinking, applying basic principles of design of experiments (DoE), and combining material science and manufacturing knowledge to solve engineering problems.

The feedback from both the industrial advisory board and graduating students has indicated a strong ask for more hands-on experiences that directly apply classroom knowledge to real-life design challenges. This WIP reflects our commitment to continuously advancing engineering education, ensuring that graduates are well-equipped with the skills necessary to flourish in the changing landscape of the engineering profession.

In the subsequent sections of this paper, we will present the specific details of the experimental laboratories, discuss the integration of project-based learning, and present the outcomes expected from the implementation of this transformative approach.

Methodology

The learning objectives focus on understanding the material characterization and manufacturing processes through mechanical properties, microstructure production and control, and manufacturing processes. Multiple applications of laboratory learning achieve these objectives, mechanical testing for instance tensile, fatigue, bending, impact, and shear testing experiments. Microstructure control through heat treatment, cold rolling, sample preparation, and microscopy. Manufacturing through machining, casting, welding, and additive manufacturing.

The PBL methodology is designed with ABET student outcomes 1,2,3,5, and 6 in mind. The problem selection involves the three main areas addressing the learning objectives. Students are divided into groups of four to five students and provided a prompt that involves the fabrication of an engineering component with geometrical constraints, pre-specified tolerances, and desired material properties. The students are provided with a list of materials and processes available on-site that they will use to manufacture their parts. The project leads the students to the appropriate selection of material, process, standards, and path of production that would achieve the requirements. The project is phased into three sections: identifying critical loads, experimental exploration through guided experimental sets, and finally implementation of design knowledge through the application of knowledge gained through the guided experiments. The student groups will determine the most appropriate material choice through gained knowledge in mechanical testing, apply proper manufacturing techniques through knowledge of manufacturing processes, and lastly fabricate, heat treat, and evaluate the final design through a technical report. Case studies will involve mechanical components such as shafts, links, control arms, and

Student engagement, critical thinking, and effective communication are key goals for excellence in engineering education. The benefits of PBL have challenged the traditional methods of teaching especially laboratory courses, where limitations of equipment limit laboratory engagement beyond the hands-on experience of students. Engaging students with purposeful experiments is anticipated to strengthen technical skills, allow critical thinking, and bridge the gap between material and manufacturing in undergraduate students. Figure 1 shows the methodology of PBL. A hybrid approach for project-based learning, incorporate the traditional teaching of laboratory sessions will incorporate knowledge for completing the project through learning about material testing and manufacturing methods as outlined in laboratory structure section. Students will utilize their material testing values to select the appropriate material for manufacturing their project component, where they will use a benchtop manual lathe for their manufacturing.

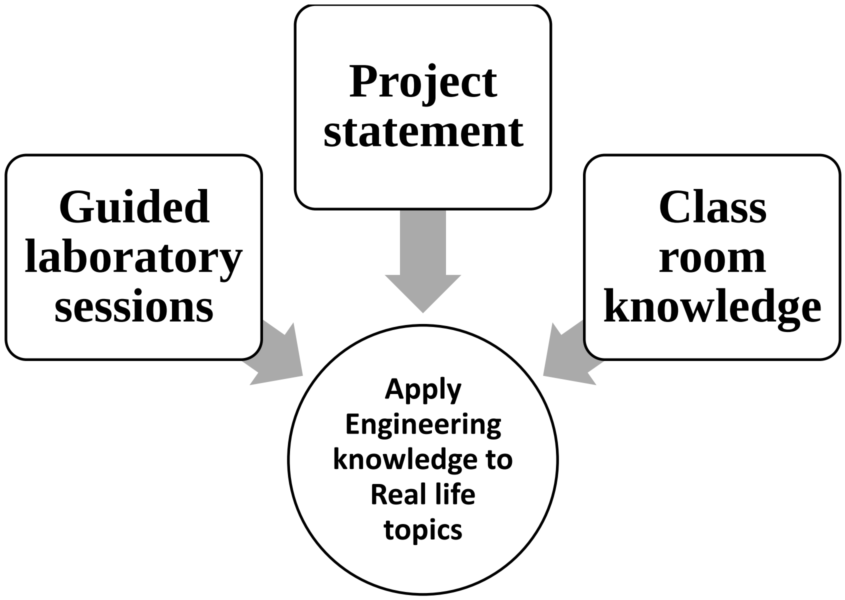

Figure 1 PBL Framework.

