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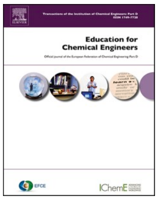

Critical thinking activities in fluid mechanics – A case study for enhanced student learning and performance

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ABSTRACT

We describe the implementation of Critical Thinking Activities (CTA) designed to encourage 'critical thinking' in an undergraduate engineering Fluid Mechanics course. Critical thinking can be a vague term both difficult to grasp and even more so to measure. Using a longitudinal case study we analyse quantitative and qualitative data collected over three years to explore the overarching question: "how do we know students have thought critically?". We investigate and evaluate the quantitative data that emerged from students undertaking the CTA and the impact of this on their performance. The results indicate that students who performed well in the CTA achieved a final grade for the course of 5 or more (Credit, Distinction or High Distinction). Qualitative data from student feedback demonstrated that the CTA was a significant factor in reinforcing student learning, enabling us to identify areas of misconception and areas in which they could improve. While the study is situated in an engineering context at the University of Queensland, the paper is an exemplar of embedded and sustainable practice, is equally transferable to other disciplinary contexts.

1. Introduction

The significance of "critical thinking" is known to many educators, but it has been diversely conceptualized. As a result, its exact meaning is difficult to define (Ralston & Bays, 2015) and although many educators may claim critical thinking to be an important educational objective, only 20% are able to provide a clear explanation (Paul et al., 1997). Historically the literature has characterized critical thinking simply, as one or more skills, mental processes, or sets of procedures (Bailin et al., 1999) which led to the view that critical thinking could be taught simply by practicing or demonstrating it. However, some studies argue that critical thinking must be characterized in terms of specific performance criteria in which critical judgment is developed through applying knowledge in many contexts, and that improvement is made through frequent feedback and evaluation with respect to the quality of thinking demonstrated (Abrami et al., 2008; Behar-Horenstein & Niu, 2011) and through the meaningful and constructive interpretation of information (de Acedo Lizarraga et al., 2012). Thus, despite the difficulty of defining critical thinking, the elements of critical judgment, reflection interpretation and justification of decisions seem to be fundamental to it. Teaching and assessing these elements of critical thinking presents a challenge for lecturers in Higher Education.

In engineering education there is a need for a more cohesive approach to conceptualize and (better) understand critical thinking (Ahern et al., 2019). The teaching of critical thinking skills should be based on a shared understanding (Lim, 2021) but also include constructive discussions on pros and cons of various practices and pedagogies that enhance student learning. The quality of engineers is determined by how they think, and subsequently the quality of what they design and produce. Systemic and critical thinking skills (Adair & Jaeger, 2016; Lönngren & Svanström, 2015) are an essential component of an engineer's skill set and it is these skills that enable students to adapt to a changing world. In this sense, teaching critical thinking involves articulating assumptions in problem solving, selecting appropriate hypotheses and methods for experiments, and structuring open design problems (Adair & Jaeger, 2016). As well as developing critical thinking dispositions through interpersonal interactions, the 4 C skills framework incorporating collaboration, communication, creativity and critical thinking (Lin and Shih, 2022) has been used to articulate the skills engineers require. These are often considered part of the regulated graduate attributes that students require and go beyond knowledge and comprehension to include the application of this knowledge, the critical

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analysis of situations, evaluation of concepts to construct knowledge and creativity (Wu and Wu, 2020). These attributes are used to identify learning outcomes that develop students' ability to define and analyze problems, to apply critical reasoning to issues through independent thought and informed judgement, and to evaluate opinions, make decisions and to reflect critically on the justifications for decisions. In this study we explore the development of critical thinking skills through the implementation of a Critical Thinking Activity (CTA). By encouraging students to draw conclusions through deducing or inferring answers to questions and then reflecting on the quality of the reasoning (Ralston & Bays, 2015) the design of this intervention targets the fundamental elements of critical thinking These fundamental elements of critical thinking cannot be learned by drill and practice but also require opportunities for reflection and feedback. In addition, we suggest that by providing students with opportunities to examine problems in a variety of contexts more involved thinking is required and that this encourages the development of critical thinking skills. We then describe the benefits to student motivation, engagement and understanding from student feedback of how the implementation of the CTA enacted student meta learning.

