Project-Based Learning (PBL) for Developing Critical Thinking Skills in Engineering Students

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Abstract

This full paper explores project-based learning as a pedagogical tool for cultivating critical thinking and scientific reasoning skills among engineering students. While critical thinking and scientific reasoning are central to the world of engineering, they are often not explicitly taught in conventional engineering curricula. Recent innovations in engineering education have included teaching these essential skills through dedicated courses. However, these new courses rely on traditional lecture-based pedagogy typically used in the humanities, which has proven ineffective for engineering students. Alternative pedagogical approaches, such as peer-to-peer learning and flipped classrooms, provide more engaging and contextualized learning experiences, particularly for skill-based courses. The novel approach which is investigated in this research paper is the use of project-based learning as an effective pedagogy to teach an intensive theoretical course on critical thinking. The course, titled 'The Art of Thinking and Reasoning', was designed and taught to 137 first-year students, aiming to instill in them the cognitive skills of critical thinking and scientific reasoning in an engineering context. The course was structured in two parts: the first part employed traditional lecture-driven pedagogy, and the second part utilised a project-based learning approach. Each part included an assessment, the first assessment was a traditional assignment focused on conceptual and reflective thinking through the writing of scripts. It challenged students to envision the future of critical thinking, scientific reasoning, and inquiry, by writing out a 'Future Manifesto'. In contrast, the second assessment required students to compare and revise Bloom's Taxonomy and build a taxonomy of engineering thinking in four stages of a project. Through this exercise, students critiqued existing models and proposed a new taxonomy tailored to engineering problem-solving. This project-based assignment necessitated that students apply their thinking skills in a concrete and hands-on manner, effectively bridging theory and practice. This paper argues that project-based approaches are more effective in embedding critical thinking skills in engineering students by introducing engineering-specific stages that reflect the practical and iterative nature of problem-solving. The practical engagement required by the taxonomy project better mirrors the problem-solving nature of engineering, making it a more suitable method for developing critical and innovative thinking.

Keywords: Project-based Learning, Learning Environment, Humanities, Engineering Curriculum, Pedagogy

Introduction

Thinking is the systematic transformation of mental representations of knowledge to characterize actual or possible states of the world, often in service of goals [1]. Mustafina suggests that 'engineering thinking' is a special type of thinking which is formed and revealed during technical problem-solving, which ‘provides quick, accurate and original solving aimed at meeting technical knowledge, ways and technique demands to create technical means and technologies’ [2]. Engineering thinking is not innate; it is a learned skill that requires consistent engagement with a broad spectrum of fields to explore and understand problems deeply. Allsopp acknowledges the potential disconnect engineering students may feel between theoretical pedagogy and their preferences for active learning approaches. In his work, he argues for embracing new modes of thought and digital tools to bridge this gap and create a more engaging learning experience for students [3]. These ideas resonate with the current need to move beyond traditional theory-based pedagogy used in teaching courses to engineering students and create a learning environment that fosters critical thinking using innovative and student-centred pedagogies for engineering students.

This paper explores initiatives at Plaksha University in India aimed to encourage cognitive skills such as critical thinking among engineering students. The initiative was a two-credit course titled ‘The Art of Thinking and Reasoning’ (AoT) taught to second-semester students. The course structure included a theory-based lecture delivery pedagogy in the first half of the semester, followed by a project-based learning (PBL) approach in the latter half. The course aimed to teach how to meticulously develop the skills of thinking, reflecting, and enquiring critically, as well as being able to reason scientifically with evidence. The first part of the course, ‘On Being Human’ was taught using the conventional lecture-based pedagogy. It explored the essence of being human, questioning thought processes, and addressed the fundamental question about the nature of thinking. The second part of the course, named ‘Deconstruct Thinking’, critiqued Bloom’s taxonomy. While influential for over 70 years, Bloom's taxonomy has faced criticism, including a revision in 2001. The course offered a critical engagement and critique of Bloom’s taxonomy and proposed a taxonomy of thinking that is suitable for the field of engineering. However, this part of the course was taught using a PBL pedagogy, which required the engineering students to build a new taxonomy of engineering thinking. This research aims to investigate if the PBL approach is effective in teaching critical thinking to engineering students. To assess the effectiveness of the PBL pedagogical approach, as opposed to the traditional lecture-based approach, we used end-of-course student feedback surveys to gauge student course perceptions and evaluation of project submissions to identify student performance in the course. We performed statistical analysis to find out if the PBL approach was more effective in teaching thinking skills to engineering students. Thus, this paper examines the effectiveness of implementing a PBL approach to foster critical thinking in engineering students.

