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Student-led Multi-Disciplinary Approach for the Design of Experiments in Engineering: A Methodology

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Abstract

This paper introduces a methodology for teaching the Design of Experiments (DoE) Mechanical Engineering course. The concept centers on three principles: a multidisciplinary approach, student empowerment, and real-life engineering challenges. The DoE course curriculum centers around two phases, Project 1, and Project 2, with critical problem-solving as the core focus. Project-based learning involves teams selecting real-life challenges and adopting a connection between students' missions and global issues. It progresses through establishing project needs, cultivating ownership through role-playing, and developing technical knowledge. Work Plan Development encompasses drafting experimental plans, data collection strategies, and weekly progress meetings. Project 2 builds on Project 1, expanding to a three-factor, three-level experiment. It challenges students with advanced analysis tools, promoting personal ownership and leadership in structured problem-solving. The methodology extends beyond the classroom, impacting students in diverse learning environments and enhancing knowledge beyond technical domains through ownership and personalization of problems. Student projects in the academic years 2022-2023 showcase engagement, critical thinking, and tangible results that extend beyond the classroom, leading to the engagement of 30% of class students in undergraduate research on their MEEN 404 topics after completion of the course work. Specific learning outcomes demonstrate how the Paradigm fosters skills in structured problem-solving, work plan development, time management, storytelling, public speaking, knowledge translation, adaptability, teamwork effectiveness, and self-leadership. The ABET scores showed an improvement, with an average increase of approximately 10-15% across various student learning outcomes over the evaluated years, highlighting the effectiveness of the implemented teaching paradigm in elevating student achievement in engineering education. The assessment methodology supports the success of the methodology, empowering students to tackle real-world engineering challenges and excel academically.

Introduction

In an era of digital transformation and artificial intelligence domination, the requirements of graduating engineers have changed. A study by McKinsey done on 18,000 people in 15 different countries identified 56 foundational skills of future workplace skills grouped into four categories: cognitive, interpersonal, self-leadership, and digital skills [1]. Academic curriculums and teaching methods must meet these changing needs by equipping graduates with tools to thrive in these environments. ABET specifies student learning outcomes that guide certified institutions in meeting the changing needs of the workforce. For instance, student outcomes (SO) 2, 5, and 6 specify skills that are directly related to cognitive and interpersonal skills. Engineering curriculums implement specific courses to satisfy the experimental methods requirements of SO 6. MEEN404 Engineering laboratory is an undergraduate mechanical engineering class for systematic design and investigation of experiments, where students form groups and establish need, function structure, conduct experiments, analyze, interpret, and report results orally and in documents. The course implements a Design of Experiments (DoE) structured approach for testing and optimizing processes, products, and systems.

The DoE approach allows for efficiently identifying and addressing problems or challenges in various domains, from manufacturing to scientific research. However, the course assessments are traditionally focused on technical aspects of experiments, such as factorial design, hypothesis testing, statistical analysis, ANOVA, and error propagation techniques. This method equips students with strong technical skills on how to conduct and analyze an experiment but does not provide the skills of planning or critical thinking. Students often approach these classes with a technical mindset of theories and how to implement calculations and satisfy a hypothesis test correctly. DoE can be a challenging concept to master, often applied within a multifaceted, interdisciplinary context. It demands not only a strong grasp of its principles but also the exercise of critical thinking and decision-making skills. The significance of DOE extends beyond its theoretical framework. It underscores the importance of equipping individuals with the capacity to navigate the intricate terrain of experimentation and to make choices that drive progress and innovation.

The importance of student engagement and motivation in the learning process has been consistently supported by educational research [2]. Educators have emphasized that students benefit significantly when actively involved in their own learning, particularly when they collaborate in groups [3]. Various forms of collaborative learning have been implemented in college-level courses, with positive outcomes reported across different disciplines.

Studies exploring collaborative learning methods at the higher education level have consistently highlighted several advantages. Educators incorporating collaborative approaches have noted heightened student satisfaction with the learning experience [4] and a reduction in academic anxiety [5]. Additionally, research findings consistently suggest that collaborative learning environments foster outcomes that surpass those achievable by individual students working independently [6]. These insights highlight the pedagogical significance of ownership and collaborative learning in providing a foundation for enhancing both student engagement and overall educational outcomes.

Methodology

In this paper, we present a methodology for teaching the DoE Mechanical Engineering course. The methodology centers around three essential principles: (1) Embracing a Multidisciplinary approach, (2) Empowering students as leaders, and (3) Real-Life Engineering Challenges. Figure 1 shows the paradigm of the MEEN 404 methodology with critical problem-solving at the core of the methodology. With this in mind, we structure the course into two phases: Project 1 and Project 2.

Real-life Challenges: In Project 1, students form teams, each comprising four to five students, and are tasked with selecting a real-life problem or proposing a new product development that addresses a challenge in real life, this fits within the overarching goal of connecting students with their mission of addressing sensible and tangible problems they encounter in their life and increase their awareness of problems in different parts of the world.

