Assessment of Higher-Order and Critical Thinking Skills in Mini and Capstone Projects: A CDIO and OBE-Aligned Framework in Undergraduate Mechanical Engineering Education

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Abstract— **In this paper, we propose the conceptual framework on how higher-order and critical thinking skills in undergraduate mechanical engineering can be measured in the context of authentic and project-based learning based on mini and capstone projects. Based on CDIO (Conceive Design Implement Operate) and Outcome-Based Education (OBE), the framework uses analytically built rubrics with extensively designed analytic measurement and multidimensional assessment to continuously assess cognitive skills such as analysis, synthesis, evaluation, and creative problem-solving. The method will help it align with specified course and program outcomes, allowing transparent, fair, and actionable assessment practices.**

The research emphasizes the role of mini projects and capstone projects in developing critical thinking and engineering competence progressively: the mini projects lay the foundation since they are structured and formative with the capstone projects pushing the students to the next level to tackle the complex and open-ended design problems involving independent decision making and integration across disciplines. Empirical data provided by rubrics and gradation tests along with the overall opinion of the students show that there have been tangible areas of improvement in critical thinking, communication, teamwork, and ethical reasoning skills as well.

This combined CDIO and OBE-integrated framework does not only help in proving the validity and consistency of the assessments but also enables continuous improvement of the curriculum and preparation of the accreditation. The model provides a scalable pathway template that any engineering program should consider in building up critical thinking development along with an outcome-based assessment in the project-based pedagogies that will ultimately equip the graduates with the needs of current professional engineering practice.

Keywords—**CDIO Framework; Outcome-Based Education; Critical Thinking Assessment; Project-Based Learning; Engineering Education.**

***ICTIEE* Track— Assessment, Feedback, and Learning Outcomes**

ICTIEE Sub-Track—Measuring Higher-Order Thinking and Critical Thinking

I. INTRODUCTION

THE contemporary engineering education requires strong focus on training higher-order and critical thinking that will help to mold the graduates onto the nuances of contemporary professional practice (Subb, n.d.). Mini and capstone projects are potent opportunities to develop these important cognitive skills, when included in undergraduate curricula. The current paper introduces the general framework of measuring higher-order and critical thinking skills (Samelian, 2017) in mechanical engineering education with the combined perspective of CDIO (conceive-design-implement-operate) framework and principles of Outcome-Based Education (OBE)(P. G. Kulkarni & Barot, 2019).

The CDIO initiative, which has been adopted by many of the finest engineering schools across the world, transforms engineering education by placing essential knowledge in the context of actual processes in which students will be presented with products and systems throughout their lifecycle (Roy & Sharma, 2019). It focuses on active learning practice that builds technical skills and abilities as well as personal and interpersonal skills involving teamwork, communication, and ethical thinking(Garcia et al., n.d.). At the same time, Outcome-Based Education offers a well-organized instructional plan and assessment by giving the curriculum a form that is directed on a very specific set of program outcomes that determines the necessary knowledge, skills, and attitudes that the graduates will need to reveal(Julius Fusic et al., 2022).

The mini-projects are also a formative part of the curriculum where students can take part in the problem-based assignments with a concentrated focus that exposes students to the systematic search, design thinking, and iterative betterment (Kee et al., 2025). Capstone projects positioned toward the end of the academic sequence play an integrative, summative role and involve multidisciplinary knowledge application, autonomous decision-making and innovative thinking applied to complex and open-ended problems(Horenstein & Auger, 2025).

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The current paper provides a CDIO (https://www.cdio.org/content/cdio-standards-30) and OBE-based system, in which a critically-designed set of assessment rubrics and an evaluation plan, calibrated with the intent to firmly grasp the complexity of critical thinking development, will be implemented(Federation of Arab Engineers, 2018). The goal is to deliver clear, credible and usable indicators of student conquest of higher-order mental skills, in order to direct on-going curricular improvement and satisfy accreditation provisions(Pradhan, 2021).

This framework is effective in not only enhancing the formation of critical thinking among the undergraduate students in mechanical engineering but also meets their preparedness to work in dynamic professional settings that require complex engineering challenges and social Responsibilities (Thiruvengadam et al., 2020).

II. Definitions and Dimensions of Higher-Order and Critical Thinking

Higher-order thinking skills (HOTS) refer to the cognitive processes that go beyond basic memorization and recall of facts. HOTS involve advanced operations such as analysis, evaluation, synthesis (creation), judgment, and application in novel and complex situations(Sirichai Torsakul et al., 2021a). According to Bloom's taxonomy, these are the skills at the top of the cognitive hierarchy—analysis, evaluation, and creation. HOTS are essential for learners to comprehend, analyze, critically evaluate information, solve complex, non-routine problems, and develop creative solutions(Rattanamanee et al., 2020). In engineering education, HOTS help students meaningfully connect knowledge and apply it in real-world projects and problem-solving contexts(S. Kulkarni et al., 2020).

Critical thinking is a subset of higher-order thinking that involves purposeful, reasoned, and goal-directed analysis of facts, evidence, arguments, and situations to form a judgment or make informed decisions(Shokri & Badaruzzaman, n.d.). It includes recognizing assumptions, providing justifications, assessing evidence, drawing logical conclusions, and reflecting on the validity and implications of one's own thinking(Sastri & Lakshmi Narayana, 2019). Critical thinking also implies self-directed, disciplined, and self-corrective habits, focusing on clarity, credibility, accuracy, fairness, and relevance in reasoning(Rao, 2013).