Background

The question addressed in this research is to evaluate the effectiveness of PBL pedagogy in teaching critical thinking skills to engineering students. The traditional engineering pedagogy focuses on learning through lectures to build foundational knowledge where students predominantly absorb information. Engineering thinking is oriented to solving non-standard problems arising during the production process. Modern engineering is integrative, combining design, creativity, and resource management to create objects with specific characteristics [4].

The peculiarities of engineering thinking, including its unique principles and norms, worldview guidelines, and ethical components and ideals, form the basis of the creative nature of engineering [4], [5]. Key aspects of engineering thinking include identifying contradictions (logical, technical, or physical) and applying imagination. This leads to the transformation of ideas into tangible technologies, balancing technological, ethical, and aesthetic considerations to achieve desired outcomes. In contrast, critical thinking allows engineers to re-approach old problems with creativity, flexibility, and a desire to improve the world around them. Engineering thinking, on the other hand, is done with the activity of design or production in mind. Thinking is an active process for engineers which is quite different from philosophical thinking, which requires a contemplative posture of removing oneself from the world of activities. Thus, the role of critical thinking in engineering education goes beyond the laboratory.

According to Marin and Steinert, critical thinking is 'thinking aimed at forming a judgement, i.e., making up one's mind about what to believe or do'. Critical thinking is a fruitful way to form judgements about values, especially in cases of emerging technologies [6]. Core critical thinking skills are interpretation, analysis, inference, explanation, evaluation, and self-regulation. According to Facione, good critical thinkers approach specific problems, questions, and issues with clarity, orderliness, diligence, reasonableness, care, persistence, and precision. [7]. Some of the studies which have explored teaching thinking skills in engineering classrooms suggest that engineering students must 'ask questions' [9]. According to Masek and Yasmin, 'critical thinking' has the following principles:

(i) Analysis = identifying and examining ideas and arguments.

(ii) Inference = drawing conclusions.

(iii) Interpretation = clarifying meaning through categorization and translation.

(iv) Self-regulation = self-assessment and reflection.

(v) Explanation = justifying results, arguments or procedures.

(vi) Evaluation = assessing arguments. [8]

Teaching critical thinking is as important for an individual as being educated. Past research points out that teaching critical thinking is about teaching students to appropriately use concepts, principles, and procedures so that they can produce fruitful outcomes and critical judgments. Additionally, critical thinking has an important implication for the transfer of knowledge and application of problem-solving skills to novel situations [8]. Traditional teaching models are based on the premise that students must know the theories to apply them in solving a problem. The PBL approach reverses this order, positing that students acquire knowledge by actively engaging in the process of solving a problem [12], an aspect that results in a higher quality of information [13]. This relates to the thesis put forward by Merrill that learning is actualized when knowledge is applied and integrated into the real world [14].

Research Questions

1. How does the implementation of PBL impact the development of critical thinking skills among engineering students?

2. How does PBL compare to traditional lecture-based pedagogy in developing critical thinking and scientific reasoning skills in engineering students?

The hypothesis tested in this research is that a PBL approach could be a more effective pedagogical alternative for teaching thinking skills to engineering students as it enables the students to have direct contact with the object of study and ends with the realization of a work project by the students which was initially proposed by the teacher [10], by applying their knowledge and skills [11].