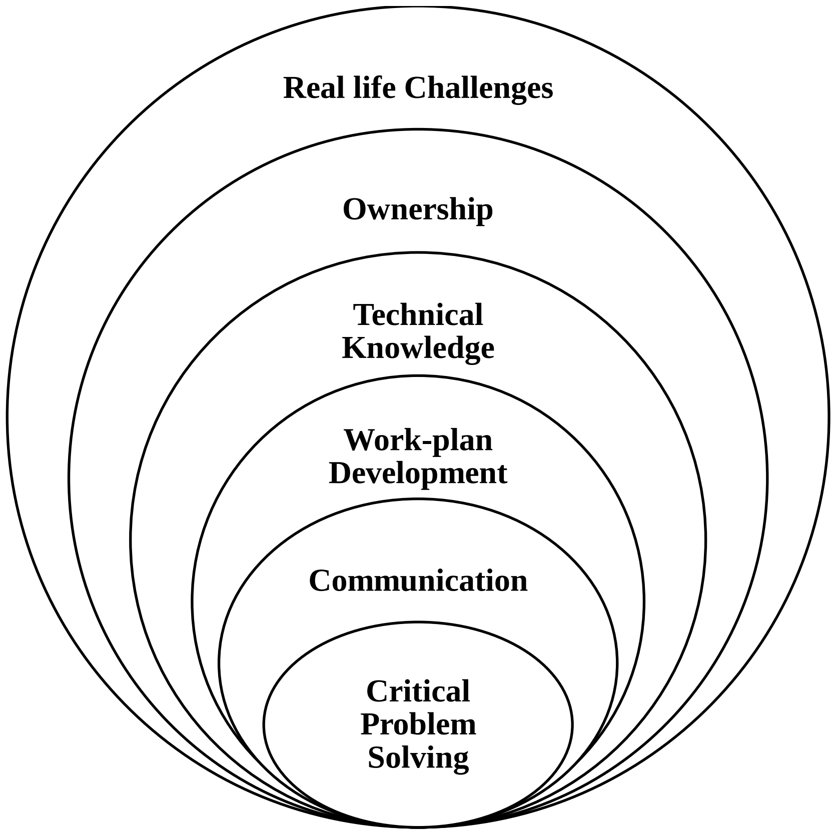

Figure 1 MEEN 404 DoE Paradigm

Ownership: Project 1 unfolds in three key phases: first establishing the need for studying such a project, where students assume a scenario, assume a company name, build interest, highlight significance, and find statistics that back up the need. This serves the second aspect of the methodology of ownership of the topic; students connect to the project mission by being employees of their hypothetical company and drafting their mission statement and focus.

Technical Knowledge: Students explore potential factors, levels, and outcomes while justifying their choices, and relating them to actual scenarios they are developing. Also, students are required to define their analysis methods and success criteria for their analysis. Project 1 serves as the foundational learning experience and focuses on a manageable two-factor, two-level scope.

Work Plan Development: The third phase entitles drafting the experimental plan, data collection strategy, data analysis, repeatability, randomization, and experimental work.

Communication: Students formally meet weekly with the instructor to present their progress and discuss any challenges they face. The students are expected to start by introducing the challenge they are addressing, present their viewpoint as engineers or consultants for a company, present their company's mission, and define the scope of their problem.

Critical Problem Solving: Project 2 takes the lessons learned from Project 1 and elevates them. It expands the scope to a three-factor, three-level experiment, challenging students to apply advanced analysis tools such as factorial design, Taguchi design of experiments, ANOVA, main effect analysis, Pareto diagrams, interaction plots, regression, and model prediction to extract valuable insights from their results.

This approach encourages students to take personal ownership, leadership, and responsibility for their learning building up to structured problem-solving through their interests and involvement with the issue they are solving as engineers. Often these problems are multi-disciplinary requiring knowledge in different fields such as materials, environment, acoustics, air quality, chemical reactions, and business. This paradigm aims to impact students in multiple learning environments and extend their knowledge beyond classroom and technical knowledge.

Impact

The projects developed by the students not only broaden their understanding of their specific project but also learn and get educated on other topics from their peers in different areas and topics. Students have demonstrated engagement and critical thinking in engineering problems, producing tangible results that extend beyond the classroom, leading to the engagement of 30% of class students in undergraduate research on their MEEN404 topics after completion of the course work. Table 1 shows examples of projects conducted in the academic years 2022-2023 at Texas A&M University at Qatar.

These projects have included creating filaments using recycled PET bottles, optimizing sound deadening material in a machine shop, improving air quality through easily accessible material, enhancing concrete performance using recycled polymer materials, creating luggage handles using 3D printing, removing dyes from wastewater using membrane technologies, optimizing electric vehicle battery charging routines in harsh climates, uses of chemical itching of 3D printed parts for biomedical prosthetic molds, and reducing cooling loads using highly reflective paints.

The specific learning outcomes are highlighted below with reference to selected student's projects.

