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Facilitating Critical Thinking in Engineering Students: An Exploration of Effective Methods

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ABSTRACT

CONTEXT:

The urgency of integrating critical thinking (CT) skills in engineering education is becoming increasingly important due to the escalating complexity of modern engineering challenges. Traditional teaching methodologies often fall short in fostering CT skills, necessitating a shift towards more interactive and problem-solving centric educational practices.

PURPOSE:

This study aims to investigate the different pedagogical strategies employed in teaching CT skills within the engineering education framework. This encompasses an examination of their prevalence, the range of CT skills they aim to nurture, and their overall effectiveness in enhancing these skills among engineering students.

APPROACH:

The study adopts a comprehensive literature review as its methodology, analysing 23 relevant articles. The analysis encompasses a wide array of teaching strategies from General, Infusive, Immersion, and Mixed methods to formulate an effective CT skills pedagogical framework.

OUTCOME:

The outcomes indicate a significant preference for problem-based learning strategies, particularly those involving case studies grounded in real-world situations, leading to a marked improvement in CT skills. The study proposes an innovative teaching framework, offering a practical roadmap for educators to enhance CT skills in engineering education by integrating suitable engineering units, proposing scaffolded learning across the course, and designing an effective rubric for different academic levels.

CONCLUSIONS:

The research concludes that a shift towards problem-based learning strategies can offer a robust solution to enhance CT skills in engineering students. By providing a detailed framework and the rationale behind each element, the study aims to guide engineering educators in preparing their students for real-world problem-solving challenges.

KEYWORDS: Critical thinking, Engineering Education, Teaching Methods, Problem-based Learning, Scaffolded Learning.

Introduction

Engineering is a dynamic and evolving discipline that serves as the cornerstone of societal development and technological innovation. This domain requires professionals who can deftly handle not only the technical aspects of the field but also grapple with the wider, more complex issues that characterise the evolving landscape of engineering projects. Consequently, engineers with strong critical thinking (CT) skills have become an imperative in today's world. CT skills are an amalgamation of various high order cognitive abilities, including but not limited to problem-solving, decision-making, logical thinking, and the capacity for independent thought (Prayogi et al., 2019). These skills allow engineers to analyse problems from various perspectives, contemplate possible solutions and their implications, and eventually reach well-reasoned conclusions. Recognising the paramount importance of these CT skills, several prominent professional bodies and regulatory organisations have taken a proactive stance. They have reinforced the necessity of these skills by mandating their inclusion in engineering curricula. For instance, Engineering Australia (EA), the premier body for the engineering profession in Australia, has firmly integrated CT skills into its competency standards. Specifically, five of the 16 mandatory elements of EA's Stage 1 competency standards emphasise the requirement for CT skills (EngineersAustralia, 2019). The importance of CT skills for engineering students is also reiterated across various educational resources and literature, further highlighting the consensus regarding their indispensability (Ahern et al., 2012).

Despite the near-universal recognition of the pivotal role of CT skills in the engineering field, there are considerable challenges in effectively nurturing these skills among engineering students. The prime challenge lies in successfully fostering these higher-order cognitive skills while ensuring the students' robust comprehension of the engineering sciences' fundamentals. Essentially, engineering education faces the complex task of marrying in-depth theoretical understanding with the capacity to apply this knowledge to solve real-world problems. This conundrum presents an enduring challenge that educators and curriculum designers grapple with daily.

To address these complexities, educators have implemented a myriad of pedagogical strategies with the shared goal of nurturing CT skills among engineering students. These strategies include active learning environments where students play an engaged and interactive role in their own learning journey, thereby bridging the gap between passive information acquisition and active knowledge construction (Lumb & Blowers, 1998; Taverna et al., 2019). Also employed are real-world case studies that enable students to tackle concrete engineering problems, thereby fostering an understanding of the practical application of theoretical concepts (Bonney, 2015). Another tactic is the use of student portfolios that encourage self-assessment and reflective thinking, thereby inculcating metacognitive skills integral to CT (Lam, 2016).