Methodology

Data was collected from a total of 137 engineering students from the second semester of Plaksha University. The course was divided into two parts: part one was taught using the traditional lecture-based pedagogy and part two of the course was taught using the PBL approach. The first section of the course focused on exploring fundamental philosophical questions: What does it mean to be human? and What does it mean for a human to think? This section encouraged rigorous, nonlinear inquiry into structures, assumptions, and beliefs that shape human thought and behaviour. The second section of the course sought to deconstruct the activity of thinking itself. It critiqued Bloom's taxonomy and encouraged students to develop a revised engineering thinking taxonomy. Different instructors taught each of the two sections, ensuring that the pedagogical styles, teaching methodologies, and course materials remained independent and distinct. The course aimed to enhance students' cognitive abilities such as critical thinking, scientific reasoning, and structured argumentation. The structured transition from reflective inquiry to applied taxonomy building allowed students to engage with both conceptual and applied aspects of thinking.

A comparative methodology was used to analyze student performances in parts one and two of the AoT course. Comparison is a fundamental tool of analysis. It sharpens our power of description and plays a central role in concept formation by bringing into focus suggestive similarities and contrasts among cases. Comparison is routinely used in testing hypotheses, and it can contribute to the inductive discovery of new hypotheses and to theory-building. A central and legitimate goal of comparative analysis is assessing rival explanations [15].

This data analysis method allows for a deeper understanding of how students' performance varied in these two parts of the course by analyzing assessment results, participation levels, and responses to different pedagogies. This comparative methodology enabled a critical enquiry into the pedagogical approaches used to determine which was more effective in fostering critical thinking skills among engineering students.

Data was collected in three stages: For part one of the course, performance data of student submissions of a script on ‘Future Manifestos’ from the top six student teams consisting of 30 students were graded by the Teaching Assistants (TAs) of the course. For part two of the course, performance data of student submissions of Videos and Scripts on the new engineering thinking taxonomy of the top six student teams consisting of 30 students were graded by the Teaching Assistants (TAs) of the course. Finally, In-person interviews of 3 teams consisting of 15 students were conducted by the research team, comprising open-ended questions were conducted to assess student perceptions of the two parts of the course.

Data Analysis and Findings

Analysis of the performance data of parts one and two was done using the below 10-point rubric:

Table 1: 10-point Rubric

Criteria	**Weightage**
Analytical Thinking	10%
Critique (Critical Thinking)	10%
Application of Concepts	10%
Creativity & Innovation	10%
Clarity of Thought	10%
Relevance to Engineering Thinking & Observational Skills	10%
Reflective Thinking	10%
Engagement with Readings and Course Material	10%

Aesthetic Sensibility	10%
Collaboration & Intra-Group Communication	10%

The rubric was designed using the following reasoning:

1. Linearly independent metrics: This rubric is a metric tool for generating a radar chart due to its design, which ensures minimal overlap and maximal synergy.

2. Weightage: The equal weightage (10%) assigned to each criterion creates a balanced graph where no single metric dominates, ensuring a holistic view of student abilities.

3. Capturing the salient features of the course: The rubric is designed to evaluate all the forms of thinking that were taught in the course.