1- Structured problem solving

Research indicates that problem-based learning, such as the one employed in this methodology, increases student engagement and enhances critical thinking skills [7]. As students assume roles within their hypothetical company, they not only learn to articulate the need for their chosen project but also develop a deeper understanding of its societal impact. This aligns with the findings of studies emphasizing the importance of real-world context in enhancing problem-solving abilities [8]. The technical knowledge phase is informed by the incorporation of practical scenarios, allowing students to apply theoretical concepts to real-world situations. This integration of theory and practice is recognized as a key driver for effective engineering education [9]. The emphasis on communication and weekly progress meetings aligns with research highlighting the positive impact of regular feedback on student performance and understanding [10]. Project 2 then expands on these foundations, incorporating advanced analysis tools, aligning with research suggesting that exposure to diverse analytical techniques enhances problem-solving proficiency [11]–[13].

The work of the "Electra-Q" group, investigating the influence of extreme temperatures, charging, and discharging rates on Li-ion battery capacity. This project showcased structured problem-solving as students justified their choices for experimental factors and levels, aligning them with real-world scenarios in Qatar. The "Printopia" group, focusing on enhancing the surface finish of 3D-printed prosthetic mold cavities, exemplified structured problem-solving. Their approach involved a systematic exploration of factors such as chemical treatments, time, and surface assessment techniques. The work plan development phase included drafting strategies for experimental procedures and data analysis, reinforcing the structured methodology.

2- *Work-plan development.*

In Project 1, students methodically create experimental plans, data collection strategies, and analysis methods. This reflects best practices in project-based learning, recognized for successful project execution. The emphasis on repeatability and randomization aligns with established experimental design principles, ensuring robust and valid results. This phase integrates insights from project management, optimizing resource allocation and timelines [14]. The iterative nature of work plan development improves the adaptability in students, reflecting the dynamic nature of real-world engineering projects. Research highlights that involving students in planning enhances their ownership and responsibility [15].

Table 1 Sample projects for years 2022-2023

Project title	**Group Name**	**Primary field**	**Secondary field**
Recycling of PET in circular economics, a systematic assessment of printability	Fantastic Plastic	Materials	Chemistry
Rating sound insulating systems of machine shop	E&E	Acoustics vibrations	Materials
Improving thermal insulation by adding plastic to a concrete mixture	PlastoCrete	Materials	Civil
Investigating the effects of air filter and humidity levels on indoor air quality in Qatar	Wind busters	Measurements	Fluids
Assessing the impact of recycling cycles on PET plastics manufactured in Qatar	PolyCycle	Materials	Chemistry
Factorial design of membrane technology for dye wastewater treatment	Memtech	Chemistry	Fluids
Increasing the flexural strength of 3D-printed PLA specimens using Taguchi experimental design	Print-A-Part	Materials	Manufacturing
Influence of extreme temperatures, charging, and discharging rates on Li-ion battery capacity	Electra-Q	Electrical	Chemistry
Reducing energy expenditure using cooling paint	Cool Paint	Chemistry	Energy
Enhancing the surface finish of 3D printed prosthetic mold cavities using the design of experiments	Printopia	Biomedical	Chemistry
The effect of polypropylene fiber reinforcements, water, and superplasticizers on the compressive and flexural strength of 3D-printed concrete	Concreators	Civil	Materials

3- Time management

The course structure emphasizes the importance of allocating time efficiently to Project 1 and Project 2 over 14 weeks. Students are encouraged to develop a realistic schedule that accommodates various project phases, ensuring steady progress. Structured time management positively influences student outcomes in project-based learning environments [12]. Weekly meetings with the instructor provide an opportunity to discuss challenges and refine timelines, promoting continuous improvement. The integration of time management principles not only enhances project efficiency but also equips students with a valuable skill set crucial for their future.

4- Storytelling and public speaking

The importance of effective communication is demonstrated through the diverse projects conducted by student groups. Each project becomes a narrative, with students acting not only as engineers but also as storytellers who must convey the significance of their work to varied audiences. The ability to convey complex engineering concepts with clarity is evident in presentations where students share their findings, methodologies, and real-world implications.

For instance, the "Fantastic Plastic" group, working on the recycling of PET in circular economics, had to narrate the story of sustainability and environmental impact, making their work accessible to both technical and non-technical stakeholders. Similarly, the "Print-A-Part" group, exploring the flexural strength of 3D-printed PLA specimens, had to effectively communicate the intricacies of their experimental design to ensure effective communication with luggage handle companies.

Weekly progress meetings, a key component of the MEEN 404 structure, provide a platform for students to enhance their public speaking skills. These meetings require students to not only report on their project progress but also to narrate their engineering journey, emphasizing challenges, solutions, and the broader impact of their work. This intentional integration of storytelling and public speaking skills ensures that MEEN 404 graduates possess not only technical proficiency but also the ability to convey their engineering narratives convincingly, a skill highly valued in the professional world.