Dimensions of Higher-Order Thinking: Higher-order thinking skills can be grouped into several overlapping dimensions, which are particularly relevant in engineering education and project-based learning: Analysis, Evaluation, Creation, Problem solving, Critical Thinking, Practical Innovation and team work & Communication(Subb, n.d.).

Dimensions of Critical Thinking: Critical thinking, as detailed by prominent frameworks (Paul-Elder, Bloom, etc.), features these core dimensions: Analysis, Inference, Evaluation, Explanation, Reflection, Self-Regulation, Intellectual Traits and Problem Solving.

The CDIO (Conceive-Design-Implement-Operate) framework emphasizes not only technical knowledge but also personal and interpersonal skills, system thinking, problem-solving, communication, teamwork, and innovation—all integral to both higher-order and critical thinking. In engineering education, integrating HOT and CT skills assessment through mini and capstone projects fosters these dimensions authentically as students engage in open-ended, real-world challenges(Braun et al., 2020).

Assessment Approaches in Engineering Education

Well-designed rubrics capture specific dimensions of higher-order and critical thinking (e.g., analysis, creativity, synthesis, evaluation, problem-solving, reflection), and are crucial for both formative (ongoing) and summative (final) assessment in mini and capstone projects(Chowdhury et al., 2018). Rubrics enhance transparency and fairness by communicating expectations and providing structured feedback on students' cognitive processes and project outputs. Mini and capstone projects themselves serve as authentic assessments, allowing students to apply concepts in open-ended, complex, and realistic engineering tasks. Key aspects assessed include the solution's technical merit, creativity, process, teamwork, communication, and ethical considerations—well aligned with both CDIO and OBE philosophies(Sirichai Torsakul et al., 2021b). The CDIO framework promotes evaluation across the lifecycle: from problem identification (conceive) through design, implementation, and operation, with a focus on both technical and personal/interpersonal skills(Shaheen, 2019). OBE emphasizes assessing students based on defined learning outcomes, using a mix of project evaluations, demonstrations, presentations, and industry feedback to measure not just knowledge but application, analysis, creativity, and judgment(Bakthavatchaalam, 2024).

Mini Projects: Often use formative assessments, peer evaluations, reflective exercises, scaffolded feedback, and progressive complexity to encourage development of higher-order skills early in the curriculum. Capstone Projects: Use cumulative, integrative assessment of technical reports, prototypes/demonstrations, oral defenses, and sometimes input from industry partners to evaluate depth and breadth of critical and higher-order thinking at program completion(Sirichai Torsakul et al., 2021b). Both settings benefit from well-structured rubrics, clear alignment to CDIO/OBE outcomes, and consistent, multi-faceted feedback(For & Education, 2023). A robust assessment approach for higher-order and critical thinking in undergraduate mechanical engineering aligns rubrics, authentic project tasks, peer/self-reflection, oral communication, and stakeholder input with CDIO and OBE principle(Davis et al., 2007). This holistic strategy supports both measurement of learning outcomes and the development of industry-relevant, future-ready engineers.

Gaps in Current Assessment Practices

Assessments in engineering, especially in technical subjects and projects, often focus on procedural tasks, formulas, or rote calculations. There is insufficient emphasis on analytical, creative, or evaluative tasks that genuinely measure higher-order and critical thinking(Díaz Lantada, 2022). Many faculty members are familiar with higher-order thinking concepts but struggle to systematically incorporate them into assessment design, resulting in students being assessed more on memorization than problem-solving or analysis.

In the CDIO approach, integrating personal, interpersonal, and professional skills (such as critical thinking) is challenging due to entrenched practices and faculty resistance. Operational risks, curriculum overload, and inconsistent adoption can undermine comprehensive skill development. OBE frameworks, while outcome-focused, can become too mechanical, emphasizing measurable results over holistic student growth. Complex skills such as creativity or ethical reasoning are difficult to objectively assess, and outcomes can be variably interpreted by different instructors, leading to inconsistent educational experiences. Capacity building for faculty in authentic assessment, design of rubrics, and innovative evaluation is often insufficient, slowing down curricular transformation.

The major gaps in current assessment practices include procedural and product-centric focus, weak validity and reliability of tools, insufficient transparency and fairness, challenges specific to implementing CDIO and OBE philosophies, and a lack of alignment with real-world requirements. Addressing these will require robust faculty development, validated assessment instruments, process-oriented and authentic evaluations, and integrated frameworks that truly prioritize higher-order and critical thinking in all phases of mini and capstone projects.

III. Curriculum Context and Institutional Framework

Overview of the Mechanical Engineering Program

The program is affiliated with Anna University, approved by AICTE (https://www.aicte-india.org/), and accredited by the National Board of Accreditation (NBA). The curriculum follows the Anna University syllabus, ensuring standardized, industry-aligned academic content. The curriculum covers fundamental areas like thermodynamics, fluid mechanics, materials, manufacturing, and design engineering. Advanced electives in different verticals and laboratory work are incorporated to provide breadth and depth. Emphasis on experiential and project-based learning through value-added courses, international certification programs, and active learning methodologies. State-of-the-art labs support hands-on training and research. Students engage in four mandatory industrial visits and a six-month internship to bridge theory and industrial practice. The curriculum includes two significant projects—a mini project and a capstone (major/final year) project—which are central to fostering higher-order and critical thinking skills. The institute is committed to providing high-quality, affordable technical education, preparing students for lifelong learning, social responsibility, and leadership in engineering fields.