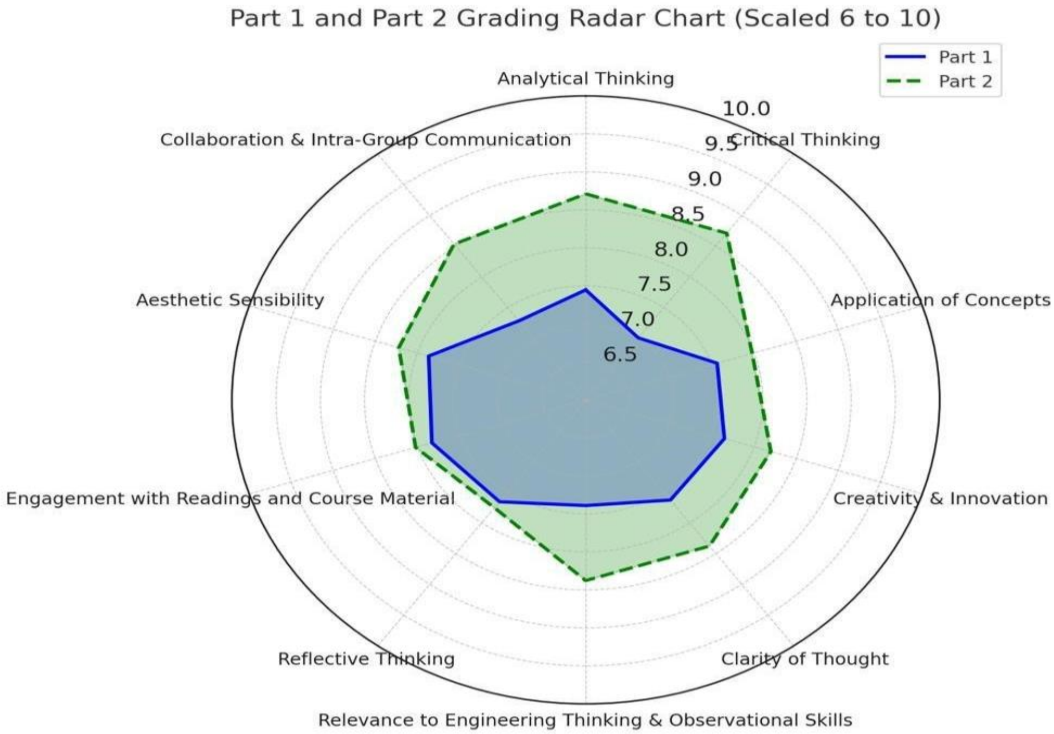
A radar chart was used to analyse the performance data of parts one and two of the course using the 10-point rubric. The radar chart provides a comprehensive comparison of student performance for part one and part two assessment submissions of the course. Peaks and valleys in the graph offer actionable insights, enabling educators to identify and address specific areas for improvement. Additionally, the radar chart facilitates comparative analysis of individual performances, group trends, and ‘pre and post’ assessment progress, making it an effective visualization for both assessment and targeted skill development (critical thinking, scientific reasoning, discernment of cognitive processes).

Table 2: Analysis of Both Parts using 10-point Rubric

Metric	**Analytical Thinking**	**Critical Thinking**	**Application of Concepts**	**Creativity & Innovation**	**Clarity of Thought**
Part 1	7.45	7.01	7.56	7.65	7.6
Part 2	8.71	8.71	7.98	8.20	8.38

Metric	**Relevance to Engineering**	**Reflective Thinking**	**Engagement with Readings and Course Material**	**Aesthetic Sensibility**	**Collaboration & Intra-Group Communication**
Part 1	7.39	7.66	7.83	7.87	7.29
Part 2	8.38	7.76	8.02	8.22	8.53

Figure 1: Radar Chart showing Grading of Parts One and Two



The results show that the PBL approach encourages students to engage more deeply with different types of thinking through their involvement in the projects. A table with values has been created so that scores of student submissions from both parts of the course can be compared. The quantitative performance data shows the efficacy of the PBL approach, thus proving the hypothesis of this research. Finally, in-person semi-structured interviews were conducted to gain student perceptions of both parts of the AoT course. The interview questions revolved around three parameters concerning course submissions. The three parameters are AI utilization, involvement of critical thinking and allocation of time to do the assignments. Below is the thematic analysis of the interview responses to questions for both parts of the course.