5- Translating knowledge to different contexts

The "Wind Busters" group's investigation on the effects of air filters and humidity levels on indoor air quality in Qatar is a key example. This project not only addressed a local concern but also showcased the ability to apply engineering principles in the specific context of Qatar's climate, emphasizing the importance of adapting knowledge to different environments. Similarly, the "Cool Paint" group's focus on reducing energy expenditure demonstrated knowledge translation. By integrating chemistry and heat transfer principles, they applied their findings to develop solutions for minimizing cooling loads, showcasing the versatility of engineering knowledge across multiple domains. Additionally, the "Printopia" group's work on enhancing the surface finish of 3D-printed prosthetic mold cavities exemplifies knowledge translation in the biomedical and chemical context. Their understanding of chemical treatments and materials science was adapted to improve the precision of biomedical applications, highlighting the interdisciplinary nature of engineering knowledge.

6- Adaptability

The project undertaken by the "Electra-Q" group serves as an example of adaptability. Focused on investigating the influence of extreme temperatures, charging, and discharging rates on Li-ion battery capacity, the group encountered a time limitation due to the extended battery cycle testing required. Demonstrating adaptability, they adjusted their approach by employing smaller batteries to expedite the testing process while still capturing valuable insights. Leveraging local resources and adapting to the constraints of time, the "Electra-Q" group showcased a practical and flexible mindset. This adaptability allowed them to overcome challenges inherent in the extended testing cycles, ensuring that their project remained feasible within the given time frame. The ability to adjust methodologies in response to real-time constraints not only demonstrates adaptability but also prepares students for the dynamic nature of engineering projects in professional settings.

7- Teamwork effectiveness (Motivating different personalities, resolving conflicts, collaboration, coaching, and empowering)

Projects like the sound insulation assessment conducted by the "E&E" group show a diverse skill set within the team that was connected to motivating different personalities, ensuring each member's unique strengths contributed to the project's success. The team demonstrated conflict resolution, collaboration, coaching, and empowerment, creating a collaborative environment where individual contributions aligned with the collective goal of evaluating sound insulating systems. This project not only showcased technical expertise but also highlighted the collaborative spirit essential for effective teamwork in engineering. Within the "E&E" group, each member was tasked with individual tasks related to their interest and expertise. Some members were tasked with finding local insulating materials at low cost, others were tasked with creating a small-scale of university machine shop, and others worked on understanding the acoustics measurements and explaining to their peers. Continuous learning and empowerment strategies ensured each team member took ownership of specific project aspects.

8- Self-leadership (entrepreneurship, passion, driving change and innovation, self-development, ownership, and decisiveness)

"PolyCycle" group during their project on assessing the impact of recycling cycles on PET plastics manufactured in Qatar. The group exhibited entrepreneurial qualities by proactively addressing a critical environmental concern at Qatar's growing economy and plastic waste. Their passion for driving change and innovation was evident as they navigated the complexities of materials engineering. Taking ownership of their project, the group showcased decisiveness in selecting a project aligned with their mission. Their commitment to self-development was apparent in the thorough exploration of recycling cycles' impacts on PET plastics. By employing analysis tools and techniques, such as factorial design, the group exemplified a self-leadership mindset, pushing the boundaries of traditional engineering approaches and innovative thinking necessary for driving positive change in the field of engineering.

These examples highlight how the MEEN 404 DoE Paradigm fosters structured problem-solving skills among students. By guiding them through ownership, technical knowledge acquisition, and work plan development, the curriculum ensures a comprehensive and methodical approach to engineering challenges. This structured problem-solving mindset not only enhances students' ability to address complex issues in diverse fields but also equips them with a valuable skill set for their future professional careers.

Evaluation criteria

The course's evaluation is structured around four key components: presentation performance, laboratory proficiency, report writing, and personal reflective essays. Assessments show positive engagement, increased awareness of modern world problems, and enhanced critical thinking in engineering, which reflect the enhanced ABET outcome scores compared to traditional teaching styles. In practice, this methodology has empowered students to take control of their projects, develop a profound understanding of engineering principles, and apply their knowledge to tackle real-world issues. It encourages excellence in engineering education, endorsing student-led projects and project-based learning.

The assessment methodology is based on three milestones, the first project is scored lower due to the learning curve of MEEN404, which emphasizes the second project. Each project is graded on four aspects report, final presentation/poster, weekly presentations, and lab work as illustrated by Table 2.

Project reflections are individualized writing intensive assignments, which prompt students to engage in a critical reflection on their role in a project, emphasizing the importance of their individual contributions to the overall project completion. Students are encouraged to speak about their specific contributions and recognize the interconnectedness of their efforts with those of their team members. The reflective exercise aims to provide insights into the dynamics of teamwork and highlight the collaborative nature of project work. Additionally, students are prompted to explore lessons learned from the project, identifying key takeaways such as effective communication, adaptability, and time management in the context of collaborative attempts. The assignment encourages students to envision a hypothetical repetition of the project, prompting them to contemplate and articulate changes they would implement based on their reflections.

Furthermore, the assignment guides students to acknowledge and articulate the skills and tools they autonomously acquired throughout the project. This self-directed learning component highlights the adaptability required in complex projects and emphasizes the importance of continuous learning in the context of collaborative work. Overall, the assignment serves as a comprehensive reflective analysis, fostering an understanding of individual growth, teamwork dynamics, and the iterative nature of project-based learning.