At a more systemic level, several structured frameworks have been proposed and implemented to foster CT skills in engineering education. For instance, the FRISCO model—Focus (argument), Reasons, Inference, Situation, Clarity, Overview (H. Ennis, 1996) is designed to promote analytical thinking by helping students question underlying assumptions, critically evaluate available evidence, and derive reasoned conclusions. Similarly, the IDEAS technique—Identify, Determine, Enumerate, Assess, Scrutinize (Facione, 2011) urges students to break down complex problems into smaller, more manageable components, promoting methodical and meticulous thinking.

Given the diversity of these pedagogical strategies, they can be broadly classified into four categories: 'general', 'infusion', 'immersion', and 'mixed' (Eldridge, 2010; Ennis, 1989).The 'general' mode primarily aims to teach CT skills independently of any subject-specific content, whereas the 'infusion' mode integrates CT instruction within the existing subject content with clearly articulated CT objectives. The 'immersion' mode, on the other hand, places students in challenging learning situations and expects them to utilise their CT skills without explicit CT instruction. The 'mixed' mode combines elements from the general mode with either the infusion or immersion modes, offering a tailored teaching methodology to fit the unique requirements of specific learning environments.

However, evaluating the effectiveness of these pedagogical approaches in cultivating CT skills is a daunting task. It requires a comprehensive understanding of the myriad factors at play, including the learning environment, the students' prior knowledge and aptitudes, the teaching methodology employed, and the specific engineering discipline under consideration. This challenge is compounded by the absence of a universally accepted assessment methodology for CT skills. Current methodologies vary widely in their approach and robustness. They range from direct methods such as standardised tests and exams, which provide quantifiable measures of CT skill acquisition, to indirect methods such as surveys and self-report measures, which provide qualitative data on students' perceptions and attitudes towards the acquisition of CT skills (Ruminski & Hanks, 1995).

Several standardised assessment methods exist, such as the Halpern CT Assessment (de Bie et al., 2015), the California CT Disposition Inventory (Facione N., 1994), and the Cornell CT Test (Ennis, 1993). However, their suitability and effectiveness are highly variable and context-dependent. Other methods, including open-ended questions (Ku, 2009), reflective writing (Richardson & Maltby, 1995), and peer assessments (Macpherson, 1999), offer alternative avenues for CT skill assessment. Yet, these methods too have their limitations and applicability constraints. These issues underscore the nuanced challenge of assessing CT skills and further highlight the need for a comprehensive, robust, and nuanced approach to CT skill evaluation.

Given these complexities and challenges, this study aims to provide a systematic review of the teaching methodologies currently employed in engineering education to cultivate CT skills, while simultaneously evaluating their effectiveness. This comprehensive review will involve a meticulous analysis of English language literature conducted in three sequential steps: identification of relevant articles, initial screening of these articles, and a deep-dive analysis of the selected articles.

The search for relevant articles will be conducted across several search engines such as SCOPUS, Web of Knowledge, and Google Scholar, targeting peer-reviewed journals. The focus will be on studies related to teaching CT in engineering courses at higher education universities, published between 2004 and 2022. This will ensure the review incorporates the most recent advancements in CT instruction and the evolving landscape of engineering education.

The initial screening process will entail identifying articles that provide clear descriptions of the learning strategy employed, the research method utilised, and the use of CT for the assessment of engineering students. Furthermore, the articles will be further assessed to ensure they provide information about the field of engineering, the duration of the experiment, the approaches to teaching CT, and the skills developed in students by using the CT approach.

The selected articles will then be analysed to provide an in-depth discussion about the intervention approaches, the various aspects of CT, such as problem-solving and analytical skills that students gained, and the effectiveness of these strategies. This analysis will provide invaluable insights into the teaching methodologies for CT in engineering education, their effectiveness, and potential gaps or limitations.

