Engineering Educators Bringing the World Together
2025 ASEE Annual Conference & Exposition
Palais des congrès de Montréal, Montréal, QC • June 22–25, 2025
Paper ID #48210

Mapping Complex Engineering Problem-Solving in a Capstone Design Project: Insights into Student Performance and Real-World Integration

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1 Introduction

The World Economic Forum (WEF) has highlighted the importance of complex problem-solving in its Future of Jobs reports of 2020, 2023 and 2025, consistently ranking it among the top skills needed for the future workforce [1], [2], [3]. Further, WEF emphasized that skills requiring nuanced understanding, like complex problem-solving, show a limited current risk of replacement by GenAI [1], which highlights its critical importance in current and future jobs regardless of discipline. In engineering, the International Engineering Alliance (IEA), supported by the World Federation of Engineering Organization and the United Nations Educational, Scientific, and Cultural Organization, released the Graduate Attributes and Professional Competencies (GAPC) in 2021, which underscored complex engineering problem (CEP) solving as a crucial competence of all engineering professionals and attributes of all engineering graduates, regardless of discipline [4]. As described under the Washington Accord (WA) standards, the report distinguished engineering professionals from engineering technologists and engineering technicians by being able to deal with CEPs. In terms of engineering education, the same report also shows how CEP is deeply knitted in all the graduate attributes. For example, engineers must not only know how to identify and design creative solutions to any problems, but primarily CEP (i.e., WA2: Problem analysis and WA3: Design/development of solutions). However, recent findings have highlighted deficiencies in the understanding of CEP among engineering educators and students. Phang et al. [5] found that only a minority of educators had a thorough understanding of CEP, primarily incorporating these problems into projects and final examinations. Fernando et al., [6] argued that while senior engineering students believe that they have experienced solving CEP in earlier courses, they do not fully understand what it means and how to classify a problem as CEP. Thus, the relevance and available evidence of how engineering students tackle CEP warrant further and in-depth investigation.

The inclusion of the Philippines as a signatory member of the WA in 2023, through the Philippine Technological Council (PTC), underscores the critical need for Filipino engineering graduates to meet international standards in engineering education. This membership signifies a commitment to ensuring that engineering programs in the Philippines produce graduates capable of tackling CEP, a crucial requirement for global recognition of their qualifications. Given this context, it becomes imperative to explore how CEP is addressed within the Philippine setting, particularly in the capstone design projects that serve as a culmination of engineering students' academic journey.

This study seeks to answer key research questions:

1. Do students deal with CEP in their capstone design project?
2. What themes emerge when the attributes of CEP are mapped out in the capstone design project?
3. What framework can be proposed to guide the integration of complex engineering problem-solving in capstone design projects?

2 Literature Review

2.1 Complex Engineering Problem (CEP) Defined

Originating from critiques of traditional, static approaches to problem-solving, complex problem-solving was conceptualized in the 1970s by Dörner and colleagues, who emphasized the dynamic and exploratory nature of solving problems that evolve over time and allow for multiple solutions [7]. Funke [8] further elaborated on this concept, identifying key characteristics of complex problems, such as their inherent complexity, interconnected variables, evolving situations, lack of transparency, and the presence of multiple, sometimes conflicting goals. This aligns with the work of Chi and Glaser [9], who described ill-structured problems as lacking clear definitions and solutions. Liew et al. [10] also characterized such problems as having diverse and non-linear solution paths, unconstrained by specific content domains. In short, complex problems are real-world problems with multiple possible divergent solutions due to one or more trivial elements of a solution.

In engineering, IEA clearly distinguished engineers from engineering technologists and engineering technicians by means of the ability to solve CEP as shown in Table 1.

Table 1: Range of Problems Dealt by Engineers, Engineering Technologists and Engineering Technicians [4]

Common Stem	Engineer	Engineering Technologist	Engineering Technician
Apply knowledge of mathematics, science, engineering fundamentals, and an engineering specialization…	…as described in the engineer knowledge profile to ***the solution of complex engineering problems.***	…as described in the engineering technologist knowledge profile to *defined and applied engineering procedures, processes, systems or methodologies.*	…as described in the engineering technician knowledge profile to *wide practical procedures and practices.*

IEA defined CEP by giving 7 attributes namely, (a) depth of knowledge; (b) range of conflicting requirements; (c) depth of analysis required; (d) familiarity of issues; (e) extent of applicable codes; (f) extent of stakeholder involvement and conflicting requirements; and (g) interdependence. Table 2 shows these 7 attributes coupled with characteristics that a problem should have for it to be properly called CEP. According to IEA, CEP have characteristic WP1 and some or all of WP2 to WP7. This means that CEP must exhibit "Depth of Knowledge Required" plus at least two or more of the attributes. Otherwise, the kind of problems may fall under either that being solved by an engineering technologist or engineering technician.

Table 2: Attributes of Complex Engineering Problems (CEP) [4]

Attribute	**CEPs** have the characteristic WP1 and some or all of WP2 to WP7:
Depth of knowledge required	**WP1:** Cannot be resolved without in-depth engineering knowledge at the level of one or more of WK3, WK4, WK5, WK6 or WK8 which allows a fundamentals-based, first principles analytical approach.
Range of conflicting requirements	**WP2:** Involve wide-ranging and/or conflicting technical, non-technical issues (such as ethical, sustainability, legal, political, economic, societal) and consideration of future requirements.
Depth of analysis required	**WP3:** Have no obvious solution and require abstract thinking, creativity and originality in analysis to formulate suitable models.
Familiarity of issues	**WP4:** Involve infrequently encountered issues or novel problems.
Extent of applicable codes	**WP5:** Address problems not encompassed by standards and codes of practice for professional engineering.