Table 2 Grade breakdown

<table>
<tr><td>Project 1</td><td>30%</td><td rowspan="4">Project breakdown</td><td>Report</td><td>40%</td></tr>
<tr><td>Project 2</td><td>40%</td><td>Final Presentation</td><td>30%</td></tr>
<tr><td rowspan="2">Reflection(s)</td><td rowspan="2">30%</td><td>Weekly presentations</td><td>20%</td></tr>
<tr><td>Lab work</td><td>10%</td></tr>
</table>

ABET Score Tracking

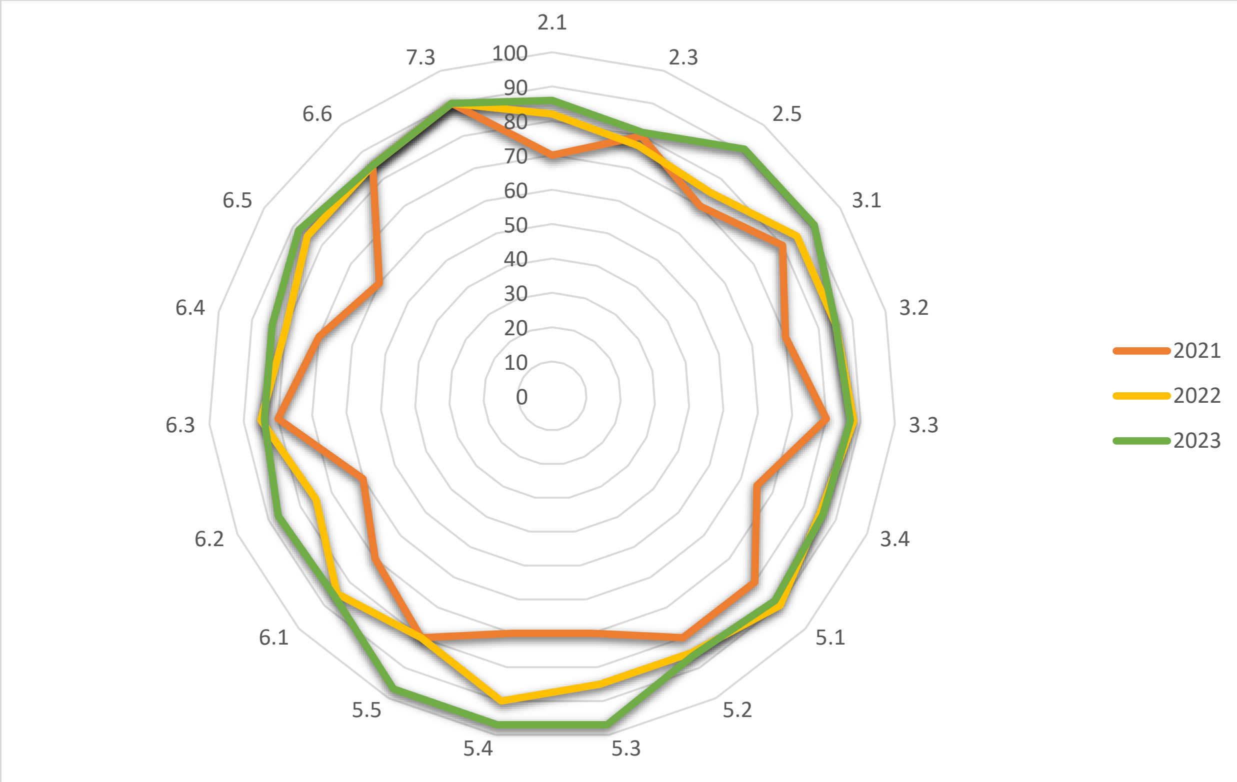

Figure 2 ABET scores for MEEN404 years 2021-2023

There is an improvement in scores from 2021 to 2023, indicating that students are better equipped to ensure the robustness of their DoE. This improvement can be attributed to the emphasis on critical problem-solving, multidisciplinary approach, and real-life engineering challenges integrated into the MEEN 404 methodology. To demonstrate the impact of the paradigm for teaching DoE courses on ABET scores, Figure 2 shows the trends across the three years (2021/2022, 2022/2023, and 2023/2024).

Improvement in ABET Scores:

SO 2.1 - Identify the need statement: Through the MEEN 404 methodology, select real-life problems or propose new product developments to address challenges. This emphasizes the importance of identifying the need statement in engineering projects. The improvement in ABET scores over the years suggests that students have enhanced their ability to identify and articulate the need for their projects, which aligns with the structured approach of the course.

SO 2.3 - Identify appropriate engineering standards for the design: The methodology involves students in real-life engineering challenges, requiring them to ensure the robustness of their designs in terms of public health, safety, and welfare. This indicates that students are exposed to and apply appropriate engineering standards during the design process. While there was a slight decrease in scores in one year, the overall trend shows improvement, suggesting reinforcement of understanding over time.

SO 2.5 - Ensure the robustness of the design in the context of public health, safety, and welfare (FMEA): The improvement in scores over the years indicates that students are better equipped to ensure the robustness of their designs. The projects presented describe how students engage in critical problem-solving, and real-life engineering challenges, which likely contribute to this improvement.