Project Prompt and Schedule

Appendix A shows a sample project for Spring 2024. The project presents a hybrid implementation of laboratory traditional sessions but with a focus on collecting necessary data for completing the project. Table 1 shows a typical laboratory schedule. The laboratory is designed to present materials science and testing attributes and a manufacturing attribute. The materials testing provides the students with knowledge on materials testing, characterization, and standard methods such as the American Society for testing and Materials (ASTM), and the International Organization for Standardization (ISO) standards of testing of materials.

In a hybrid model, the students will test a range of materials, collect data, analyze data, and report on their findings. This includes tensile properties such as tensile strength, yield stress, Young's modulus, percentage elongation, and ductility. Impact toughness, fatigue, cold work, surface roughness, and hardness for materials characteristics. During these materials' characterization labs, they build knowledge of how materials testing is performed and collect data that aids them for materials selection in their projects. The guided laboratory sessions on manufacturing introduce various processing techniques such as injection molding, additive manufacturing, lathe machining, milling machining, casting, and welding laboratories. These guided laboratories are necessary for students to build their proficiency in manufacturing that they later can use for their project implementation.

The project connects students with various mechanical engineering undergraduate curricula. For instance, realizing forces and drawing a free body diagram necessary for calculating stresses on the shafts is an application of engineering mechanics classes. Figure 2 shows the project process.

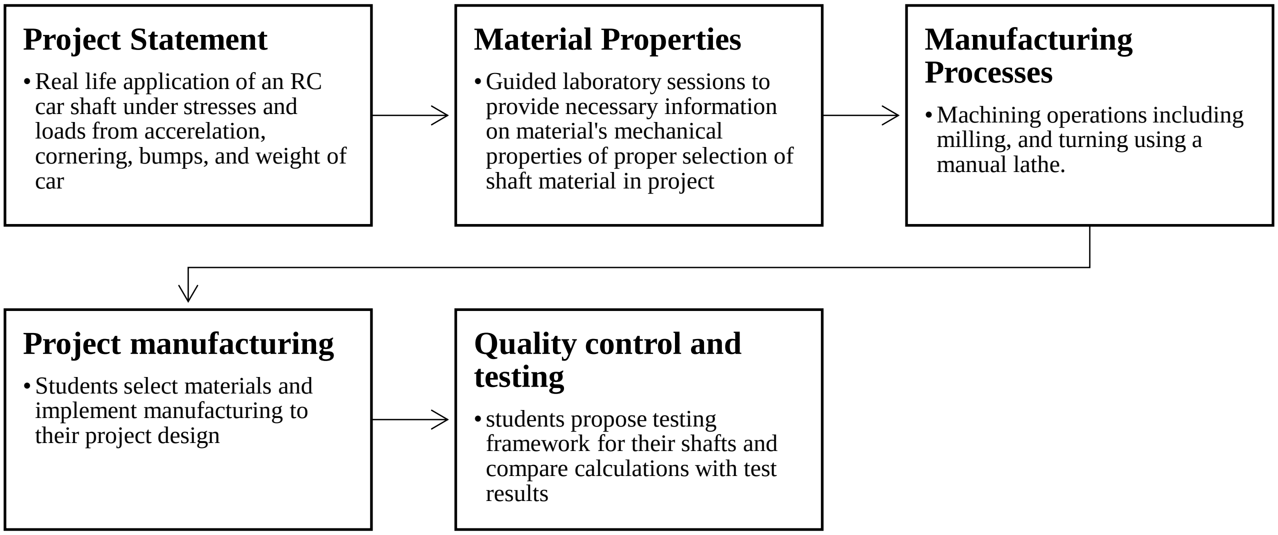

Figure 2 Project lifecycle.

Table 1 MEEN361 Laboratory Schedule

Week	Attribute	Topic
1	Management	Lab Safety Project Prompt
2	Materials	Tensile Test Metal
3	Materials	Fatigue + Impact
4*	Manufacturing	Additive Manufacturing + Injection Molding
5*	Materials	Tensile Polymer, Bending+ Hardness
6*	Manufacturing	Machining I- Lathe
7*	Manufacturing	Machining II – Milling
8		
9	Materials	Cold work and Hardness
10*	Project	Students Manufacture their parts
11*	Project	Students test their parts
12	Manufacturing	Casting
13	Manufacturing	Welding
14	Materials	Steel Heat Treatment Microscopy

Expected Outcomes

1. **Enhanced Critical Thinking Skills:** Students are expected to develop advanced critical thinking skills through the analysis of complex engineering challenges presented in the project prompt. By navigating through the various stages of material selection, manufacturing processes, and component testing, they will develop a deeper understanding of decision-making in engineering contexts.