Extent of stakeholder involvement and conflicting requirement	**WP6:** Involve collaboration across engineering disciplines, other fields, and/or diverse groups of stakeholders with widely varying needs.
Interdependence	**WP7:** Address high level problems with many components or sub-problems that may require a systems approach.

Note: See Appendix A for the definition of each Knowledge Profile for engineers (WKs)

The concept of CEP must be investigated to ensure that engineering graduates are equipped with the necessary skills to tackle real-world challenges that are multifaceted and dynamic. Understanding how students approach and solve CEPs can reveal gaps in education and provide insights for enhancing engineering curricula to better prepare students for professional practice.

2.2 Identify, Formulate, and Solve: Stages of Solving CEP

Student Outcome 1 of the Accreditation Board for Engineering and Technology (ABET) emphasizes that by the time of graduation, engineering students must possess the "ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics" [11]. Similarly, the PTC Student Outcome (e) stipulates that students must demonstrate the "ability to identify, formulate, and solve complex engineering problems" [12]. These outcomes can be viewed as a simplistic framework that divides the process of complex engineering problem-solving into three fundamental stages: **identification, formulation, and solution.**

A. **Identifying CEP**: The first stage involves recognizing and defining the problem within a given context. According to Jonassen [13], identifying problems in ill-structured environments requires students to interpret and frame the situation accurately, often necessitating an understanding of the various interrelated factors. This stage demands a keen awareness of both the technical and non-technical aspects of the problem.
B. **Formulating Solutions to CEP:** Once a problem is identified, the next stage is to devise a strategy or model for solving it. This involves generating hypotheses, selecting appropriate methodologies, and planning the execution of solutions. Funke [8] highlights the importance of dynamic reasoning in this stage, where multiple variables and constraints must be considered to develop viable solutions. The formulation stage bridges theoretical knowledge and practical application.
C. **Solving CEP:** The final stage involves implementing the formulated solution and testing its effectiveness. This phase includes execution, testing, and evaluating outcomes against expected results. This stage integrates hands-on experimentation and theoretical principles to resolve the problem.

2.3 Solving CEP through Design

Solving ill-structured problems, such as CEP, closely mirrors the design process, making design education a fundamental component of engineering curricula [13], [14]. Design education enables students to enhance their problem-solving capabilities by learning to synthesize, integrate, and analyze diverse knowledge areas. Recognizing the significance of design skills, the IEA, ABET, and PTC emphasize design competency as a critical graduate attribute. For example, one of the IEA's graduate attributes, WA3, focuses on design competency: “Design creative solutions for complex engineering problems and design systems, components, or processes to meet identified needs with appropriate consideration for public health and safety, whole-life cost, net zero carbon, and other factors" [4]. The IEA defines engineering design knowledge as encompassing codes, standards, processes, empirical information, and knowledge derived from past designs. Similarly, ABET and PTC mandate that engineering curricula culminate in a significant design experience, where students apply their accumulated knowledge to real-world engineering challenges, adhering to practical limitations and relevant standards [11], [12]. This requirement underscores the notion that CEP are best assessed in design projects, providing a structured yet flexible framework for evaluating students' ability to tackle complex issues.

Further supporting this perspective, Isa et al. [15] found that complex engineering activities are most effectively addressed in projects that require deep engagement with the design process. Their study highlights the capstone design project as a critical venue for assessing CEP attributes, demonstrating how students navigate the intricacies of identifying, formulating, and solving such problems in a practical context. Additionally, studies like Atman et al. [16] illustrate that design projects foster iterative problem-solving approaches, essential for addressing the multifaceted nature of CEP.

Capstone design project provides an ideal setting for investigating CEPs, as it simulates real-world engineering challenges requiring students to apply their knowledge in a practical, integrative manner. This culminating experience allows for assessing students' abilities to identify, formulate, and solve CEPs, offering valuable insights into their problem-solving processes and readiness for professional practice. By engaging in these comprehensive design experiences, students develop not only technical proficiency but also the critical thinking and adaptability necessary for tackling the complexities of modern engineering problems.

3 Methodology

3.1 Research Design

This study employs a single-case qualitative design to explore how engineering students tackle Complex Engineering Problems (CEP) in their capstone design projects. A single-case design is particularly suited for in-depth, contextual analysis of a bounded system [17]. It allows researchers to closely examine specific phenomena within a real-life context, providing rich, detailed insights. In the context of this study, the single case is defined by a group of engineering students engaged in a capstone design project. This project serves as a platform to assess their ability to identify, formulate, and solve CEPs as outlined in the GAPC framework. By focusing on this single case, the study can delve into the nuanced processes and strategies students use, which might be overlooked in broader surveys or multiple case studies.

3.2 Case Selection

The selection criteria of the case is aligned with the aim to conduct an in-depth investigation of how CEPs are tackled in capstone design projects:

1. The project is finished to ensure that the entire design process has been comprehensively documented and analyzed.
2. The project addresses real needs identified through a needs analysis conducted with stakeholders.

3. The project involved the development of multiple potential solutions based on identified constraints and trade-offs.
4. The chosen solution incorporated advanced technologies, demonstrating a high level of technical sophistication and innovation.
5. The final design was developed, tested, and evaluated against the identified real needs of the clients/users.

These attributes make it an exemplary project for exploring how engineering students tackle CEP in capstone design projects.

