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Engineering Thinking: Preparing Students for the Workforce with Novel Tertiary Pedagogy Design

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CONTEXT
Engineering Thinking (ET) describes the cognitive process practising engineers use to analyse engineering problems effectively. This phenomenon encompasses critical thinking, problem-solving, and other high-order thinking skills. This study investigates numerous pedagogies and educational frameworks that effectively improve thinking skills. Elements of these have been purposefully curated to develop a novel teaching method that can be implemented at a tertiary institution to boost ET awareness and proficiency in first-year engineering students.

PURPOSE
Chief among the skills and competencies expected by the engineering profession of its incoming graduates are those associated with ET. However, these skills are widely considered deficient in this cohort (Khoo et al., 2020). Therefore, it is vital for tertiary institutions to develop ET by implementing novel or innovative practices. Consequently, this research aims to design a novel teaching method comprised of an assessment framework with associated feedback that effectively improves the level of ET taught at universities, further preparing engineering students for the workforce and improving the quality of their professional work.

APPROACH
Through the exploration of engineering education pedagogies, relevant elements of various methodologies were used to develop a teaching method to nurture first-year engineering sentiment towards and skill in ET. The teaching method consists of two elements: assessment and feedback. The restructured assessments involving authentic, ill-defined problems were inspired by Price et al. (2020), and associated feedback solution videos were adapted from the *try-see-tell-do* method proposed by Nguyen et al. (2022).

OUTCOMES
The developed teaching method in this study is designed by combining high-utility elements of several pedagogies to optimise the education of ET in first-year engineering courses.

SUMMARY
ET is a fundamental skill desired by both students and industry and is lacking in tertiary education (Khoo et al., 2020). It is recommended that the ET-enhancing teaching method developed in this study be tested and evaluated in tertiary engineering courses.

KEYWORDS
Engineering Thinking; Tertiary Education; Engineering Education.

Introduction

Engineering Thinking (ET), also referred to as Engineering Habits of Mind (EHoM), denotes the cognitive process utilised by practising engineers to analyse complex engineering problems efficiently and effectively (Lucas et al., 2014). This phenomenon encompasses critical thinking and problem-solving skills alongside understanding, evaluating, adapting, and creative thinking. Proficiency in ET is considered of great importance for engineering graduates, as it represents a key set of skills and competencies highly valued by the engineering profession (Friesel et al., 2022). However, there is a prevailing perception of deficiencies in these skills among the current cohort (Khoo et al., 2020). Therefore, it is vital for tertiary institutions to instil ET in their students by implementing practices to improve the high-order thinking of graduating engineers. The effectiveness of tertiary pedagogies targeting improved levels of these abilities remains under-explored, with the majority of studies published in the past ten years (Leao & Ferreira, 2023).

Incorporating ET into education has the potential to provide students with a comprehensive set of problem-solving and critical-thinking skills that are essential in the STEM industry. Prior research indicates that developing an engineering mindset prepares students for real-world engineering work demands and equips them with lifelong skills that can be applied in various personal and professional situations. Thus, implementing ET pedagogy in education may give students a competitive edge in the job market and enable them to make meaningful contributions to society through innovative and effective EHoM.

Existing educational frameworks, such as the Conceive, Design, Implement, and Operate (CDIO) Framework, Project-Based Learning (PBL), Design Theory (DT), and Case-Based Learning (CBL), outline some of the pedagogical techniques used to enhance students' development of ET in a classroom. While these frameworks have shown promising outcomes, their application often places a significant burden on students to independently comprehend and internalise the EHoM. Particularly at the entry level of engineering courses, students may face challenges in fully grasping the intricacies of ET, given its complex cognitive nature. Therefore, a more nuanced and student-centric approach is essential to foster the development of these cognitive skills, leading to the proposition of a new teaching method.