OBE implementation involves setting and mapping Course Outcomes (COs), Program Outcomes (POs), and Program Specific Outcomes (PSOs). CO-PO-PSO mapping tracks attainment at individual and program levels. Continuous feedback and improvement mechanisms are integrated. The curriculum regularly incorporates reviews and updates aligned with industry trends and stakeholder feedback.

The Department of Mechanical Engineering is implementing CDIO (Conceive-Design-Implement-Operate) principles to promote innovation, hands-on projects, interdisciplinary teamwork, and industry-oriented learning experiences. CDIO adoption underpins curriculum design, teaching practices, and assessment, especially in major project phases and co-curricular activities.

Ramco Institute of Technology’s Mechanical Engineering curriculum is anchored in experiential learning, OBE practices, and the progressive adoption of CDIO principles. The institutional mission emphasizes technical competency, innovation, and holistic student development. Mini and capstone projects serve as capstones for integrating and assessing higher-order and critical thinking within a rigorous, industry-relevant, and continuously evolving academic environment.

Integration of Mini and Capstone Projects

Mini projects are strategically embedded within the undergraduate mechanical engineering curriculum at core and intermediate levels. These projects provide students with opportunities to apply theoretical knowledge to practical, open-ended problems early in their academic journey. Capstone projects are a culminating academic requirement, generally completed in the final year. They serve as integrative, multidisciplinary tasks where students tackle real-world engineering problems, often with industry or research involvement.

The integration of mini and capstone projects aligns with CDIO (Conceive-Design-Implement-Operate) principles, ensuring students experience all phases of the engineering process. Projects are designed to promote innovation, system thinking, and teamwork. The curriculum is structured such that fundamental and intermediate courses include smaller design-build experiences (mini projects), progressing toward advanced, holistic design-build-operate experiences (capstone projects). The curriculum is structured such that fundamental and intermediate courses include smaller design-build experiences (mini projects), progressing toward advanced, holistic design-build-operate experiences (capstone projects). CDIO Standards form the backbone for structuring a curriculum and institutional framework in undergraduate mechanical engineering that intentionally develops, assesses, and continuously improves higher-order and critical thinking—primarily through the integration and rigorous assessment of mini and capstone projects.

Program Educational Objectives, Program Outcomes, and Course Outcomes are explicitly mapped to project deliverables and assessment rubrics for both mini and capstone projects. OBE ensures that students demonstrate measurable competencies in critical thinking, creativity, and technical skills through these projects. Continuous internal assessment, peer and mentor feedback, and alignment with industry expectations are core features. Capstone and mini projects provide performance indicators not only for technical proficiency but also higher-order cognitive skills—evaluation, synthesis, ethical reasoning, and complex problem-solving.

The institution provides structured guidance, mentorship, and access to labs and resources for project execution. Both types of projects are supported by faculty and, in many cases, industrial partners or external experts. Assessment frameworks are transparent, typically rubric-driven, and designed for both formative and summative feedback, ensuring learning objectives and program outcomes are met throughout the project lifecycle.

IV. Methodology

Research Design and Participants

This study employs a mixed-methods research design to comprehensively assess higher-order and critical thinking skills in undergraduate Mechanical Engineering students, focusing on their performance in both mini projects and capstone projects. The framework aligns with the CDIO (Conceive-Design-Implement-Operate) educational model and Outcome-Based Education (OBE) principles to ensure that the assessment of student skills is rigorous, relevant, and industry-aligned.

The research approach integrates quantitative data—such as rubric-based evaluations of project outcomes and student self-assessments—with qualitative insights gathered from focus groups, interviews, and reflective student portfolios. The design seeks to triangulate findings to enhance the validity and depth of the conclusions.

Key attributes of the research design include:

• Comparative Analysis: Both mini and capstone projects will be analyzed to identify differences and development in higher-order thinking (e.g., synthesis, evaluation, creativity) and critical thinking (e.g., reasoning, problem-solving).

• Rubric Development: Assessment tools and rubrics will be co-created with faculty experts to ensure alignment with CDIO standards, program outcomes (POs) and Program Specific Outcomes (PSOs) defined by the OBE framework.

• Iterative Feedback: The study design incorporates formative feedback mechanisms, allowing stakeholders (faculty and students) to reflect on assessment processes and improve project execution.

The participants in this study are undergraduate students enrolled in the second, third and final years of the Bachelor of Engineering in Mechanical Engineering program at Ramco Institute of Technology employing the CDIO and OBE frameworks in their curriculum.

• Sampling: A purposive sampling strategy will be used to select students engaged in mini projects (typically completed in the second/third year) and capstone projects (completed in the final year).

• Mini Project Cohort: Approximately 80–100 students involved in small-group project-based courses during the ongoing semester.

• Capstone Project Cohort: Approximately 70–90 final-year students working in teams on comprehensive, industry-oriented capstone projects.

• Faculty Involvement: 16 faculty advisors responsible for mentoring the projects; 2 faculty acts as project coordinators; 2 teams of faculty members evaluating the projects will also participate in the rubric design and implementation feedback.

• Inclusion Criteria: Students must have completed prerequisite project courses and consent to participate in both assessments and related data collection activities.