SO 3.1 - Organize presentation/report: The methodology highlights the importance of effective communication through presentations and reports. Students are required to formally meet weekly with the instructor to present their progress, discuss challenges, and present their findings. This structured approach likely contributes to the improvement in scores over the years, reflecting enhanced organization and communication skills among students.

SO 3.2 - Produce meaningful content and visuals: The methodology emphasizes the development of meaningful content and visuals through project presentations and reports. Students are encouraged to effectively convey the significance of their work and findings to varied audiences. The positive outcomes reported in student satisfaction with the learning experience suggest that students are successfully producing meaningful content and visuals, leading to improved scores.

SO 3.3 - Convey problem and technical results to audience (presentation): The weekly progress meetings with the instructor provide students with opportunities to present their progress and findings, enhancing their ability to convey problem and technical results to an audience. The paper indicates that students are actively engaged in these presentations, which likely contributes to the improvement in scores over the years.

SO 3.4 - Respond to questions at oral presentations: The structured approach, including weekly progress meetings, provides students with opportunities to respond to questions at oral presentations. Through these interactions, students develop the ability to effectively address queries and engage in discussions, leading to improved scores over time.

SO 5.1 - Contributes to the team by establishing goals, planning tasks, and meeting objectives: The collaborative nature of the course, where students form teams and work on real-life engineering challenges, fosters teamwork skills. The paradigm describes how students establish goals, plan tasks, and meet objectives throughout the project phases, contributing to improved scores in this outcome over the years.

SO 5.2 - Contribute individually to the project: While the course emphasizes teamwork, students are also expected to contribute individually to the project. The structured approach, including weekly progress meetings, ensures that each student's contributions are recognized and evaluated, leading to improvement in scores over time.

SO 5.3 - Appreciate the contributions of other team members: The collaborative learning environment encourages students to appreciate the contributions of other team members. Through weekly progress meetings and project reflections, students reflect on their team dynamics and recognize the importance of teamwork, contributing to improved scores in this outcome.

SO 5.4 - Respond to conflict: The collaborative nature of the course exposes students to potential conflicts within teams. Through continuous communication and reflection exercises, students learn to respond to conflicts effectively, leading to improved scores in this outcome over the years.

SO 5.5 - Evaluate the work of peers: The structured assessment methodology, including project reflections, provides students with opportunities to evaluate the work of their peers. By reflecting on their own contributions and recognizing the efforts of others, students develop the ability to evaluate peer work, contributing to improved scores over time.

SO 6.1 - Design an experiment to investigate an engineering problem: The methodology involves students in designing experiments to address real-life engineering problems. Through Project 1 and Project 2, students develop the skills to design experiments systematically, leading to improved scores in this outcome over the years.

SO 6.2 - Choose appropriate tools for the experiment: Students are required to choose appropriate tools for their experiments. The structured approach of the course ensures that students have the necessary knowledge and skills to select appropriate tools, contributing to improved scores in this outcome.

SO 6.3 - Employ tools to conduct the experiment: The methodology requires students to employ tools to conduct their experiments, as evidenced by the project descriptions in the paper. Through hands-on experience and guidance from instructors, students develop proficiency in using various tools, leading to improved scores over time.

SO 6.4 - Analyze experimental results using appropriate methods: Students are tasked with analyzing experimental results using appropriate methods, as described earlier. The methodology emphasizes critical thinking and decision-making skills, ensuring that students can analyze results effectively, leading to improved scores in this outcome.

SO 6.5 - Evaluate significance of experimental results: By connecting their findings to real-life engineering challenges, students develop the ability to assess the importance of their results, contributing to improved scores over time.

SO 6.6 - Present details of experiment in an appropriate format: The emphasis on presentation skills in the course ensures that students can present the details of their experiments effectively. Through project presentations and reports, students learn to communicate their experimental methods and results in a clear and concise manner, leading to improved scores in this outcome.

The analysis of ABET scores and the description of the teaching methodology suggests a positive correlation between the paradigm for teaching the DoE course and the improvement in student outcomes. The structured approach, emphasis on real-life challenges, collaborative learning, and comprehensive assessment methodology have contributed to enhancing student engagement, critical thinking, and technical proficiency, thereby aligning with ABET requirements and preparing graduates for the evolving needs of the workforce.

Concluding Remarks

The presented methodology for teaching the DoE Mechanical Engineering course encapsulated in the MEEN 404 Paradigm, represents a transformative approach to engineering education. By integrating multidisciplinary principles, empowering students as leaders, and addressing real-life engineering challenges, this methodology goes beyond traditional teaching methods. The structured problem-solving mindset developed through ownership, technical knowledge acquisition, and work plan development provides students with a comprehensive and methodical approach to engineering challenges.

The impact of this methodology is in the engagement and critical thinking demonstrated by students in their engineering projects. The diverse range of projects conducted, as showcased in Table 1, reflects not only technical proficiency but also the ability to address complex issues in various fields. The chosen examples show how the Paradigm fosters essential skills such as structured problem-solving, work plan development, time management, storytelling and public speaking, knowledge translation, adaptability, teamwork effectiveness, and self-leadership.