The designed teaching method in this study amalgamates the student-led and educator-led approaches to nurture and advance first-year students' capability of learning the process required to develop holistic solutions. This study adapts and combines elements from various pedagogies to form a teaching pedagogy that is designed to be implemented in the first year of tertiary engineering courses to boost awareness and proficiency in ET among students. The design implements a two-part strategy formed by assessment and feedback. The teaching method combines (1) posing authentic, ill-defined problems inspired by Price et al. (2020) that require high-order thinking and (2) solution videos according to the *try-see-tell-do* method proposed by Nguyen et al. (2022). This combination aims to optimise the time spent in the classroom by effectively imparting ET education to students.

Background

Engineering Thinking (ET) Skills

High-order thinking is the cognitive process that allows humans to assess and analyse complicated problems. High-order thinking can be broken down into four primary sub-thinking skills: problem-solving, critical thinking, creative thinking, and decision-making (Alkhatib, 2022; Costa, 1985). ET, as defined in this study, encompasses a wide range of skills, including systems thinking, adapting, problem-finding, creative problem-solving, visualising, and predicting. The multi-faceted ET mindset, collectively known as Engineering Habits of Mind (EHoM), facilitates real-life engineering objectives.

Elaby et al. (2022) discuss the relationships between critical thinking and problem-solving in engineering. The study claims that one of the key learning outcomes of engineering education is problem-solving, which is defined as the ability to identify, formulate, and solve engineering problems. It is essential to recognise that problem-solving involves many different skills that apply to ET, including analysis, conceptual knowledge, metacognition, and collaboration (Aqlan & Zhao, 2022). On the other hand, critical thinking is an amalgamation of thoughts and processes that ultimately justifies beliefs and actions (Caratozzolo et al., 2022). Critical thinking skills involve the ability to evaluate, interpret, compare, analyse, criticise, and synthesise information while also exploring, investigating, and scrutinising various approaches (Gonzalez-Cacho & Abbas, 2022; Li et al., 2022; Navarro et al., 2021).

Critical thinking, problem-solving and other ET skills belong in a holistic engineering curriculum yet appear to be lacking among the current student cohort (Friesel et al., 2022). Despite critical thinking skill development being a primary aim of higher education, little effort has been made to develop effective teaching methodologies that enhance these skills (Douglas, 2012). Moreover, accreditation boards have recognised the requirement to develop problem-solving skills, and pedagogical methods have been implemented in engineering courses to engender improvement (ABET, 2021). Without a solid foundation in problem-solving *and* other ET skills, engineers would lack the necessary qualities to become proficient employees (Ismail et al., 2017). Hence, a need to explore pedagogies that enhance critical thinking, problem-solving, and other EHoM arises.

Historically, universities' main priority was teaching students technical knowledge, thereby creating specialists rather than generalists who could exhibit thinking skills and apply methods to a variety of jobs (Richerzhagen, 2001). Price et al. (2020) critique the current engineering curriculum by highlighting the discrepancy between the simplified, well-defined problems used in assessments and the complexity of authentic, ill-defined scenarios encountered by practising engineers. Rohrs et al. (2021) suggest a way to improve the current assessments, referring to a method to teach problem-solving involving a more complex mode of thinking when tackling questions, emphasising initiative, iterations, and questioning rather than memorising equations. Similarly, Kersten (2022) claims that the single invariant feature, ubiquitous in engineering work, are problems that require situational thought patterns and processes rather than a fixed algorithm, justifying the need to develop these skills at universities. Ultimately, a redesign of university engineering curricula to be better suited to the evolving industry's need for adaptable, generalist engineers is encouraged (Kolmos et al., 2016).