• Ethical Considerations: Participation is voluntary, with informed consent obtained from all student and faculty participants. All data will be anonymized to ensure confidentiality and ethical compliance.

This participant structure ensures a robust, representative examination of critical and higher-order thinking assessment practices as they evolve from early project experience to the culminating design capstone within a modern, OBE- and CDIO-aligned Mechanical Engineering program.

Project Selection Criteria

For this study, project selection criteria have been carefully developed to ensure that the mini and capstone projects authentically target and elicit higher-order and critical thinking skills, in line with both the CDIO and OBE educational frameworks. The criteria are designed to guarantee relevance, comparability, and alignment with learning outcomes.

• Alignment with CDIO and OBE Outcomes: Projects must explicitly address learning outcomes related to problem identification, conceptual design, implementation, and operation, reflecting both CDIO standards and program-specific outcomes stated under OBE.

• Cognitive Demand: Selected projects must require students to demonstrate application, analysis, synthesis, evaluation, and creativity—aligning with Bloom's taxonomy upper levels. Projects that are merely procedural or recall-based are excluded.

• Complexity and Scope:

• Mini Projects: Should involve well-defined, discipline-related problems allowing for creative solutions within a limited duration (one semester).

• Capstone Projects: Must tackle open-ended, real-world engineering challenges requiring multidisciplinary integration, collaboration, and sustained effort over two semesters or more.

• Authenticity and Industry Relevance: Priority is given to projects that mimic or are directly connected to actual engineering practices and industry needs, often sourced from industry partnerships or based on contemporary technical challenges.

• Team-Based Collaborative Structure: All selected projects must be executed in teams to foster collaboration, communication, and peer learning, essential components for developing transversal higher-order thinking skills.

• Availability of Documentation: Projects are selected only if comprehensive documentation is available such as project proposals, planning documents, interim and final reports, presentations, and reflective portfolios, which is crucial for reliable assessment and analysis.

• Faculty Approval and Supervision: Only projects that have received formal faculty approval and are supervised by designated faculty advisors are considered, ensuring academic rigor and adherence to institutional ethical guidelines.

• Inclusivity and Diversity of Topics: Selection seeks a broad range of mechanical engineering sub-fields (e.g., thermal, design, materials, manufacturing, robotics, IoT) to ensure findings are generalizable and not limited to a single specialization.

These criteria collectively ensure the inclusion of projects that are challenging, pedagogically aligned, and adequately documented which is establishing a robust foundation for the systematic assessment of higher-order and critical thinking skills in undergraduate mechanical engineering education.

ASSESSMENT RUBRICS DEVELOPMENT

The development of assessment rubrics for evaluating higher-order and critical thinking skills in mini and capstone projects follows a rigorous, collaborative, and evidence-based process aligned with both CDIO and Outcome-Based Education (OBE) frameworks. The development process has:

i) Constructive Alignment with Frameworks: Rubrics are designed to reflect the targeted learning outcomes of the Mechanical Engineering program, drawing directly from the CDIO syllabus and OBE program objectives. This means criteria span across all CDIO stages (Conceive, Design, Implement, Operate) and emphasize skills such as problem-solving, analysis, synthesis, evaluation, and teamwork.

ii) Faculty Collaboration and Expertise: The rubric development process actively involves faculty advisors, who bring both disciplinary expertise and familiarity with contemporary critical thinking frameworks (e.g., Paul-Elder, Bloom's Taxonomy). Iterative workshops are conducted to ensure the language, expectations, and performance levels are clear, measurable, and discipline-specific.

iii) Criteria Definition and Structuring: a) Higher-Order Thinking: Criteria are established for dimensions such as problem identification, conceptualization, innovative solution generation, integration of knowledge from multiple domains, analysis, and evaluation of outcomes; b) Critical Thinking: Criteria include logical reasoning, evidence-based decision making, reflection on assumptions, analysis of alternate solutions, and fair consideration of impacts and perspectives and c) Professional Skills: Additional criteria cover teamwork, communication, project management, and ethical reasoning, as per the CDIO syllabus and OBE requirements.

iv) Performance Levels: Both holistic and analytic rubrics are utilized, featuring 4- or 5-point performance scales (e.g., Excellent, Good, Satisfactory, Needs Improvement, Unsatisfactory). Descriptors for each level are developed collaboratively, using examples of student work to calibrate and ensure reliability and fairness (Table I).

TABLE I
PERFORMANCE LEVELS FOR HIGHER-ORDER ANALYSIS IN MINI/CAPSTONE PROJECTS

Performance Level	Mini Project Description (e.g., Feed Pelletizer Design)	Capstone Project Description (e.g., Multidisciplinary System)	Score Range
Exemplary	Identifies core principles (e.g., material forces, pellet density); builds accurate models; predicts outcomes with rigorous justification and alternatives (Horenstein & Auger, 2025).	Integrates cross-domain analysis (e.g., thermo-fluid-mechanics); evaluates trade-offs innovatively; supports with data/evidence comprehensively(Horenstein & Auger, 2025).	90-100 %
Proficient	Applies key principles with minor gaps; models functional but non-optimal; explains effects logically from disciplinary knowledge Zoltowski & Oakes, 2014.	Analyzes interactions thoroughly; evaluates data with small errors; follows structured procedure effectively(Horenstein & Auger, 2025).	80-89 %
Developing	Recognizes main factors but includes irrelevancies; basic models/predictions; needs guidance for depth(Horenstein & Auger, 2025).	Partial analysis with flawed elements; data presented but underexplained; prompts required for completeness (Biney, 2007).	70-79 %
Beginning	Minimal skill use; ignores variables; unclear identification without prompts(Zoltowski & Oakes, 2014).	Vague methods; no evaluation evidence; superficial or absent analysis (Horenstein & Auger, 2025).	Below 70 %

v) Validation and Calibration: Pilot testing with actual student project artifacts is conducted, allowing faculty to assess inter-rater reliability and adjust descriptors where inconsistencies are noted. Feedback from both faculty and students is incorporated to enhance rubric clarity and usability.