2. **Improved Problem-Solving Abilities:** The PBL approach encourages students to apply theoretical knowledge to real-world design challenges. As a result, students are anticipated to demonstrate improved problem-solving abilities as they tackle issues related to material selection, manufacturing processes, and component testing.

3. **Increased Technical Proficiency:** Through hands-on engagement in laboratory sessions and guided experiments, students are expected to enhance their technical proficiency in material testing, characterization, and manufacturing techniques. This will translate into a more skilled understanding and application of engineering principles.

4. **Effective Communication Skills:** The collaborative nature of the project, combined with regular reporting and documentation requirements, is designed to enhance students' ability to communicate effectively. This includes clear articulation of design choices, material selection rationale, and interpretation of experimental results.

5. **Teamwork and Collaboration:** The group-based structure of the project prompts students to work collaboratively in small teams. This fosters the development of teamwork and collaboration skills, aligning with ABET outcomes related to effective collaboration in engineering projects.

6. **Application of Design Principles:** The PBL methodology guides students through the application of design principles in a real-world context. Students are expected to integrate theoretical knowledge from material testing and manufacturing processes into the creation of a functional engineering component – the axle shaft.

Connection to ABET Student Learning Outcomes:

1. **ABET Outcome 1:** The project aligns with ABET Outcome 1 (An ability to identify, formulate, and solve complex engineering problems) by presenting students with a multifaceted design challenge that necessitates problem identification, formulation, and solution.

2. **ABET Outcome 2:** (An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors) is addressed through the design and manufacturing aspects of the project, requiring students to consider a range of factors in creating a functional axle shaft.

3. **ABET Outcome 3:** The PBL methodology supports (An ability to communicate effectively with a range of audiences) by necessitating clear communication within student groups, as well as the presentation of findings and decisions through technical reports.

4. **ABET Outcome 5:** (An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives) is integrated as students work together in teams to address the challenges posed by the project prompt.

5. **ABET Outcome 6:** The project is specifically designed to align with Outcome 6 (An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions) through the incorporation of guided experimental sets and data analysis in the PBL process.

These expected outcomes and connections to ABET student learning outcomes will strengthen the student's educational standards and provide a clearer understanding of the classroom concepts.

Assessment

In Appendix B, the assessment survey of student's knowledge is aimed at evaluating the efficacy of the PBL initiative in materials and manufacturing. The assessment is designed to measure the student's understanding and application of theoretical concepts to real-world engineering challenges as presented by the RC car axle shaft project. It involves various dimensions, including materials testing, manufacturing processes, and the integration of design principles into the fabrication of a functional engineering component – the axle shaft. The assessment evaluates students' critical thinking skills through the analysis of complex engineering problems presented in the project prompt. Furthermore, it examines their ability to apply engineering design principles, communicate effectively, collaborate within teams, and function independently in problem-solving scenarios. The assessment aligns with the ABET outcomes, particularly focusing on outcomes related to experimentation, teamwork, and effective communication. By analyzing students' performance in these areas, the assessment aims to provide insights into the overall impact of the PBL approach on their knowledge acquisition, practical skills, and self-efficacy in the field of engineering.

Conclusion

The transformation of the conventional materials and manufacturing laboratory into a PBL environment represents an effort to bridge the gap between education and workplace challenges. This WIP responds to the declining involvement in experimental curricula by introducing a dynamic framework that enhances students' critical thinking, problem-solving abilities, and practical skills. The integration of PBL aligns with the evolving demands of the workforce, emphasizing foundational skills identified by studies in the field. The feedback from both the workforce and graduating students highlights the demand for hands-on experiences that directly apply classroom knowledge to real-life design challenges.

By systematically guiding students through open-ended experiments, the presented methodology aims to bridge the gap between theoretical concepts and practical application. This work-in-progress reflects our commitment to continually advancing engineering education, ensuring that students are equipped with the multifaceted skills demanded by the contemporary job market.

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Appendix A: Project Prompt Spring 2024

"The selection of material requires extensive thought and research to ensure that the selected material will not fail during service. The composition, structure, and processing requirements are considered to determine the appropriate material for different applications.

You have recently joined Texas A&M University at Qatar RC car design competition and your team was tasked with designing the Axle shafts of the RC car. These shafts often experience excessive loads and support loads of the vehicle on the road. As a student in mechanical engineering joining the competition, your group was tasked with designing and manufacturing an Axle shaft of your RC car according to design specifications. Axle shafts are cylindrical components commonly used in automotive applications to transmit power from the differential to the wheels in a vehicle.