3.3 Data Collection

Data collection involved a detailed content analysis of the final capstone design project report. The report was divided into sections that correspond to the major stages of solving CEPs as shown in Table 3:

Table 3: Stages of Solving CEP and Sections of Capstone Design Project Report

Stage	Report Section
Identify	**The Problem and Its Background**. This section outlines the context, stakeholders, problem nature, boundaries, and terminology.
Formulate	**Literature Review and State of the Art**. This part reviews existing literature and current technologies or methods related to the problem.
	Design and Development Plan. This section details the design requirements, setting constraints and tradeoffs, and planning the solution and validation.
Solve	**Design Results and Discussion**. This part presents the outcomes of the solution development, validation through testing and evaluation, and reflection on challenges.
	Summary, Conclusion, and Recommendation. This section summarizes the project, draws conclusions, and provides recommendations based on the findings.

3.4 Data Analysis

The capstone design report was segmented according to the stages of CEP. Thematic analysis followed Braun and Clarke's six-phase approach [18], ensuring a structured and rigorous process. To support trustworthiness, coordination with the student group and faculty mentor was maintained to clarify technical content and decision-making. The coding was guided by the IEA's CEP attributes and descriptors, providing a consistent analytic framework. Data were analyzed iteratively using NVivo 14, with matrix coding queries and cluster analysis conducted to explore patterns and relationships between CEP attributes and design stages.

4 Case Description

The case selected for this study is the development of an advanced machine learning-based system for detecting and preventing Coffee Leaf Rust (CLR) in Amadeo, Cavite, Philippines. The project was conducted by five (5) senior Electronics Engineering students mentored by a senior faculty member. The project spanned four (4) terms, approximately 16 months, and culminated in a final technical report of 82 pages, including appendices, diagrams, test results, and stakeholder documentation.

CLR is a severe fungal disease that spreads rapidly and significantly affects coffee yields. Given the impact of CLR on coffee yields, which can occur up to five times a year, this problem embodies the attributes of a complex engineering challenge requiring a sophisticated, multi-faceted solution integrating deep learning, wireless sensor networks, and image processing. Specifically, the following describes the complex problem at hand:

- The system must detect CLR in its early stages to enable timely intervention.
- It must function reliably in remote coffee farm environments with limited infrastructure.
- The design needs to be user-friendly for farmers with limited technical expertise.
- Cost-effectiveness is crucial, given the tight margins of coffee farming operations.
- The labor-intensive nature of traditional CLR monitoring methods underscores the need for automation.

The design process, as documented in the report, reflected not only the final product but also detailed the iterative decision-making, needs assessments, design trade-offs, and stakeholder feedback incorporated at each stage. These elements provided a rich dataset representing the students' problem-solving process, not merely the project outcome.

Collaborating with the Farmers' Information and Technology Services (FITS) Center in Region IV-A, the team identified the dual requirements of functionality and cost-effectiveness. These insights guided the alignment of the solution with both technical specifications and user needs.

Three primary design alternatives were proposed:

1. Drone-based crop monitoring
2. Sensor-based monitoring with an image processing and deep learning notification system
3. An IoT-based system integrating wireless sensor networks and deep learning

These alternatives were evaluated against constraints such as functionality, safety, testing time, cost, and technical expertise requirements. Trade-off analysis highlighted functionality and cost-effectiveness as pivotal factors. Ultimately, the integration of deep learning and wireless sensor networks was selected as the optimal solution, balancing advanced technology with practical application in resource-constrained environments.

The development of the chosen solution encompassed design, development, testing, and evaluation phases. The system's core components included:

- Wireless Sensor Network: For collecting environmental data to predict CLR outbreaks.
- Image Processing: Using a Raspberry Pi-based camera for capturing and analyzing coffee leaf images.
- Deep Learning Algorithm: A CNN model for classifying leaves as healthy or infected.

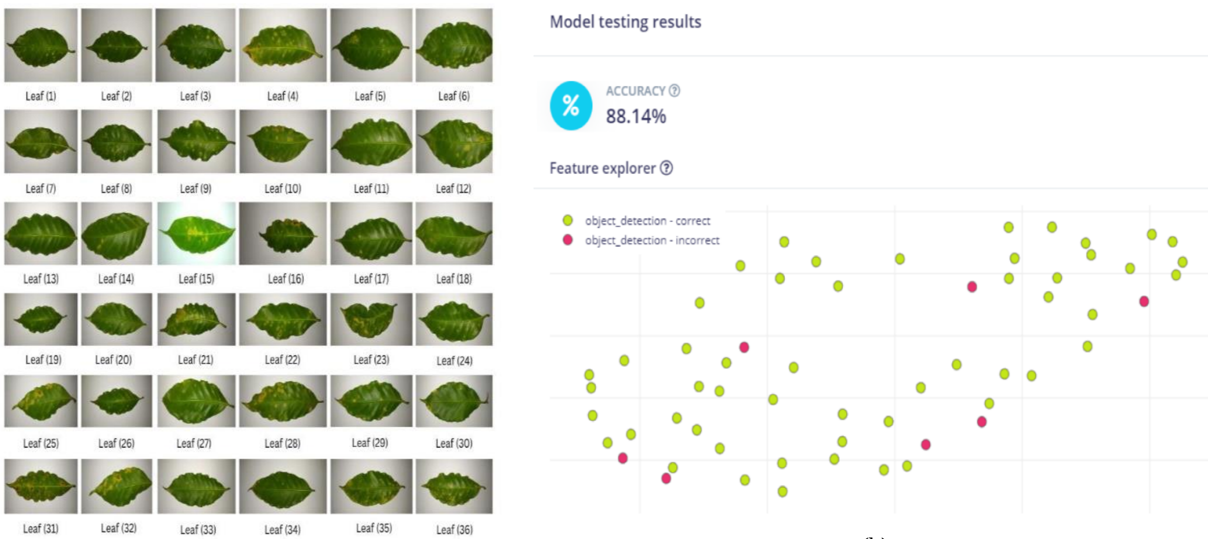
The development process involved hardware assembly, software development, and integration testing to ensure cohesive operation. Comprehensive testing covered:

- Camera Module: Ensuring high-quality image capture under various conditions.
- Microcontroller System: Verifying sensor accuracy in measuring environmental factors.