Tertiary Pedagogies

Numerous pedagogical approaches in tertiary engineering education share overlapping goals to foster thinking skill development. Some seek to reform traditional lecture-based methods, moving away from technical course structures. The Conceive, Design, Implement, and Operate (CDIO) Framework operates on the fundamental belief that hands-on experience is a vital foundation for building technical engineering knowledge (Edström et al., 2020). Similarly, Project-Based Learning (PBL) extends the experiential focus and promotes that students can learn practical engineering skills, including various desirable EHoM, by tackling real-world problems. This pedagogy emphasises that real-world engineering projects only come to fruition when a team dedicates time to them and that problems vary significantly in reality, partially due to the myriad of project opportunities (Dym et al., 2005). In juxtaposition to the lecture-based approaches, Design Theory (DT) is a pedagogical approach that emphasises that engineers have clients who, in turn, service end users who are the end beneficiaries of the product. DT focuses on stakeholder consultation while working on engineering problems, instilling a capability for tolerating ambiguity or handling uncertainty and thinking & communicating in several design languages (Dym et al., 2005). Likewise, Case-Based Learning (CBL) employs a combined theory and practical problem-solving approach. Both DT & CBL underscore a key issue with the current lecture-based methods focusing on technical skills and knowledge rather than applying methods and thinking skills. Nair et al. (2009) completed a gap analysis of engineering employers exploring 23 key attributes, including being knowledgeable and having the ability to apply methods and problem-solving skills. The results reveal that whilst technical knowledge is essential for any engineer, the ability to adapt and solve diverse problems is more sought after (Friesel et al., 2022; Khoo et al., 2020).

Additionally, some pedagogies alter elements such as teaching style, feedback systems, or content delivery to emphasise the development of thinking skills. The Flipped Classroom approach aims to address both the theoretical and practical side of engineering. It enables students to gain hands-on experience using materials, tools and machinery and encourages both individual and team problem-solving. However, students find this pedagogy challenging due to the heavy contrast compared to the present-day pedagogical approaches of theory-based learning throughout schooling (Reidsema et al., 2017). Likewise, Experiential Learning – a common pedagogical method in engineering education – employs a learning approach focused on building knowledge, soft skills and technical skills (Mohsen et al., 2019). This approach is a drastic reform of lecture-based pedagogies and requires significant time, resources, and authority to be integrated into academic courses.

Alkhatib (2022) posits that high-order thinking can be assessed successfully via a model of multiple-choice questions and performance items. This model can address less-tangible items such as understanding, evaluating, and predicting. Similarly, an additional three frameworks for high-order thinking and their assessment methods were presented by Kaupp and Frank (2014): the Cornell-Illinois Model, the CLA Model and the Paul-Elder Model, all of which are widely accepted to be valid and reliable assessments. The Cornell-Illinois Model suggests the use of the Cornell Critical Thinking Test (CCTT): Level Z, which is a 52 multiple-choice question quiz. The CLA Model utilises The Collegiate Learning Assessment, which presents students with problems and then ranks the skills used by the students in their responses. This is not an explicit model; rather, it tests generally and requires large amounts of time and resources to manage. Lastly, the Paul-Elder Model is accompanied by the International Critical Thinking Test – an essay-style test. Kaupp and Frank (2014) conclude that despite these models being suitable for engineering education, they cannot holistically assess the application and development of thinking skills.

Methods

First-Year Context

Monash University offers ten engineering specialisations in a four-year Honours level degree, which are accredited by Engineers Australia to the Stage 1 Competency Standards. The degree is structured with a common first-year, which consists of five core engineering units and three elective units to accommodate students requiring foundational mathematics, physics, or chemistry knowledge. Students select their specialisation before beginning their second-year units. The unit ENG1011 – Engineering Methods involves fundamental mechanics, engineering design skills, and engineering tools such as CAD and 3D printing. The unit has no formal prerequisites and typically has up to 700 student enrolments per semester. This unit was used as a basis to explore the designed teaching method.

Assessment & Feedback

Little to no literature discusses pedagogies that are specifically designed for ET education in first-year engineering. Thus, elements from various existing educational frameworks were taken with the aim of introducing a novel teaching method that addresses the lacuna. Both PBL and CBL have informed the decision to utilise ill-defined problems due to their grounding in authentic problem-solving. These problems are designed to simulate real-world scenarios, requiring the formulation of assumptions and the filtration and organisation of relevant information.