These skills are not only crucial for the academic success of students but also prepare them for the dynamic and evolving landscape of the engineering profession. The integrated evaluation criteria, encompassing presentation performance, laboratory proficiency, report writing, and personal reflective essays, ensure a holistic assessment that aligns with the evolving demands of the workforce. The methodology is further substantiated by positive outcomes, increased awareness of real-world problems, and enhanced critical thinking, as reflected in the ABET outcome scores.

The analysis demonstrates a clear alignment between the teaching methodology outlined in the paper and the improvement trends observed in ABET student learning outcomes over the years. By emphasizing structured problem-solving, collaborative learning, real-life engineering challenges, and comprehensive assessment strategies, the methodology equips students with the necessary skills and knowledge to excel in their engineering education and future professional endeavors. The positive impact of this paradigm for teaching the Design of Experiments course underscores its effectiveness in preparing students to meet the evolving demands of the workforce and contribute meaningfully to the field of engineering. Moving forward, continued refinement and integration of such innovative teaching methodologies will be essential in ensuring the continued success and relevance of engineering education in addressing global challenges and driving innovation.

The MEEN 404 Paradigm stands as an example of excellence in engineering education, promoting student-led projects, project-based learning, and the development of a profound understanding of engineering principles. By encouraging students to take control of their projects, fostering a reflective mindset, and endorsing a dynamic learning approach.

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Appendix A: ABET Data for MEEN404

Table 3 ABET Data Summary

Student Outcome	Description	2021/2022	2022/2023	2023/2024
SO 2.1	Identify the need statement	70	82	86
SO 2.3	Identify appropriate engineering standards for the design	80	77	81
SO 2.5	Ensure the robustness of the design in the context of public health, safety, and welfare (FMEA)	70	75	91
SO 3.1	Organize presentation/report	80	85	91
SO 3.2	Produce meaningful content and visuals	70	85	85
SO 3.3	Convey problem and technical results to the audience (presentation)	80	88	87
SO 3.4	Respond to questions at oral presentations	65	85	86
SO 5.1	Contributes to the team by establishing goals, planning tasks, and meeting objectives	80	90	88
SO 5.2	Contribute individually to the project	80	85	86
SO 5.3	Appreciate the contributions of other team members	70	85	97
SO 5.4	Respond to conflict	70	90	97
SO 5.5	Evaluate the work of peers	80	80	97
SO 6.1	Design an experiment to investigate an engineering problem	70	85	86
SO 6.2	Choose appropriate tools for the experiment	60	75	87
SO 6.3	Employ tools to conduct the experiment	80	85	84
SO 6.4	Analyze experimental results using appropriate methods	70	80	84
SO 6.5	Evaluate the significance of experimental results	60	85	88
SO 6.6	Present details of the experiment in an appropriate format	85	85	85
SO 7.3	Assemble a bibliography from sources outside of the curriculum for a project	90	90	90

Table 4 ABET Scores changes

Student Outcome	**Description**	**Change 2021-2022**	**Change 2022-2023**	**Change 2021-2023**
SO 2.1	Identify the need statement	17	5	23
SO 2.3	Identify appropriate engineering standards for the design	-4	5	1
SO 2.5	Ensure the robustness of the design in the context of public health, safety, and welfare (FMEA)	7	21	30
SO 3.1	Organize presentation / report	6	7	14
SO 3.2	Produce meaningful content and visuals	21	0	21
SO 3.3	Convey problem and technical results to audience (presentation)	10	-1	9
SO 3.4	Respond to questions at oral presentations	31	1	32
SO 5.1	Contributes to the team by establishing goals, planning tasks, and meeting objectives	13	-2	10
SO 5.2	Contribute individually to the project	6	1	8
SO 5.3	Appreciate the contributions of other team members	21	14	39
SO 5.4	Respond to conflict	29	8	39
SO 5.5	Evaluate the work of peers	0	21	21
SO 6.1	Design an experiment to investigate an engineering problem	21	1	23
SO 6.2	Choose appropriate tools for the experiment	25	16	45
SO 6.3	Employ tools to conduct the experiment	6	-1	5
SO 6.4	Analyze experimental results using appropriate methods	14	5	20
SO 6.5	Evaluate significance of experimental results	42	4	47
SO 6.6	Present details of experiment in an appropriate format	0	0	0
SO 7.3	Assemble a bibliography from sources outside of the curriculum for a project	0	0	0

Appendix B: Evaluation Criteria, Data and Methods

Program Learning 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.

Measure 2.1 - Identify need

Data 2.1.1 (MEEN 404) - Need statement to design, plan and conduct experiments defined and discussed during regular weekly progress meetings and in the final report.
Method 2.1.1 – grading of the motivation and introduction section of the report and during regular progress meeting discussions and presentations.

Measure 2.3 – Identify appropriate engineering standards
Data 2.3.1 (MEEN 404) – Identified and applied the testing standards for the experiments and tests they conduct. Reported these standards and how they were applied in the experimental work section of their project Reports.
Method 2.3.1 – grading of Experimental procedure section of the Project Reports.