- Deep Learning Algorithm: Achieving an 88.14% accuracy rate in leaf classification, surpassing the 80% target.

The system prototype was evaluated with feedback from FITS Center experts, who acknowledged its effectiveness and ease of use. Suggestions for improvements, such as enhanced lighting and battery operation, were noted for further refinement.

Overall, the report and project outputs reflect a comprehensive record of both the engineering process and the final product, making it a robust example of a capstone design project that addresses the attributes of a CEP. Figure 1 shows the training data to detect CLR as well as the accuracy test result of the system.



(a) (b)

Figure 1: (a) Sample dataset for leaves with CLR; (b) Accuracy test of the image processing technique.

5 Results and Discussion

5.1 CEP Attributes Throughout the Design Project

The result of matrix coding indicates that all seven CEP attributes were exhibited throughout the design project, as shown in Table 4, showcasing the multifaceted nature of the engineering problem-solving approach taken by the students. The "Identify" stage had the strongest emphasis on WP4 (Familiarity of issues) with 68 occurrences. This indicates a significant focus on understanding and contextualizing the problem, specifically related to Coffee Leaf Rust Disease, which requires knowledge outside the typical electronics engineering curriculum. In the "Formulate" stage, WP2 (Range of conflicting requirements) was the most prominent, with 45 occurrences. This highlights the complexity of balancing various constraints and making trade-offs while formulating the solution. For the "Solve" stage, WP1 (Depth of knowledge required) and WP3 (Depth of analysis required) were most significant with 19 and 20 occurrences, respectively, demonstrating the need for deep technical knowledge and the ability to analyze data generated by multiple technologies to achieve effective problem resolution.

Table 4: Matrix Coding of CEP Attributes Across Stages of the Capstone Design Project Report

Attribute of CEP	Identify	Formulate	Solve
WP1: Depth of knowledge required	20	36	19
WP2: Range of conflicting requirement	3	47	7
WP3: Depth of analysis required	8	29	20
WP4: Familiarity of issues	25	43	4
WP5: Extent of applicable codes	4	1	0
WP6: Extent of stakeholder involvement and conflicting requirements	17	17	7
WP7: Interdependence	3	28	5

On the other hand, WP5 (Extent of applicable codes) had the least occurrence across all stages, with no instances in the "Formulate" and "Solve" stages. This suggests a potential gap in integrating and applying relevant engineering standards and codes during the project, which is a critical area for curriculum enhancement.

Further, WP7 (Interdependence) and WP6 (Extent of stakeholder involvement) were moderately represented, emphasizing the interconnectedness of subsystems and the importance of stakeholder engagement in the design process.

As shown in Figure 2, the cluster analysis is visualized using 3D Cluster Plot to show the proximity of the 7 attributes based on their coding similarity, indicating which attributes are closely related in terms of how they appear or are coded in the data. Items that are grouped closely together share common patterns or are frequently associated.

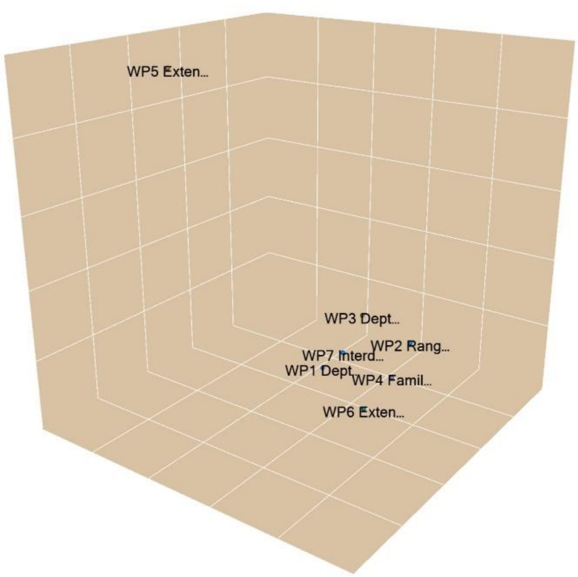


Figure 2: 3D Cluster Plot of the 7 Attributes of CEP Based on Coding Similarity

Figure 2 shows that several attributes such as “Depth of analysis required,” “Range of conflicting requirements,” “Depth of analysis required,” “Familiarity of issues,” “Extent of stakeholder involvement and conflicting requirements,” and “Interdependence” appear closely grouped. This suggests that in CEPs, these factors are interrelated. For example, dealing with a wide range of conflicting requirements often demands a deeper analysis and greater knowledge. However, "Extent of applicable codes," appears somewhat isolated, indicating it may be a distinct factor that is not as closely linked to the others or is unique in its implications within the context of the chosen design project.