Further, the restructured pedagogy incorporates a robust feedback system comprising a think-aloud video solution guide for each problem. Traditional tertiary education follows the protocol of posing questions and providing an associated answer sheet with varying depth of explanation. Educators found that the best results in students' understanding, and use of new thought patterns were through a think-aloud method (Walidainismawati et al., 2021). The think-aloud method is the process of talking through one's thoughts as the question is being solved, providing valuable insights, which are typically absent in a written solution sheet. This method is supported by the

‘*Try-See-Tell-Do*’ method proposed by Nguyen et al. (2022), who suggest that student comprehension of thought processes is enhanced when they are privy to model thought processes. Video solutions were found to be more effective than in-person think-aloud solutions, stemming from the ease of access and the flexibility and control they provide the students (Bhardwaj & Gupta, 2022).

Evaluation & Integration of Teaching Methods

Aqlan and Zhao (2022) propose having students self-report the thinking skills used while answering questions to allow improvements in ET skills to be measured. Similarly, open-ended questions and the dissection & analysis of contradictory concepts can be utilised as assessment methods (Elaby et al., 2022). Using a selection or combination of these techniques, alongside the traditional assessment framework, permits the performance of ET to be sufficiently evaluated.

Results & Discussion

Assessment Design

Price et al. (2020) emphasise the significance of considering crucial information, exploring solutions, and stating assumptions and approximations to holistically solve scenario-based problems. Purzer (2014), Brookfield (2012), and Alkhatib (2022) supply a more concrete list of questions that can be posed to students to elicit responses that consider the principles of ET. This study’s assessment framework consists of an example scenario demanding ET to devise a solution, complemented by feedback videos that explain the solution using a format and question framework inspired by the cited studies. These questions are structured according to the thematic grouping elucidated in the study by Li et al. (2022), outlining a critical thinking framework. Deriving from the questions catalogued by the aforementioned authors, four main themes were identified: Context, Challenges, Assumptions, and Evaluation & Prediction. Context involves providing insight into the background information, stakeholder requirements, and real-world implications of the solution. Challenges encompass the specific difficulties or obstacles that must be addressed to resolve the problem, such as missing information, irrelevant data, and constraints such as cost and time. The Assumptions section highlights the approximations and simplifications made during the solution process, requiring students to specify materials used, their properties, the expected lifespan of the object, and other relevant inferences. Additionally, students may discuss the need for verifying or validating assumptions. Lastly, Evaluation & Prediction tasks students with employing ET skills to speculate on outcomes under different conditions and assess the potential consequences of the proposed solution. Table 1 presents example questions representing each theme in the assessment design based on prior works (e.g. Li et al. (2022); Price et al. (2020))

Table 1: Assessment Framework

Theme	Questions
Context	• Why might this be useful? • What are you trying to solve?
Challenges	• What information are you missing? What information is irrelevant? • What are the limitations? E.g. cost, time, materials. • Which methods/equations are most applicable? • Is there more than one solution? If so, why is one better than the other?
Assumptions	• What materials is it made from, and what properties must they have? • How long should the object last? • Could you verify/check any of the assumptions? • What approximations/simplifications are you making?
Evaluation & Prediction	• What would happen if ___? • Should ___ happen, what would change? • What experiment could validate the results?

An example engineering scenario problem is provided below:

You are tasked with designing a bridge for a small local council community project. The bridge will be used to connect two parts of the town separated by a small river. Could you please talk about:

- *The purpose of the project.*
- *The Information required at the outset.*
- *The challenges you might encounter during the design, build and maintenance phases.*
- *The assumptions you are making throughout this process.*
- *How you might be able to verify your designs and assumptions.*
- *Any external factors (i.e. unexpected events/behaviours) that may affect your design? How would you combat them?*

<u>*You are not expected to come up with a specific design solution; rather, the focus should be on using your thinking skills to holistically analyse the scenario.*</u>