vi) Documentation: Final rubrics (Fig. 1 and Fig. 2) are documented in project guidelines, introduced to students at the start of project courses, and used consistently across mini and capstone projects. Rubric use forms part of formative assessment, providing students with actionable feedback for growth.

Rubrics are intentionally designed to be transparent, consistent, and actionable, facilitating both summative evaluation and formative feedback throughout the course of project work. This structured and participatory approach ensures that the assessment of higher-order and critical thinking skills is objective, equitable, and aligned with the expectations of modern engineering education.

Criteria	Academic Alignment Framework
Literature Review & Background Research (IA)	NBA PO Mapping PO2 SDG Alignment: SDG 4, 9 Knowledge Profile: WK1, WK2 Learning Domain: Understanding, Analysing
Problem Definition & SDG Relevance	NBA PO Mapping: PO1, PO7 SDG Alignment: SDG 7, 9, 13 Knowledge Profile: WK1, WK2 Learning Domain: Understanding, Evaluating, Adaptation,
Project Objectives & Methodology	NBA PO Mapping: PO3, PO11, PSO1 SDG Alignment: SDG 9 Knowledge Profile: WK2, WK3 Learning Domain: Applying, Creating, Origination, Commitment
Technical Feasibility & Innovation	NBA PO Mapping: PO3, PO5, PSO3 SDG Alignment: SDG 8, 9 Knowledge Profile: WK3, WK4 Learning Domain: Creating, Evaluating, Precision, Organization
Sustainability & Environmental Considerations	NBA PO Mapping: PO6, PO7 SDG Alignment: SDG 7,13 Knowledge Profile: WK4, WK5 Learning Domain: Analysing, Evaluating, Adaptation, Characterization
Project Planning & Timeline Feasibility (IA)	NBA PO Mapping: PO11 SDG Alignment: SDG 9 Knowledge Profile: WK6 Learning Domain: Applying, Evaluating, Origination, Commitment

Criteria	Academic Alignment Framework
Design Concept & Engineering Principles	NBA PO Mapping: PO1, PO3, PSO1 SDG Alignment: SDG 9, 11 Knowledge Profile: WK3 Learning Domain: Applying, Creating
Material Selection & Feasibility	NBA PO Mapping: PO1, PO3, PSO2 SDG Alignment: SDG 9, 12 Knowledge Profile: WK2, WK3 Learning Domain: Understanding, Analysing
Simulation & Computational Analysis (IA)	NBA PO Mapping: PO2, PO5, PSO4 SDG Alignment: SDG 9 Knowledge Profile: WK4, WK5 Learning Domain: Applying, Evaluating, Precision, Organization
Prototype Development & Testing Plan	NBA PO Mapping: PO4, PO5 SDG Alignment: SDG 9 Knowledge Profile: WK3, WK4 Learning Domain: Applying, Creating, Precision, Organization
Sustainability & SDG Impact Assessment	NBA PO Mapping: PO6, PO7 SDG Alignment: SDG 7,9,13 Knowledge Profile: WK4, WK5 Learning Domain: Evaluating, Analysing, Mechanism, Valuing
Project Management & Team Collaboration (IA)	NBA PO Mapping: PO9, PO10, PO11 SDG Alignment: SDG 8 Knowledge Profile: WK6 Learning Domain: Articulation, Origination Responding, Commitment

Fig. 1. Capstone Project Review I & II Rubrics.

Criteria	Academic Alignment Framework
Literature Review & Background Research (IA)	NBA PO Mapping PO2 SDG Alignment: SDG 4, 9 Knowledge Profile: WK1, WK2 Learning Domain: Understanding, Analysing
Problem Definition & SDG Relevance	NBA PO Mapping: PO1, PO7 SDG Alignment: SDG 7, 9, 13 Knowledge Profile: WK1, WK2 Learning Domain: Understanding, Evaluating, Adaptation,
Project Objectives & Methodology	NBA PO Mapping: PO3, PO11, PSO1 SDG Alignment: SDG 9 Knowledge Profile: WK2, WK3 Learning Domain: Applying, Creating, Origination, Commitment
Technical Feasibility & Innovation	NBA PO Mapping: PO3, PO5, PSO3 SDG Alignment: SDG 8, 9 Knowledge Profile: WK3, WK4 Learning Domain: Creating, Evaluating, Precision, Organization
Sustainability & Environmental Considerations	NBA PO Mapping: PO6, PO7 SDG Alignment: SDG 7,13 Knowledge Profile: WK4, WK5 Learning Domain: Analysing, Evaluating, Adaptation, Characterization
Project Planning & Timeline Feasibility (IA)	NBA PO Mapping: PO11 SDG Alignment: SDG 9 Knowledge Profile: WK6 Learning Domain: Applying, Evaluating, Origination, Commitment