The clustering suggests that the solution of CEP in the case considered required addressing multiple, interdependent attributes simultaneously. This interdependence may have necessitated the students to engage in a multidisciplinary approach, as the intricacies of stakeholder involvement, conflicting requirements, and deep analytical needs are closely interwoven. This cluster analysis reinforces the complexity and interconnectivity of various attributes inherent in CEP, highlighting the need for comprehensive, integrated approaches in both education and professional practice.

5.2 Emerging Themes in Solving CEP in Capstone Design Projects

5.2.1 Depth of Knowledge Required (WP1)

As shown in Table 5, “Machine Learning” and “Sensors” emerged as the most frequently coded, emphasizing that students are engaging deeply with cutting-edge technologies that are essential for solutions needed. Although other topics had fewer occurrences, overall, all topics reflect the students' engagement with innovative approaches and emerging technologies. This underscores the necessity for students to develop proficiency in established and emerging technologies, which are pivotal in modern engineering design and development. More emphasis must be given in incorporating courses in advanced technologies and its application within the engineering curriculum. This also underscores the need for interdisciplinary curriculum that includes elements of computer science, electronics, and data science, reflecting the interconnected nature of modern engineering challenges. The integration of real-world projects that require the application of these advanced concepts can help students develop practical skills and deeper understanding that would prepare them for the challenges they will face in their professional careers.

Table 5: Matrix Coding and Sample Texts for WP1 (Depth of knowledge required)

WP1 Codes	Coded Text	Sample Text
Machine Learning	26	“This study investigates cutting-edge machine learning techniques that utilize diverse data sources to precisely identify and diagnose plant diseases.”
Sensors	26	“The proposed project benefited from the integration of various sensors, such as temperature, NPK (Nitrogen, Phosphorus, and Potassium), and humidity sensors, alongside the camera and machine learning.”
Image Processing	19	“For image processing, a convolutional neural network (CNN) on the RPI is utilized.”
Automation	6	“The microcontroller system incorporates the ESP8266 as its core component, serving as the central control unit for seamless communication and coordination.”
New technology	5	“The identified constraints for this design included functionality, safety, testing time, cost, and the need for advanced technological knowledge.”

5.2.2 Range of Conflicting Requirements (WP2)

As shown in Table 6, “Design testing” emerged as the most frequently coded occurrence, emphasizing the importance of testing various design aspects to ensure that solutions meet the conflicting requirements effectively. The high occurrence of “Multiple constraints” highlights the challenges students face in balancing different factors such as cost, time, performance, and resources, which indicates the complexity of decisions that engineers must navigate to find optimal solutions. Both of these topics suggests that students are actively engaging in iterative processes to refine their solutions, reflecting real-world engineering practices. Other topics concur to the idea of CEP being an ill-structured problem that needs exploration of multiple possible solutions, which requires multifaceted requirements and analysis. However, the relatively low occurrence of tradeoff analysis indicates a potential area for improvement in students' ability to systematically evaluate and balance competing factors in their designs. This requires increased emphasis on teaching methods for tradeoff analysis, which will help students develop a more nuanced understanding of how to make balanced decisions. Enhancing project-based learning to include scenarios with multiple constraints and conflicting requirements can provide students with practical experience in handling complex situations. This approach can also foster critical thinking and problem-solving skills.

Table 6: Matrix Coding and Sample Texts for WP2 (Range of conflicting requirements)

WP2 Codes	Coded Text	Sample Text
Design testing	28	“During the test, various scenarios were simulated to assess the capability of the camera module to capture images under different lighting conditions, angles, and distances.”
Multiple constraints	19	“The constraints imposed on the design were functionality, safety, testing time, cost, and the physical capability of the system.”
Alternative solutions	5	“The designers generated three design options: Integration of a Wireless Sensor Network and Deep Learning for Coffee Leaf Rust Prevention, An IoT-Based Monitoring System for Coffee Crops, and Identifying coffee leaf rust using an image processing technique.”
Availability of resources for testing	4	“The test required the following resources: a camera module, Raspberry Pi board, battery for power supply, and other necessary components.”
Tradeoff analysis	1	“Using tradeoff analysis, the researchers analyzed the requirements of each design alternative.”

5.2.3 Depth of Analysis Required (WP3)

As shown in Table 7, “Analysis of data” emerged as the most prominent, indicating that a significant portion of the students’ efforts is dedicated to thoroughly analyzing data to derive meaningful insights and support decision-making. “Identification of solution” is also evident in the project, which is critical as it requires creative thinking and the need for originality in problem-solving. The high occurrence of data analysis underscores the importance of equipping students with robust analytical skills and the ability to handle large data sets, which is essential for developing innovative engineering solutions. On the other hand, the relatively fewer occurrences of choosing and finalizing solutions suggest a potential gap in students’ ability to confidently select and conclude the best course of action from their analyses, pointing to a need for improved decision-making frameworks in the curriculum.

Table 7: Matrix Coding and Sample Texts for WP3 (Depth of analysis required)

WP3 Codes	Coded Text	Sample Text
Analysis of data	25	“The quality of the images was thoroughly assessed to ensure they met the desired standards for accurate disease detection.”
Identification of solutions	17	“However, researchers have identified areas for improvement in the extant systems, particularly with regard to the local farmers, highlighting the need for more effective solutions to address this problem.”

Improvement of design	9	“The results obtained from the tests provided valuable insights and allowed for necessary adjustments and improvements to be made, ensuring a robust and reliable system.”
Choosing the best solution	4	“Among the proposed alternatives, this design solution proves to be the best as it offers higher accuracy in disease detection while being more cost-effective than using drones.”
Finalize solution	3	“Overall, the project yielded a successful outcome, laying the foundation for potential deployment to assist coffee farmers in combating the disease and protecting their crops.”