Feedback Design

An integral element of this teaching method is the incorporation of video solutions provided by engineering educators. The feedback provided to students will not consist of a breakdown of their solutions; rather, it will be in the form of think-aloud suggested solutions, showcasing the thought processes employed by experienced engineers during problem-solving. Similar to the think-aloud protocol used by interviewers to understand the interviewees' thoughts (Walidainismawati et al., 2021), the presentation of recommended thought patterns through the think-aloud video solutions allows students to learn from the perspective of experts in the field. This think-aloud method aligns with the *try-see-tell-do* method proposed by Nguyen et al. (2022), which has proven effective in fostering active cognitive skills, such as problem-solving and critical thinking. Therefore, the teaching method for enhancing ET includes a think-aloud video solution that follows the framework described in Table 1 as a complementary component to the assessment activities. In addition to the suggested problem solution, the videos should contain targeted feedback based on the shortcomings and areas of improvement illustrated in students' answers. This feedback should be specific to the student cohort of the unit.

Marking rubrics were created to evaluate the thought processes utilised by the student rather than their ability to solve the assessment problem. There were two main considerations in the construction of the rubric and marking methods: the assessor, who will be marking the activity, and the criteria. Three possible groups were considered to be the assessors: educators, industry experts, and the students. The recommended method utilises both educators and students as assessors. The assessments should be self-assessed by students to promote metacognition and high-order thinking and are graded by educators to bestow students with constructive criticism. Educators should identify and evaluate thought processes to properly assess students' ET abilities. This two-pronged assessment stems from a study by Baele (2017), who presents two marking rubrics: one for educators and one for students.

The marking rubrics – for educators and students – employed in this academic assessment delineates criteria across a spectrum from Excellent (5) to Inadequate (1). Aligning with the overarching goal of fostering robust ET skills, the criteria should be structured around the themes of the assessment, namely Context, Challenges, Assumptions, Evaluation & Prediction, and Understanding of ET:

- Context: Analyse the assessment of the problem's context and the clarity of explanation.
- Challenges: Identifies of relevant challenges and the depth of insights provided.
- Assumptions: Examines the justification of assumptions, considering all necessary factors.
- Evaluation & Predictions: Assesses the thoroughness and accuracy of evaluations and predictions, considering various scenarios that may affect the design solution.
- Understanding of Engineering Thinking: Draws on the relevance of engineering principles, effective application, and holistic problem analysis.

In support of this concept, Alkhatib (2022) presents a problem structure whereby the recommended evaluation of the solution is on the basis of problem-solving, critical thinking, creative thinking and decision-making skills. Applicable elements from Alkhatib (2022) and Baele (2017) guided the marking rubric designs, enabling both educators to grade work and self-evaluation. Educators should determine the marking distribution for each unit individually based on the specific learning outcomes and assessment tasks. To promote participation, it is recommended that the final grade include both the grade given by the educator and a mark for completion of the self-assessment.

Overall, students will receive three forms of feedback to facilitate their progression: Video solutions, general written feedback, and marks from the rubric. Collectively, these resources are anticipated to empower students in fostering their ET development.

Conclusion & Future Work

This study proposes a novel teaching method aimed at developing and enhancing ET skills in first-year engineering students. The method consists of a restructured assessment framework with accompanying video solutions. The pedagogy focuses on three key elements: (1) authentic, ill-defined problems, (2) think-aloud video solutions showcasing expert thought processes, and (3) educator and student grading to foster students' evaluation and improvement of cognitive patterns. By adopting this approach, students engage with real-world engineering scenarios, cultivating ET skills at entry level. The teaching method was designed for large cohorts of students, where individual feedback was not reasonable. However, its performance in smaller cohorts should remain equally effective. Further testing and evaluation of the method will determine its efficacy in preparing students for the engineering profession. One methodology of verifying if the teaching method improves ET skills is the conducting of a mixed-methods study involving a trial of the method and interviews. Quantitative data (activity marks) and qualitative data (interview responses) can be used to assess the impact of the method. A comprehensive review of industry-based engineers should be conducted to validate that the ET skills discussed in this study align with their practical experience. Building up from the foundational ET skills taught in first-year engineering, the most applicable method that enables continuous development of these skills in subsequent years should be investigated.

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