This systematic review will offer a crucial contribution to the discourse on effective methods for instilling CT skills in engineering students. It will elucidate potential avenues for future pedagogical advancements and offer significant implications for refining teaching practices, enriching engineering curricula, and equipping future generations of engineers with the necessary critical thinking abilities to tackle the complex challenges of future.

Research Methodology:

This research employs a systematic review approach, a structured methodology that amalgamates extensive literature sources to answer the defined research questions: What teaching methods have been used in engineering education to nurture critical thinking, and how effective are these strategies? This approach is designed to be transparent, rigorous, and repeatable, providing an in-depth analysis of existing scholarly work. The process of the systematic review has been bifurcated into three primary stages:

Stage 1: Identification of Relevant Articles

The initial stage involves the recognition of pertinent articles. This stage is vital as it sets the foundation for the entire review. To ensure the relevance and credibility of the information, the search was focused on articles published in English from the years 2004 to 2022 in distinguished peer-reviewed journals, which were sourced from various academic databases and search engines such as SCOPUS, Web of Knowledge, and Google Scholar.

The primary purpose of the search was to pinpoint studies that dwell on the strategies adopted for teaching critical thinking (CT) in engineering courses within higher education universities. To further refine the search and align it with the objective of the study, articles that merely provided an overview of CT or those that focused only on the assessment aspect were omitted. The search process employed a series of keywords:

(“Critical thinking” OR “Critical thinking skills” OR “Soft skills” OR ”analytical thinking”) AND (“higher education” OR “universities” OR “tertiary education” OR “engineering student”).

This approach of using specific search terms ensured a comprehensive and targeted search, focused on acquiring the most relevant articles.

Stage 2: Screening Method

Following the identification of articles, an initial screening was executed to select relevant literature. This stage is essential for weeding out articles that do not provide substantial value to the research. The inclusion criteria were set to retain only those articles that provided a lucid description of the learning strategy, elaborated on the research methodology, and used CT as a yardstick for assessing engineering students.

The articles that met these primary inclusion criteria were further scrutinised. This scrutiny evaluated if these articles sufficiently disclosed information concerning the specific field of engineering, the duration of the experiment, the methods adopted to impart CT, and the resultant skills honed in students via the CT approach. This two-fold screening process ensured that the articles selected were germane and insightful, providing a robust foundation for the succeeding stage of the review.

Stage 3: Discussion and Results

The final stage involved a comprehensive examination of the articles shortlisted for review. The selected articles were meticulously analysed, with a focus on their intervention strategies, the various aspects of CT (such as problem-solving and analytical skills) that were developed in the students, and an evaluation of the effectiveness of these strategies. The goal of this stage was not only to summarise and analyse the findings from each individual study but also to identify and discuss any patterns, trends or insights that emerged when considering the studies as a whole.

By synthesising the data from the reviewed articles, this systematic review aims to provide a comprehensive understanding of the current pedagogical practices related to the teaching of CT in engineering education and their effectiveness.

Results and discussion

Our analysis of 23 studies in this research highlights the pressing need for pedagogical practices in engineering to transition from the traditional teacher-centred approaches towards student-centred paradigms (Ahern et al., 2012; Asunda & Hill, 2007; Barroso & Morgan, 2012; Baytiyeh & Naja, 2017; Catalano & Catalano, 1999; Chang & Wang, 2011; Claris & Riley, 2013; Fedorinova et al., 2018; Galand et al., 2012; Godfrey et al., 2014; Huntzinger et al., 2007; Jonathan Stolk & Martello, 2015; Kelley, 2009; Liu et al., 2014; Masek & Yamin, 2012; Nazir, 2010; Pan & Allison., 2010; Sahin, 2010; Stouffer et al., 2004; Tseng et al., 2013; Vogt, 2008; Woods et al., 2000; Yadav et al., 2010). Emphasizing this paradigm shift, a significant part of the literature suggests four distinct methods employed to foster critical thinking (CT) skills: General, Infusive, Immersion, and Mixed.