Table 3: In-Person Interview Analysis

Metric	Analysis of 'The Future of Thinking Manifesto' (Part One)	Analysis of PBL Video (Part Two)
AI Utilization	The average AI-generated content of all 15 students is about 80-85% generated using AI tools such as ChatGPT, primarily for structuring, content creation and research. The team relied heavily on class	AI tools were used to a lesser extent for elaborating ideas and content creation, complemented by paraphrasing and incorporating research papers. Around 30% of the content was AI-generated and later

	notes and ideas taught in class which were fed into AI models to generate texts.	rephrased. As citations and references were required for all ideas put forward.
Critical Thinking	Minimal to no critical thinking was involved. The teams claimed that they did not incorporate concepts taught in class or engage deeply with the assignment's subject matter. Most content was based on classroom understanding without deeper engagement.	Moderate critical thinking was involved, particularly in designing taxonomy structures. The team engaged in collaborative problem-focused discussions and debates. Critical thinking was exercised especially in designing the engineering thinking taxonomy. The team engaged in in-depth and thought-provoking discussions, including debates on taxonomy levels, which were resolved through voting.
Work Time Allocation	Work commenced the night before the deadline, indicating poor time allocation for deeper cognitive processes to take place. The assignment started a day before the deadline.	Work began a week in advance, with daily contributions. However, time management issues arose due to uneven participation. The project was initiated 7-10 days before the deadline allowing for preparation and contribution from all team members.

All ethical protocols were followed during the in-person interviews to minimize potential biases, utilising triangulation methods. The Teaching Assistants (TAs) and the research team independently graded the assignments and reviewed the grading to ensure consistency and reliability. Both qualitative and quantitative data, including assignment grades and interview responses, were collected and analysed.

Discussion of Results

The above analysis of the interviews showed that in part one of the course, while doing the Manifesto assignment, the dependence on AI lessened critical student involvement and limited their skill development. While doing this assignment, students used a lesser degree of their cognitive skills and mostly relied on concepts taught by the instructor. In contrast, students were more deeply engaged in part two of the course, which took the PBL approach. The students spent significantly more time collaboratively reflecting and thinking to create their respective taxonomies and the video to showcase their findings. The students even devised different creative ways, including skits, to explain their project through storytelling. They also reviewed various research papers to deepen their understanding of the concepts. Another fruitful outcome was that the use of AI tools was comparatively less for part two of the course. Thus, one could say that creating an engineering thinking taxonomy and the video, which followed the PBL pedagogy, proved to be a better approach for teaching critical thinking skills to engineering students. Importantly, the key takeaway was that project-based learning not only fosters critical thinking and creativity but also enhances essential soft skills like teamwork, communication, and research. These outcomes highlight the significance of using project-based pedagogy in engineering education.

Conclusion

This research sought to evaluate the effectiveness of Project-Based Learning (PBL) pedagogy in teaching critical thinking skills to engineering students. The question at the heart of this investigation was to determine how the implementation of PBL impacts the development of critical thinking skills among engineering students and how it compares to traditional lecture-based pedagogy in fostering these essential skills and scientific reasoning. To address this, the study analysed performance data from 137 second-semester engineering students who undertook a two-part course. The first part employed traditional lecture-based teaching, assessed through a 'Future Manifesto' script. The second part utilised a PBL approach, where students developed and presented a revised taxonomy of engineering thinking, assessed through videos and scripts. Furthermore, in-person interviews were conducted with student teams to gather their perceptions of both parts of the course, focusing on AI utilisation, critical thinking involvement, and time allocation.

The data analysis, using a 10-point rubric and a radar chart for performance comparison, alongside thematic analysis of interview responses, provided key insights. The quantitative performance data indicated the efficacy of the PBL approach. Notably, the interviews revealed a significantly higher level of engagement and moderate critical thinking involvement during the PBL-based taxonomy project compared to the minimal critical thinking reported in the lecture-based 'Future Manifesto' assignment, where AI was heavily relied upon. Students allocated more time and collaborated more actively during the PBL phase.

The results of this research indicate that the PBL approach is a more effective pedagogical alternative for teaching thinking skills to engineering students. The very act of undertaking the project necessitated students to actively exercise various forms of thinking, fostering not only critical thinking and creativity but also enhancing crucial soft skills such as teamwork, communication, and research. While traditional lectures have importance, this research argues that a PBL pedagogy offers a more engaging framework for developing critical thinking skills by requiring students to actively apply their knowledge and skills in a concrete and hands-on manner that mirrors the problem-solving nature of engineering.

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