Measure 2.5 – Ensure robustness of design (FMEA)
Data 2.5.1 (MEEN 404) – Identified and understood potential failure modes and their causes in conducting experiments. Examined the effects of failure on the system under test. Quantified the risk associated with the identified failure modes. Carried out corrective actions to address the most serious concerns.
Method 2.5.1 – grading of FMEA sections of Project Reports.

Program Learning Outcome 3 – An ability to communicate effectively with a range of audiences

Measure 3.1 - Organize presentation / report
Data 3.1.1 (MEEN 404) –progress and projects presentations to students and instructors. Written project reports and reflections presented to course instructor.
Method 3.1.1 – grading of project presentations, reports and reflections.

Measure 3.2 – Produce meaningful content and visuals
Data 3.2.1 (MEEN 404) - Do visuals used clearly convey technical information and support the text of the written reports?
Method 3.2.1 – grading of project presentations and reports.

Measure 3.3 – Convey problem and technical results to audience (presentation)
Data 3.3.1 (MEEN 404) – Identified and applied the engineering principles and technical results that govern the work done in their course projects.
Method 3.3.1 – grading of progress and final project presentations.

Measure 3.4 – Respond to questions at oral presentations
Data 3.4.1 (MEEN 404) – Were students able to answer questions about their design of experiment projects?
Method 3.4.1 – observation and grading of progress and final project presentations.

Program Learning 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

Measure 5.1 - Contributes to the team by establishing goals, planning tasks, and meeting objectives

Data 5.1.1 (MEEN 404) – observations of individual contributions to team success.

Method 5.1.1 – instructor's observations of teams' work; peer evaluations from students

Measure 5.2 – Contribute individually to the project

Data 5.2.1 (MEEN 404) – observation and documentation of individuals' work.

Method 5.2.1 – instructor's evaluation of individual student's work; weekly progress

on status, plans, and issues addressed by members of each team; peer evaluation from teammates, and reflection reports

Measure 5.3 – Appreciate the contributions of other team members

Data 5.3.1 (MEEN 404) – Acceptance of input/ideas from all team members.

Method 5.3.1 – Instructor's observation of teams' behavior, peer evaluation from teammates, and reflection reports.

Measure 5.4 – Respond to conflict

Data 5.4.1 (MEEN 404) – How teams respond to conflicts.

Method 5.4.1 – Instructor’s observations of team behavior and student peer evaluations.

Measure 5.5 – Evaluate the work of peers

Data 5.5.1 (MEEN 404) – Students' evaluation of other team members' contributions.

Method 5.5.1 – Peer evaluation of team members.

Program Learning Outcome 6 – An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions

Measure 6.1 - Design an experiment to investigate an engineering problem.

Data 6.1.1 (MEEN 404) – Identify a topic, define a need and motivation, plan, design, conduct and analyze appropriate experiments

Method 6.1.1 – grading of progress reports and presentations, grading of final project reports, and grading of post-project reflections

Measure 6.2 – Choose appropriate tools for the experiment

Data 6.2.1 (MEEN 401) – Select instrumentation for the various measurements to match the anticipated uncertainty requirements. Modify the instrumentation to match budgetary, performance or schedule limitations if necessary.

Method 6.2.1 – Grading the experimental procedure sections of the project reports.

Measure 6.3 – Employ tools to conduct the experiment

Data 6.3.1 (MEEN 404) –Conduct appropriate experiments safely and efficiently to obtain accurate data

Method 6.3.1 –. Observation of students while conducting experiments, grading of progress presentations and project reports

Measure 6.4 – Analyze experimental results using appropriate methods

Data 6.4.1 (MEEN 404) – Apply appropriate statistical analysis to the results including hypothesis testing, analysis of variance (ANOVA) and multiple regression.

Method 6.4.1 – Grading analysis methods, results and discussion section of the project reports, grading of quizzes and written assessments.

Measure 6.5 – Evaluate significance of experimental results

Data 6.5.1 (MEEN 404) – Analyze experimental data for consistency, reliability, significance and define error types, apply various statistical tests

Method 6.5.1 – Grading of results and discussion sections of the project reports, grading of quizzes and written assessments.

Measure 6.6 – Present details of experiment in an appropriate format

Data 6.6.1 (MEEN 404) – Organize and prepare a report describing the justification, objectives, experimental setup and procedure, findings, results, and conclusions of an experiment in writing and orally.

Method 6.6.1 – Grading of the final project reports and presentations

<u>Program Learning Outcome 7 –</u> An ability to acquire and apply new knowledge as needed, using appropriate learning strategies

Measure 7.3 – Assemble a bibliography from sources outside of the curriculum for a project

Data 7.3.1 (MEEN 404) -– Demonstrate ability to find resources such as journal and conference papers, standards, and reports, to help their team in their design of experiment projects, beyond those provided by the course instructor.

Method 7.3.1 – reviewing the reference section in their projects reports and references cited throughout the reports.