Figure 1 presents a visual depiction of the distribution of these teaching methods in the analysed literature. The data from this figure indicates a dominant trend towards Infusive, Immersion, and Mixed methods, with 28% Infusion, 33% Immersion, and 36% Mixed methods. The relatively low representation of General methods (3%) implies that direct standalone instruction of CT skills might not be the most preferred strategy in engineering education.

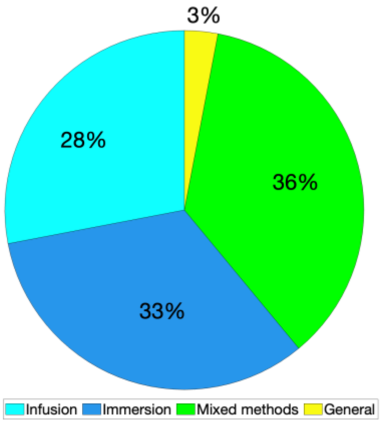

Figure 1. Prevalence of various approaches for teaching critical thinking skills

The Infusive, Immersion, and Mixed methods primarily leverage problem-based learning, project-based learning, and case-based studies that engage students in real-world project solutions. The applied and hands-on nature of these methods appears to significantly facilitate students' understanding of complex problems and development of CT skills (Masek & Yamin, 2012). This resonates with the current pedagogical focus of many universities that seek to align academic learning with industry requirements by developing skill sets to solve authentic, industry-valued problems.

Interestingly, despite the distinct focus on teaching CT skills, a clear and comprehensive definition of these skills remains elusive in a significant number of these articles. Nevertheless, the analysed literature frequently mentions six key skills: Analysis, Evaluation, Explanation, Inference, Interpretation, and Self-Regulation. Figure 2 captures the frequency of these skills in the reviewed studies, with Analysis emerging as the most commonly referenced skill. This affirms the fundamental role of these six skills in problem-solving and underscores the apparent convergence of CT skills and problem-solving abilities in most engineering contexts.

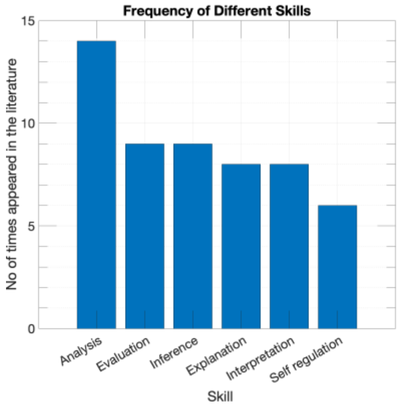

Figure 2. Frequency of critical thinking skills in the literature, ordered from most to least mentioned

When considering the assessment of the effectiveness of these teaching methods, a common method employed in the literature is contrasting control and experimental groups (Galand et al., 2012; Jonathan Stolk & Martello, 2015). Such studies allow students to learn the same subject using two divergent teaching methods: instruction only and problem-based learning. This dichotomy provides a platform to compare the outcomes of these two methods in fostering CT skills. Pre- and post-assessment of students' CT skills when implementing problem-based teaching methods further substantiate these findings (Godfrey et al., 2014; Yadav et al., 2010).

Students' perception of these teaching methods also points towards the positive impact of problem-based learning on their CT skills. This is evidenced by student feedback collected via interviews and surveys, which largely praises the problem-based teaching approach and acknowledges its benefits (Pan & Allison., 2010; Tseng et al., 2013). However, the challenges associated with assessing student outcomes in units delivered via problem-based learning methods cannot be overlooked. Given the deviation of these learning outcomes from conventional teacher-centred methods, traditional testing methods might not fully capture the learning progress. This necessitates innovative assessment methods that can evaluate students' thinking and analysis processes integral to CT. Conversely, it also suggests that problem-based learning might not always be the best fit, especially for units aiming to lay the foundation of factual and theoretical knowledge. To mitigate this challenge, the framework suggests a multi-pronged approach to assessment that incorporates but is not limited to formative assessment techniques. These methods, such as peer reviews and self-assessments, offer a more nuanced way to measure specific CT skills in real-time. For example, in a unit like "Fluid Mechanics," a formative assessment could involve students critically evaluating peer-submitted solutions for a fluid flow problem. This approach provides immediate feedback and caters to the analytical nature of CT skills. Moreover, it complements traditional assessment methods by filling the gaps they leave, especially in capturing the complexities of problem-solving and critical evaluation.