Manufacturing an axle shaft on a lathe involves turning operations to achieve the desired diameter and surface finish, as well as drilling or boring if the shaft needs to be hollow. Keyways, splines, or threads may also be machined into the shaft to accommodate the necessary hardware for attachment in the vehicle's drivetrain. After machining, the shafts are often heat-treated to improve their mechanical properties, particularly their resistance to fatigue and impact.

Here's how an axle shaft experiences loading:

1. **Tensile loading**: When the vehicle accelerates or climbs, the axle shaft is subjected to tension due to the torque applied by the powertrain to propel the vehicle forward or upward.

2. **Bending loading**: Bending loads occur when the vehicle carries heavy loads or when the wheels hit bumps in the road, causing a deviation from the purely rotational action and inducing bending stresses along the length of the axle shaft.

3. **Fatigue loading**: The rotational motion of the axle shaft, combined with the variations in loads experienced during driving (such as starting, stopping, and varying weights), can lead to cyclic stresses that result in fatigue over time. Sudden changes in speed and direction, as well as regular vehicle operation, all contribute to fatigue loading.

4. **Torsion**: Due to the acceleration and tire friction of the vehicle the shafts will experience some torsion forces.

5. **Impact loading**: Sudden impacts, such as those from hitting a pothole or debris, can create a short-term high-load scenario which may not immediately break the shaft due to its inherent toughness but can contribute to the initiation of microcracks that may propagate over time due to fatigue.

The shaft will experience the following loading while cornering:

1- Lateral Force: **X**

2- Traction Force at the wheel during acceleration (**Y1** m/s^2): **Y2**

3- Weight of car: **Z** kg

4- Impact force from bumps: **K** kN

5- The expected life of the shaft is **N** Million rotations.

Constraints:

1- Bearings should be included and provide a support **shoulder**.

2- No sharp edges to avoid injury while assembling.

3- Selection of safety factors based on team requirements you may assume a safety factor for the **shoulder** as it acts as a stress concentrator.

4- Maximum diameter is 31 mm and minimum diameter is 20 mm.

5- The minimum length of the shaft is 20 mm, and the maximum length is 30 mm.

6- A keyway should be included for the torque transmission components.

1- **Free body diagram** for loads and load cases on the shaft.

2- **Design calculations** as per group requirements.

3- **CAD drawing** for the shaft.

4- **Material selection** based on results from

   a. Tensile testing of metals
   b. Bending
   c. Hardness
   d. Fatigue to be provided.

5- **Manufacturing plan** of the shaft

   a. Turning operations for the shaft.
      i. Tools selection (HSS, carbide)
      ii. Angles
      iii. Tool path plan
         1. Feed rate.
         2. Spindle speed
         3. Material removal rate
         4. Volume of material removed.
         5. Finishing if any
   b. Milling operations for the keyway.

i. Tool selection
ii. Spindle speed
iii. Material removal
iv. Feed and rate.

6- Manufacturing of part **Week 10**

7- Testing plan **Week 11**

a. Nondestructive testing
b. Dimensional measurements
c. Surface finish
d. Weight
e. Deflection test

8- Report

Appendix B: Student Survey

Section 1: General Information

1. **Student Information:**
   - Name (Optional):
   - Age:
   - Classification:

Section 2: Project Experience

2. **To what extent do you believe the project helped you apply theoretical knowledge to real-world engineering challenges?**
   - Not at all
   - Slightly
   - Moderately
   - Very much
   - Extremely

3. **Rate your confidence in your ability to collaborate effectively with team members during the project:**

- Not confident at all
- Somewhat confident
- Moderately confident
- Very confident
- Extremely confident

4. **How well do you think the project prepared you for addressing real-life design problems in your field of study?**
    - Not well at all
    - Somewhat well
    - Moderately well
    - Very well
    - Extremely well

Section 3: Critical Thinking and Problem-Solving

5. **To what extent did the project enhance your critical thinking skills?**
    - Not at all
    - Slightly
    - Moderately
    - Very much
    - Extremely
6. **Rate your perceived ability to solve engineering problems independently as a result of the project:**
    - Not able at all
    - Slightly able
    - Moderately able
    - Very able
    - Extremely able

Section 4: Communication Skills

7. **How much did the project contribute to improving your communication skills, especially in reporting technical information?**

- Not at all
- Slightly
- Moderately
- Very much
- Extremely

Section 5: Overall Self-Efficacy

8. **Considering your experience with the project, how confident are you in your overall ability to succeed in your engineering studies and future career?**
    - Not confident at all
    - Slightly confident
    - Moderately confident
    - Very confident
    - Extremely confident
9. **To what extent do you believe the project positively influenced your self-perception as an effective engineer?**
    - Not at all
    - Slightly
    - Moderately
    - Very much
    - Extremely