5.2.4 Familiarity of Issues (WP4)

As shown in Table 8, the high frequency in “Agricultural technologies” suggests that students heavily engaged with new or less familiar technologies specific to agriculture, highlighting their exploration of innovative solutions in this field. Other topics focus on coffee-related matters indicate that students focused significantly on addressing specific aspects of coffee and coffee disease, which are specialized topics they likely had limited prior exposure to. This means that students were tackling issues not commonly addressed in typical engineering curricula, which likely pushed them to apply novel thinking and research. To better prepare students for infrequently encountered issues, the curriculum should incorporate a variety of case studies and projects that expose students to a broad spectrum of engineering challenges, particularly in niche and emerging fields. Courses and workshops that focus on emerging technologies and their applications in different industries, like agriculture, can equip students with the necessary skills to handle less familiar challenges. Integrating interdisciplinary approaches that combine engineering with other fields can enhance students' adaptability and problem-solving capabilities for unfamiliar issues.

Table 8: Matrix Coding and Sample Texts for WP4 (Familiarity of issues)

WP4 Codes	Coded Text	Sample Text
Agricultural technologies	23	“Other innovations, such as a camera module to capture the crop and image processing algorithms to detect pests and illnesses, are employed in this study.”
Coffee disease treatment	14	“Aside from the picking method, farmers use a copper spray to help control the fungal infestation in the plant.”
Coffee disease detection	13	“The goal was to develop a diagnostic model that would continuously monitor the propagation of Coffee Leaf Rust.”
Coffee Disease	9	“The classification of coffee plants into healthy or diseased categories was conducted meticulously by subjecting the dataset to multiple rounds of testing.”
Coffee quality	7	“To preserve quality, coffee farmers around the world today confront three big obstacles: (i) unpredictable climate variations, (ii) nutritional inadequacies, and (iii) pest and disease attacks.”
Coffee in the Philippines	5	“In Luzon part of the Phillipines, Cavite produced 25% of the Luzon coffee production as reported by PSA and one of the top-coffee producing region in the country because it produces quality and best-tasting coffee.”
Agricultural problems	2	“Recent studies indicate that even a 2-degree increase in global temperature will have a significant impact on agricultural productivity, particularly in tropical regions, with the effects deteriorating as temperatures continue to rise.”
Coffee in general	1	“Coffee is made from the ripe seeds of Coffea arabica Linn., a member of the Rubiaceae family.”

5.2.5 Extent of Applicable Codes (WP5)

As shown in Table 9, the emergence of this topic suggests that students engaged with quality standards specific to the coffee industry, which may not be comprehensively addressed by conventional engineering codes. This indicates that students had to consider industry-specific standards beyond the typical scope of engineering design codes. Engineering curriculum should expose students to industry-specific (non-engineering) standards and codes to prepare students for real-world scenarios where they must apply engineering knowledge outside the traditional framework. Interdisciplinary project-based learning can be of big help in exposing students to this need. However, the project did not mention any engineering-related codes and standards considering that the identified solutions are heavily technical. This oversight highlights the critical need to integrate technical standards and codes, particularly those related to advanced technologies (i.e. machine learning, sensors, and image processing for this project) into engineering education. Ensuring that students are familiar with these standards is essential for designing solutions that comply with safety, quality, and performance requirements in technology-driven industries. Incorporating these elements into engineering design education will better prepare students to navigate the regulatory landscape and enhance their ability to develop robust, compliant, and innovative solutions in their professional practice.

Table 9: Matrix Coding and Sample Texts for WP5 (Extent of applicable codes)

WP5 Codes	Coded Text	Sample Text
Coffee quality standards	5	"Furthermore, it identified factors that influenced the occurrence and spread of the disease using different parameters such as soil nutrients, moisture, and wind that were installed in the device and then implemented/applied specific actions."

5.2.6 Extent of Stakeholder Involvement (WP6)

As shown in Table 10, "Stakeholders" had the highest frequency indicating that stakeholder identification and engagement were critical components of the projects. Students had to manage diverse stakeholder interests, which likely introduced complexities in their design process. "Needs analysis" was also dominant, which underscores the importance of understanding and analyzing the needs of different stakeholders, suggesting that students prioritized identifying and addressing the requirements of all involved parties. Likewise, "Evaluation solution" was also relatively high, which shows that students actively involved stakeholders in evaluating the solutions, ensuring that the designs met the varying needs and expectations. This strong focus on stakeholder engagement and needs analysis reflects a comprehensive approach to addressing the complex needs of diverse groups, which may have directly or indirectly impacted students' skills in communication, negotiation, and conflict resolution. Those with less frequency suggest that students gave less attention to selecting appropriate stakeholders and involving them in problem definition and constraint identification. This highlights potential areas where students might need more guidance and practice, particularly in early project stages. Implementing case studies and role-playing exercises that simulate real-world stakeholder interactions can help students develop the necessary skills to navigate complex stakeholder environments. Communication skills must also be strengthen across the curriculum, particularly in multi-stakeholder contexts, to aid students' ability to convey ideas, negotiate solutions, and resolve conflicts. Courses, especially design courses and capstone design projects, must emphasize the importance of stakeholder-centric design processes in the curriculum, which can foster a more holistic approach to engineering problem-solving. It would also be helpful to come up with structured guidelines and tools for stakeholder selection and engagement can help students systematically approach this aspect of the design process, ensuring comprehensive stakeholder involvement.