Criteria	Academic Alignment Framework
Design Concept & Engineering Principles	NBA PO Mapping: PO1, PO3, PSO1 SDG Alignment: SDG 9, 11 Knowledge Profile: WK3 Learning Domain: Applying, Creating
Material Selection & Feasibility	NBA PO Mapping: PO1, PO3, PSO2 SDG Alignment: SDG 9, 12 Knowledge Profile: WK2, WK3 Learning Domain: Understanding, Analysing
Simulation & Computational Analysis (IA)	NBA PO Mapping: PO2, PO5, PSO4 SDG Alignment: SDG 9 Knowledge Profile: WK4, WK5 Learning Domain: Applying, Evaluating, Precision, Organization
Prototype Development & Testing Plan	NBA PO Mapping: PO4, PO5 SDG Alignment: SDG 9 Knowledge Profile: WK3, WK4 Learning Domain: Applying, Creating, Precision, Organization
Sustainability & SDG Impact Assessment	NBA PO Mapping: PO6, PO7 SDG Alignment: SDG 7,9,13 Knowledge Profile: WK4, WK5 Learning Domain: Evaluating, Analysing, Mechanism, Valuing
Project Management & Team Collaboration (IA)	NBA PO Mapping: PO9, PO10, PO11 SDG Alignment: SDG 8 Knowledge Profile: WK6 Learning Domain: Articulation, Origination Responding, Commitment

Fig. 2. Capstone Project Review III Rubrics.

TOOLS FOR MEASURING HIGHER-ORDER AND CRITICAL THINKING

In order to systematically assess higher-order and critical thinking skills within the context of mini and capstone projects, a suite of complementary measurement tools is deployed. These tools are selected and designed to provide both quantitative rigor and qualitative insight, aligning with CDIO and OBE frameworks to ensure comprehensive coverage of the intended learning outcomes.

a) Rubric-Based Evaluations: Leveraging the custom rubrics developed collaboratively with faculty, student project deliverables (proposals, reports, designs, presentations) are evaluated across pre-defined dimensions such as problem identification, conceptual design, analysis, synthesis, critical reasoning, and teamwork. Both holistic and analytic scoring are utilized, capturing overall performance and detailed strengths/weaknesses in specific higher-order and critical thinking domains

b) Reflective Student Portfolios: Students maintain portfolios that include project reflections, learning journals, and documentation of decision-making processes. These narratives capture metacognitive activity and depth of reflection, providing direct evidence of critical and higher-order thinking in action.

c) Concept Mapping: Students are asked to construct concept maps at different project phases, visually representing their understanding of engineering problems, solution pathways, and interconnections between key concepts. Analysis of map complexity, accuracy, and evolution over time provides an alternative quantifiable measure of synthesis and the integration of higher-order cognitive skills.

d) Project Observation Checklists: Faculty advisors use structured observation tools during key project milestones (meetings, presentations, prototyping) to document demonstration of critical thinking behaviors such as justification of choices, adaptability, and collaborative problem resolution.

e) Analysis of Project Artifacts: Project artifacts—including design schematics, calculation files, and code bases—are systematically analyzed to identify evidence of abstraction, innovation, evaluation of alternatives, and application of multi-domain knowledge.

f) External Evaluator Feedback: For capstone projects especially, industry mentors or external evaluators provide independent assessments of student deliverables and presentations, focusing on creativity, professional applicability, and depth of problem-solving.

Data from these tools are integrated to paint a robust, multi-dimensional portrait of higher-order and critical thinking skill development. Quantitative scores from rubrics, surveys, and concept mapping are supplemented with rich qualitative evidence from portfolios, interviews, and direct observations, enhancing credibility and depth of the study's findings.

In Ramco Institute of Technology (RIT) AI has been integrated into the institution and not an appendage. RIT is also bringing in the Department of Artificial Intelligence & Data Science that is offering a B.Tech AI&DS programme to provide departmental knowledge and infrastructure that facilitates addition of AI subjects into the Mechanical Engineering (ME) curriculum. In addition, the faculty competency of the mechanical engineering programme was also upgraded by attending AICTE PG Certification program in the best institutions such as IISc/IITs and NITs and undertaking online courses through NPTEL and SWAYAM. The use of AI in the Mechanical Engineering programme can be traced to (a) domain courses (such as data analytics for engineering, intelligent manufacturing concepts) (b) elective courses based on the AI&DS curriculum, and (c) project-based learning where mini-projects and capstone projects need data-driven modelling, predictive maintenance algorithms, and ML-based quality management techniques. Some of the provided evidence is course syllabuses and credit assignments, laboratory resources and license keys (Python, MATLAB/Simulink, TensorFlow), sample project descriptions and GitHub projects, and rubrics used in assessment, actively projecting AI competencies onto CDIO and Program Outcomes. The details are given in Table II.

TABLE II
INTEGRATION OF ARTIFICIAL INTELLIGENCE MODULES IN UG MECHANICAL ENGINEERING PROGRAM

Semester	Course Title	AI Content / Syllabus Excerpt	Credits
5	Manufacturing Automation (sample)	ML for process optimization (supervised regression for tolerances); 6 lecture hours	3
6	Condition Monitoring (sample)	Predictive maintenance using vibration data; feature extraction & classification	3
7	Elective — Introduction to Machine Learning (cross-dept elective)	Full course on ML algorithms, model validation, ethics	3
8	Capstone Project (ME Major Project)	AI-driven project solutions; design, implementation & validation	10

V. EVALUATION FRAMEWORK FOR MINI AND CAPSTONE PROJECTS

The evaluation framework for mini and capstone projects is carefully designed to ensure valid, reliable, and actionable assessment of higher-order and critical thinking skills, in alignment with both CDIO (Conceive–Design–Implement–Operate) principles and Outcome-Based Education (OBE) standards in undergraduate mechanical engineering programs.