With these insights from the literature, we now propose a comprehensive framework to design a CT assessment regime for engineering students. This framework begins with the mapping of common/core engineering units, particularly those that seem ideal for fostering CT skills due to their emphasis on problem-solving, decision-making, and the application of theoretical knowledge to practical scenarios. Subsequently, CT skill development can be integrated into these identified units, potentially via modifications in teaching methods or by including explicit CT tasks. Considering the distribution of teaching methods in Figure 1, our proposed framework strongly favours a Mixed method approach, incorporating elements of both Infusive and Immersion methods. This choice echoes the popularity of these methods in the literature, suggesting their potential effectiveness in an engineering education context. This also aligns with the principle of progressive complexity in CT skill development, where students are exposed to increasingly intricate tasks as they progress through their course. To elaborate, the Mixed method approach would be implemented in stages. In the first year, 70% of the coursework could utilise Infusive methods, while the remaining 30% would employ Immersive methods. By the final year, the ratio could be balanced or even reversed, depending on the specific needs and complexities of the engineering discipline.

Scaffolded learning constitutes an integral part of our proposed framework, providing a structured roadmap for students to develop and refine their CT skills incrementally. This approach offers explicit instruction, gives feedback, reduces task complexity, and gradually reduces support as students demonstrate increased competency. Scaffolded learning can help bridge the gap between current student abilities and the desired learning outcomes, thereby facilitating the efficient development of CT skills. For instance, in a unit like "Material Science," scaffolded learning could start with instructor-led sessions dissecting different material properties. As the term progresses, students might be tasked with independently researching and presenting a case study on material suitability for specific engineering applications.

The design of the rubric for different year levels is an important aspect of this proposed framework. It involves identifying key stages in the course where CT skills should be developed and evaluated. Integrating scaffolded learning into the rubric design allows mapping the development of CT skills from foundational to advanced levels over the course duration. The rubric could be divided into three main categories: comprehension and understanding, application and analysis, and synthesis and creation. Each category would have specific sub-criteria, scaled to the level of complexity suitable for the year level. For example, the 'synthesis and creation' category could include sub-criteria like 'innovative problem-solving' or 'design optimization' for final-year students.

The final stage of our proposed framework includes the development of robust assessment tools tailored to evaluate CT skills effectively. Combining traditional methods with innovative ones can ensure a comprehensive evaluation of CT skills, which goes beyond factual recall to assess application, analysis, and synthesis of knowledge, all crucial components of CT. For instance, while traditional testing methods can assess knowledge retention and basic analysis, newer methods like reflective journaling or portfolio-based assessment can provide a deeper understanding of students' thinking processes and their ability to synthesize and evaluate information. This framework presents a holistic and dynamic approach to teaching and assessing CT skills in engineering education. It leverages insights gleaned from literature, industry needs, and innovative pedagogical strategies, promising a robust approach that fosters CT skill development and prepares students for real-world engineering challenges.

Examining the rationale underlying the advocacy of a mixed approach in our proposed framework, it's crucial to understand the multi-faceted benefits that this method presents. A mixed approach, incorporating aspects of both Infusive and Immersive methods, allows for the effective integration of CT skills within the fabric of course content. Infusive methods allow CT skills to be taught in context with discipline-specific content. This aligns with the notion that CT does not exist in a vacuum but is strongly tied to domain knowledge (Ahern et al., 2012). On the other hand, Immersive methods provide students with the opportunity to engage in complex, real-world problems where they are required to independently apply and develop their CT skills. This mirrors the nature of engineering tasks in the professional world and can significantly boost students' readiness for the workplace.