Table 10: Matrix Coding and Sample Texts for WP6 (Extent of stakeholder involvement and conflicting requirements)

WP6 Codes	Coded Text	Sample Text
Stakeholders	13	“Contributing a solution to the Local Government Unit (LGU) for coffee farmers.”
Needs analysis	12	“After thorough discussions with the people of Farmers' Information and Technology Services, FITS Center of Region IV - A, the researchers gained a deep understanding of the design needs and end-user demands, focusing on functionality and cost-effectiveness.”
Evaluation of solutions	10	“User evaluations by the partner community and intended users contributed valuable feedback for refinement.”
Problem identification	6	“The farm in Amadeo Cavite suffers leaf rust which causes a lesser yield or loss of crop if not tended properly and it often happens as much as five times annually.”
Selection of stakeholders	2	“This location is the best site to consider as it is near Batangas where in 1880 epidemic of coffee leaf rust was the most critical site and the researchers decided to involve the farmers and landowners as collective stakeholders.”
Constraints identification	1	“A detailed discussion with the people of Farmers' Information and Technology Services, FITS Center of Region IV - A, was conducted to identify the constraints.”

5.2.7 Interdependence (WP7)

As shown in Table 11, “Systems with multiple parts” dominates the discussion on interdependence, indicating that students frequently dealt with complex systems composed of various interrelated components. The high number of occurrences suggests that students had to navigate and manage the intricacies of these systems, ensuring that each part functioned harmoniously within the whole. Curriculum should place greater emphasis on teaching systems thinking, where students learn to analyze and understand the interconnected nature of system component, which can be achieved through dedicated courses or integrated project-based learning. Incorporating system modeling and simulation tools in the curriculum can help students visualize and analyze the interactions within complex systems, improving their understanding and problem-solving abilities. Interdependence not only involves systems being designed but also the people who collaborate in the design process. Promoting collaboration across disciplines can expose students to diverse perspectives and expertise, enhancing their ability to manage complex systems with multiple interdependencies. Aside from systems thinking, interdependence does not stop with designing, lifecycle thinking must also be taught, where students consider the full lifecycle of systems, including design, implementation, maintenance, and decommissioning, can prepare them for the comprehensive nature of engineering challenges.

Table 11: Matrix Coding and Sample Texts for WP7 (Interdependence)

WP7 Codes	Coded Text	Sample Text
System with multiple parts	36	“This study presents a well-structured approach, integrating microcontroller systems, wireless sensors, and CNN-based image processing to monitor and assess the health of coffee leaves effectively.”

5.3 Integrating Complex Engineering Problem-solving in Capstone Design Projects

The analysis of each attribute of CEP in the capstone project revealed both effective practices and areas for improvement. A key strength of the case was its alignment with real-world constraints and stakeholder needs, demonstrating practical integration of advanced technologies and interdisciplinary design. However, a notable limitation emerged in WP5 (Extent of Applicable Codes), where students showed minimal consideration of engineering codes and standards beyond basic regulatory compliance. This gap suggests the need to more explicitly embed code-based design thinking within the capstone process. Enhancing faculty mentoring on regulatory integration, exposing students to relevant industry codes early, and requiring documentation of compliance steps throughout the design stages are recommended strategies for strengthening capstone implementation and aligning it with global engineering practice expectations.

Synthesizing all the topics coded, 5 themes emerged as shown in the proposed framework in Figure 3. The framework aims to ensure that engineering students experience complex engineering problem-solving through capstone design projects. It emphasizes the incorporation of knowledge and advanced technologies in an interdisciplinary project-based setting. The framework also promotes consideration of real-world constraints and tradeoffs as an input to iterative design, development, and testing. Additionally, it highlights the importance of stakeholder engagement from identifying their needs to satisfying them with the final solution. Systems thinking must also be given enough attention, as well as consideration to the lifecycle of systems, to ensure that the solutions are both operational and sustainable. Lastly, by integrating industry-specific standards and regulatory frameworks in the design process, solutions are not only assured of being effective and efficient technically, but also satisfy other crucial standards such as ethics. When these components are embedded in capstone design projects, students are better equipped to identify, formulate, and solve CEP effectively.