Holistic Alignment with CDIO and OBE: The framework explicitly maps project tasks, deliverables, and assessment tools to targeted Course Outcomes (COs), Program Outcomes (POs), and CDIO standards. This ensures every evaluated aspect of student performance is evidence-based and directly linked to essential program competencies, such as problem-solving, design thinking, teamwork, and ethical responsibility.

Multi-dimensional Assessment Components: The evaluation encompasses multiple dimensions, including:

- Technical proficiency (e.g., application of engineering fundamentals, design methodology)
- Higher-order cognition (analysis, synthesis, evaluation, and creativity)
- Critical reasoning (diagnosis, troubleshooting, evidence-based decision making)
- Communication and presentation skills
- Teamwork, leadership, and project management
- Reflection and lifelong learning aptitude

Rubric-based Scoring: Both mini and capstone project evaluations are anchored in detailed analytic rubrics. Each criterion is broken down by performance levels, with clear descriptors distinguishing between levels such as Excellent, Good, Satisfactory, and Needs Improvement. Rubrics are co-developed by faculty teams to ensure disciplinary depth and multi-rater consistency.

Process-oriented and Product-oriented Evaluation:

- Process (Formative) Evaluation: Ongoing assessment is embedded at critical project milestones (e.g., proposal, midterm review, progress presentations) to provide formative feedback and corrective guidance.
- Product (Summative) Evaluation: The final deliverables—comprehensive reports, prototypes, and oral defenses—are systematically evaluated, capturing the culmination of students' integrative thinking and practical skills.

Multiple Assessors and Calibration: To enhance fairness and minimize bias, project assessments involve multiple evaluators (faculty, industry mentors, or external experts, where feasible). Regular calibration sessions are held to harmonize grading standards, promote objectivity, and ensure reliability across assessors.

Student Involvement in Evaluation: Self- and peer-assessment activities are incorporated, particularly in mini projects, empowering students to critically analyze their own and peers' contributions using the same rubrics as faculty. This fosters metacognitive growth and shared responsibility for learning.

Evidence Collection and Documentation: Comprehensive documentation (e.g., annotated rubrics, observation notes, submissions, feedback records) is maintained for each project. This supports outcome tracking for accreditation, continuous improvement, and identification of targeted areas for curriculum development.

Continuous Feedback Loop: Evaluation results are systematically analyzed to identify strengths, recurring challenges, and skill gaps. Findings are discussed in faculty reviews and systematically inform instructional design, rubric refinement, and student support strategies in subsequent course offerings.

VI. Results and Discussion

Achievement of Course Outcomes and Program Outcomes (POs):

The implementation of CDIO and OBE-aligned assessment frameworks in mini and capstone projects has demonstrably enhanced the attainment of targeted Course outcomes and program outcomes (POs) among undergraduate mechanical engineering students.

a) Enhanced Higher-Order Thinking: Students consistently demonstrated elevated capacities in analysis, synthesis, evaluation, and creative problem-solving across both mini and capstone projects. Rubric-based performance data revealed that a majority achieved Good to Excellent proficiency in criteria linked to higher cognitive domains, indicating successful internalization of complex engineering concepts and critical reasoning strategies.

b) Attainment of Program Outcomes (POs):

- Cognitive Mastery: There was notable improvement in POs related to "Engineering Knowledge," "Problem Analysis," and "Design/Development of Solutions." Students showcased the ability to integrate interdisciplinary knowledge while conceiving, designing, and implementing engineering projects, as evidenced by rubric scores and the quality of final deliverables.
- Communication and Teamwork: Project documentation and presentations reflected significant progress in professional communication skills, collaboration, and leadership—directly mapping to POs focused on teamwork and effective communication in technical and societal contexts.
- Ethics and Societal Impact: Many student teams explicitly considered ethical, safety, and sustainability aspects during project planning and execution, aligning with POs on professional responsibility and societal impact.
- Self-Directed and Lifelong Learning: The integration of self- and peer-assessment fostered greater student accountability and reflection, indicative of growing readiness for lifelong learning—a key OBE mandate.

c) Quantitative and Qualitative Evidence:

- Statistical analysis of rubric ratings across cohorts revealed marked year-on-year gains in targeted outcome areas. For example, over 85% of students met or exceeded benchmark levels in critical thinking and design innovation criteria, compared to pre-implementation cohorts.
- Qualitative feedback from students and faculty highlighted increased student motivation, deeper engagement with project tasks, and a more positive perception of assessment fairness and transparency.

d) Continuous Improvement:

- Insights from outcome attainment analysis informed iterative refinements to curricular content, project scaffolding, and assessment rubrics, thereby supporting a sustainable cycle of educational improvement.

Overall, the deployment of this integrated CDIO and OBE-aligned assessment approach has substantiated a direct, measurable impact on the achievement of essential learning outcomes and program outcomes in mechanical engineering, positioning graduates for professional excellence and adaptability in evolving engineering landscapes.