Drawing parallels between the complexity of these teaching methods and the progression of engineering courses can further explain the popularity of the mixed approach. In the initial stages, students tend to benefit more from Infusive methods where CT skills are interwoven with foundational engineering concepts. As students advance through their course, transitioning towards more Immersive methods can present them with greater challenge and autonomy, pushing them to utilize and refine their CT skills. This approach mirrors the concept of Scaffolded Learning. In the early stages of the course, students are given more guidance and structure, which gradually diminishes as their competence increases. This strategy not only keeps students challenged but also prevents them from feeling overwhelmed, thereby enhancing their engagement and motivation. Mapping this pedagogical approach onto common engineering units can be realized by first identifying those units that require significant problem-solving, decision-making, and application of theoretical knowledge. Examples could be "Fluid Mechanics" where students can critically evaluate different fluid properties or "Material Science" where students can analyse the properties of different materials and their suitability in various contexts.

Identifying suitable units enables us to create a structured roadmap, illustrating where and how CT skills should be introduced, developed, and evaluated. It also allows educators to ensure that these skills are not taught in isolation but are instead contextualized within relevant engineering content.

When designing a rubric for different year levels, it is crucial to consider the progression and depth of CT skills expected at each stage. For instance, in the first year, the focus could be on comprehension and basic analysis, advancing to application and evaluation in the subsequent years. By the final year, students should demonstrate the ability to synthesize and create, reflecting a higher level of CT. An effective rubric should articulate clear and specific criteria for each CT skill at every stage. For instance, the criterion for evaluation might evolve from 'demonstrates basic understanding of different perspectives' in the first year to 'critically appraises and selects the most effective solution from various alternatives' in the final year. Including specific behaviours or outcomes for each criterion can ensure a more accurate and objective evaluation of students' CT skills.

To conclude, the proposed framework aims to design an assessment regime that not only evaluates students' CT skills but also enhances their learning experience and prepares them for future engineering practice. This holistic approach, informed by literature review findings, can serve as a robust guide for engineering educators and institutions, enabling them to cultivate competent, critical, and creative engineers ready to tackle real-world.

Conclusion

The critical importance of fostering critical thinking (CT) skills in engineering students is well-acknowledged. This study aimed to shed light on the existing methods used to teach and assess CT skills in engineering education, and propose an effective framework to improve the pedagogical approach. The analysis of the literature showed a clear trend towards student-centred approaches, as opposed to teacher-centred ones, and a prevalence of mixed, immersive, and infusive methods over general methods. It revealed that the majority of pedagogical practices involve real-world problem-solving activities, including problem-based learning, project-based learning, and case-based studies. Such approaches have proven effective in developing CT skills and preparing students for real-world engineering challenges.

The study also identified the most commonly referred CT skills in the literature, including analysis, evaluation, explanation, inference, interpretation, and self-regulation. These skills were highlighted as critical components of problem-solving abilities in engineering. The analysis demonstrated that the efficacy of teaching methods in developing these skills varied, with case-based real-world problems reported as the most effective approach. Drawing from these findings, the study proposed a mixed teaching approach for engineering units, gradually moving from infusive methods to immersive ones. This approach aligns with the principle of Scaffolded Learning and mirrors the progression of complexity in engineering courses. This framework provides a roadmap to incorporate and develop CT skills in context with engineering content throughout the course.

In designing the assessment rubric, the study recommended a progression model, focusing on comprehension and basic analysis in the initial stages, advancing to application and evaluation in the middle stages, and finally expecting synthesis and creation by the final year. This model ensures that CT skills are progressively developed and appropriately assessed at every stage of the course.

This research contributes to the growing field of engineering education by offering an evidence-based approach to enhance CT skills teaching and assessment. It provides valuable insights for educators and institutions committed to nurturing future engineers equipped with the necessary CT skills to excel in their profession. As the pedagogical landscape continues to evolve, further research is encouraged to refine and expand these strategies to meet the changing demands of the engineering profession and the higher education sector.

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