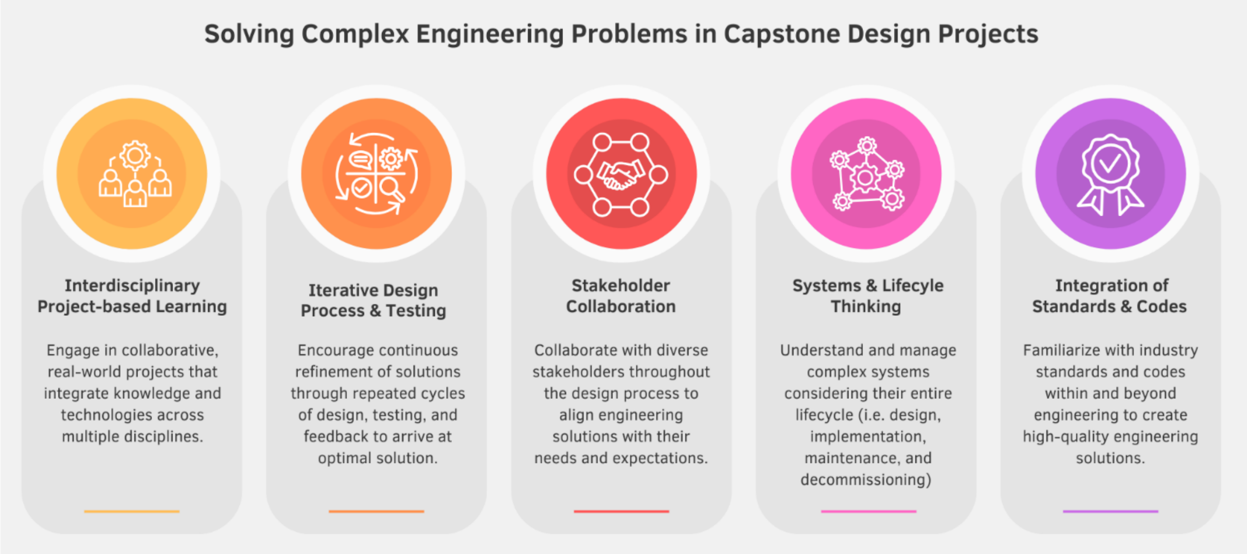


Figure 3: Framework for Solving Complex Engineering Problems (CEP) in Capstone Design Projects

6 Conclusion and Recommendations

The study explored the extent to which students engaged with Complex Engineering Problems (CEP) in their capstone design projects. The research focused on identifying the attributes of CEP exhibited by students during various stages of their projects: identifying CEP, formulating solutions, and solving CEP. The findings revealed that, in the specific case under investigation, the students indeed dealt with CEP in their capstone design projects, exhibiting critical attributes across the project lifecycle, as required by IEA/WA. In identifying CEP, students were able to engage with real-world challenges that demanded innovative thinking and adaptability. During the solution formulation phase, they navigated conflicting requirements and integrated diverse perspectives, highlighting their ability to balance multifaceted constraints. In the problem-solving stage, the students showed proficiency in data analysis and stakeholder collaboration, reflecting their capability to apply theoretical knowledge to practical scenarios. Five key themes were revealed that underscored the students' engagement with complex engineering problem-solving throughout their capstone design experience, namely, Interdisciplinary Project-based Learning, Iterative Design Process and Testing, Stakeholder Collaboration, Systems and Lifecycle Thinking, and Integration of Standards and Codes.

The insights gained from this study suggest several implications for practice in engineering education as conveyed by the proposed framework for solving CEP in capstone design projects. Incorporating interdisciplinary PBL can help students experience real-world engineering challenges that span various fields, enhancing their ability to deal with complex, multifaceted problems. Emphasizing iterative design processes in the curriculum can better prepare students to refine and optimize their solutions in response to evolving requirements and constraints. Encouraging students to engage with stakeholders throughout the project lifecycle fosters essential skills in communication, negotiation, and conflict resolution, which are critical for real-world engineering practice. Embedding systems thinking and lifecycle analysis in the curriculum ensures students understand the interconnectedness of components within a system and their implications over the system's lifecycle. Finally, educating students about relevant technical standards and codes, especially in emerging technologies, prepares them to develop solutions that comply with regulatory and industry-specific requirements.

Based on the study's findings, it is recommended that policymakers in engineering education mandate the inclusion of interdisciplinary capstone projects that incorporate real-world, complex problem-solving scenarios. It is also highly recommended to project-based learning models that align with industry practices, including iterative design and stakeholder engagement. To guide teachers and students, it is suggested to develop guidelines for integrating technical standards and modern engineering codes into capstone projects and related courses. Also, support the creation of partnerships between academia, industry, and government to provide students with practical exposure to complex engineering challenges.

Future research could expand this study by conducting multiple case studies across different institutions to compare how students from diverse backgrounds and curricula approach CEP in capstone projects. In addition to quantitative analysis of how CEP attributes are exhibited in capstone and other design-based courses, qualitative methods, such as focus groups, surveys, and interviews with students, faculty, and project stakeholders, could provide richer insights into how students identify, formulate, and solve complex problems. These methods may further capture perceptions of real-world integration, stakeholder involvement, and the effectiveness of interdisciplinary approaches in capstone experiences. Further work could refine the proposed framework by evaluating its applicability across different institutional contexts and by analyzing its impact on student performance in solving CEP within and beyond capstone design projects.

7 Acknowledgments

The author acknowledges the support provided by the CDP proponents Justenne Queen P. Gonzales, Gabriel Jerdhy D. Lapuz, Aaron M. Delos Reyes, Peter John P. Manabat, Jose Enrique M. Garrido, and their mentor, Herbert V. Villaruel.

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Appendices

Appendix A. Knowledge Profile for Engineers [4]

A Washington Accord (WA) programme provides:
WK1: A systematic, theory-based understanding of the **natural sciences** applicable to the discipline
WK2: Conceptually-based **mathematics**, numerical analysis, statistics and formal aspects of computer and information science to support analysis and modelling applicable to the discipline
WK3: A systematic, theory-based formulation of **engineering fundamentals** required in the engineering discipline
WK4: Engineering **specialist knowledge** that provides theoretical frameworks and bodies of knowledge for the accepted practice areas in the engineering discipline; much is at the forefront of the discipline.
WK5: Knowledge that supports **engineering design** in a practice area
WK6: Knowledge of **engineering practice** (technology) in the practice areas in the engineering discipline
WK7: Comprehension of the role of engineering in society and identified issues in engineering practice in the discipline: ethics and the professional responsibility of an engineer to public safety; the
WK8: Engagement with selected knowledge in the **research literature** of the discipline
A programme that builds this type of knowledge and develops the attributes listed below is typically achieved in 4 to 5 years of study, depending on the level of students at entry.