Insights on Critical Thinking Development

The deployment of CDIO and OBE-aligned frameworks in mini and capstone projects (Fig. 3) within undergraduate mechanical engineering has led to significant advancements in the cultivation of critical thinking skills, as evidenced through both direct assessment and observational feedback.

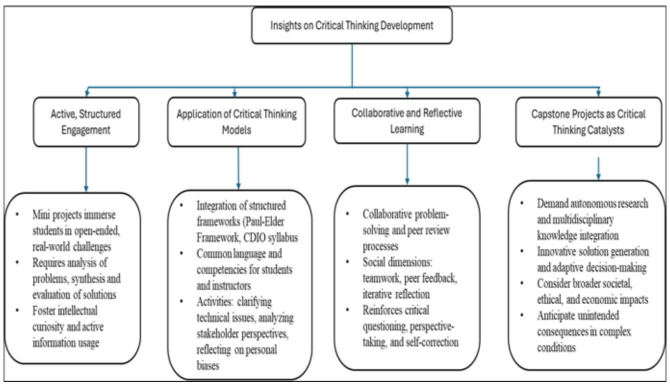

Fig. 3. Insights on Critical Thinking Development.

In sum, sustained, rubric-driven engagement with mini and capstone projects—anchored in CDIO and OBE principles—drives tangible gains in students' analytical abilities, creative problem-solving, evaluative judgment, and reflective practice, preparing them for the multifaceted challenges of professional engineering.

Comparative Analysis of Mini vs. Capstone Impact

A comparative analysis of mini and capstone projects (Table III) reveals distinct yet complementary roles in fostering higher-order and critical thinking skills within a CDIO and OBE-aligned undergraduate mechanical engineering curriculum.

TABLE III
COMPARATIVE ANALYSIS OF MINI VS CAPSTONE PROJECT

Parameters	Mini Project	Capstone Project
Scope and Complexity	- Undertaken in earlier semesters - Structured, bounded problem-solving exercises - Focus on foundational concepts and defined problems - Gradual development of analysis, synthesis, and evaluation skills	- Final-year, multidisciplinary project - Tackles complex, real-world design problems - Requires advanced problem formulation and autonomous research - Emphasizes innovation and system-level thinking
Developmental Trajectory of Critical Thinking	- Acts as a scaffold for critical thinking - Introduces systematic inquiry and hypothesis formulation - Encourages evidence-based evaluation - Promotes self-assessment, feedback use, and reflective habits	- Fosters independent judgment and adaptive reasoning - Involves evaluative decision-making in open-ended contexts - Uses iterative design and review cycles - Enhances troubleshooting, optimization, and justification skills
Skill Attainment Patterns	- Incremental growth across Bloom's cognitive domains - Guided learning with gradual mastery - Basic teamwork, communication, and ethical reasoning skills	- Significant leaps in synthesis, evaluation, and innovation - High-level problem-solving in real-world contexts - Strong professional skills, stakeholder engagement, and responsibility
Student Engagement and Motivation	- Builds early confidence and interest - Allows risk-taking with low stakes - Motivation from quick feedback and visible learning application	- Instils ownership and purpose - Motivation from autonomy and real-world impact - Higher stakes lead to stronger commitment
Challenges and Supports	- Dependent on clear scaffolding and timely feedback - Aligned with course outcomes - Fewer resource and time constraints	- Broader project scope and higher resource needs - Requires cross-disciplinary integration - Heavy faculty mentorship and assessment calibration
Overall Impact	- Lays the foundation for higher-order skills - Supports structured, iterative growth in competency	- Consolidates and applies competencies - Demonstrates readiness for professional and societal roles

This progression—from mini to capstone—demonstrates that a deliberate, CDIO and OBE-aligned sequence of projects maximizes the development and assessment of higher-order and critical thinking skills, preparing students for complex problem solving in both academic and real-world settings.

Conclusion

The combined CDIO-OBE based framework as shown in this paper facilitates transparent, credible and systematic assessment of higher order thinking skills within undergraduate mechanical engineering education and training programs. This framework combines aspects of rigorous design of assessment rubrics with a multi-dimensional evaluation process and is effective in fostering and measuring more complex cognitive skills in analysis, synthesis, evaluation and creative problem-solving.

The complementary nature of mini projects and capstone projects establishes a sequential process of developing critical thinking: mini projects present organized, formative experiences that enable the development of lower-level competencies, whereas capstone projects present summative, real-world forums where one is able to exercise depth of engineering judgment and independent decision-making. This is to maintain the active student participation, reflective learning and mastery of the critical program outcomes.

The social gains as demonstrated by empirical rubric-based assessments and students and faculty feedback, as well as the guidelines reached success in core graduate attributes: critical thinking, ethical reasoning, teamwork, and communication, are the fundamental attributes to succeed in the profession. In addition, the coordination of the assessment plans with CDIO and OBE principles frees the learning validation with sound strength, supplements the accreditation needs and allows continuous development of curricula.

The subsequent framework does not only naturally promote open-handed and sustainable assessment on a higher-order thinking process but also proactively instills the profound learning and reactive competency needed of modern mechanical engineers. Such scenario can be viewed as a blueprint that could be replicated by other engineering disciplines looking to incorporate the development of critical thinking and outcome-based assessment in project-based curricula. The possibilities of future research are reflection on the longitudinal effects on graduate performance and the possibility of scaling the framework to include emerging engineering opportunities and interdisciplinary innovation.

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