1.1. *Research Question*

This study aims to investigate how the implementation of CTAs in a 2nd year Fluid Mechanics course affected students critical thinking by analyzing how the CTA contributed to student performance. We emphasize that some studies (Kong et al., 2014), have used specific tools, such as the California Critical Thinking Skills Test (CCTST) or the Watson–Glaser Critical Thinking Appraisal (WGCTA) whilst other studies have used indicators such as demographic characteristics, previous academic achievement and individual student factors to measure the impact of learning activities on critical thinking. However, in this study we assessed the efficacy of the CTA by i) evaluating student performance in the CTA, ii) the resultant impact of this on their performance in the course overall, and iii) students' broad perceptions of how the CTA affected their performance. The broad research question guiding this study is: *"Does the implementation of a CTA improve student critical thinking as reflected by their performance in the course overall?"* Outcomes from this research will provide insight into how assessment that incorporates authentic problem-solving activities correlates to and affects students' critical thinking. This will subsequently shed light on ways the CTA can be used to enhance the student learning experience.

The CTA was part of a blended delivery approach that incorporated both online and face-to-face elements of instruction. Although data from the third year fell within the COVID response management period (shift to predominantly online delivery), a distinct advantage of the blended delivery approach having been adopted earlier was the reduced disruption to teaching and learning during this period. The focus of this study is on the impact of the intervention on critical thinking and not the transition to online delivery as a result of a response to COVID.

2. The critical thinking activities (CTA)

2.1. *Theoretical background*

Although there is diversity around the conceptualization of critical thinking (Loes et al., 2012; Mason, 2007) and how skills in critical thinking are acquired by students (Mulnix, 2012; Şendağ & Odabaşı, 2009) the connection between critical thinking and problem solving (Saiz & Rivas, 2008) and the impact of authentic real-world situations (Ahern et al., 2019) are recurring themes within the engineering literature. Critical thinking can be developed through the implementation of specific pedagogical interventions (Tiruneh et al., 2014) and it is suggested that the use of both quantitative and qualitative assessments provide a more accurate way to measure students' critical thinking (Behar-Horenstein and Niu, 2011).

The use of a problem-solving approach allows students to identify what they need to learn (either individually or collaboratively) to solve a complex problem which has been shown to be a efficient method of supporting critical thinking Carvalho et al. (2023). Students apply their new knowledge to the problem and reflect on the effectiveness of the strategies employed and what they learned. The educator acts as facilitator to the learning process rather than as a provider of knowledge (Davis & Harden, 1999; Dexter et al., 1999). Students create their own understanding by integrating their previous experience, resources they have, their own research and their current experience (Roach et al., 2018).

2.2. *Fluid Mechanics course*

The compulsory second-year course Fluid Mechanics course in the faculty of Engineering, architecture and Information Technology at the University of Queensland chosen for this study is often considered one of the most difficult in the engineering curriculum by students. Equivalent to two units within an engineering curriculum of 64 units taught over 4 years it is prerequisite to courses in later years of the curriculum. The syllabus and content is equivalent to Fluid Mechanics courses at other institutions such as fluid dynamics, fluid statics, Bernoulli's principle, energy and momentum equations, dimensional analysis, flow and friction in conduits etc. With a student cohort often between 100 and 200 students, the course includes 65 contact hours, split up into approximately 40 h of lectures, 13 h of tutorials and 12 h of laboratory work. Assessment is a combination of summative and formative assessment including an end-of-semester examination (50%) and work throughout the semester (50%). Each of the two CTAs was worth 5% of the total mark, so that combined the CTA contributes to 10% of the total grade. Student performance over the years has generally been normally distributed. The CTA was implemented in week 4 and week 10 of the course respectively, whilst the final exam and final grade are obtained in or after completion of the course (after 13 weeks of teaching).

2.3. *CTA Development*

The use of real-world experiences in which students were required to solve problems was considered essential in the development of the CTA as teaching elements of a holistic learning process (see Fig. 1). This process involved the theoretical concepts being introduced during the lectures, developed further during the tutorials through collaboration and peer mentoring, with application of important concepts and theories being practiced by students during the laboratories. Although higher-order thinking skills such as "analyze"," evaluate" and "create" from Bloom's revised taxonomy (Krathwohl, 2002) were integrated with other elements of instruction, the implementation of CTA as an additional assignment (targeting the process of solving an authentic real-world problem) would also enable students to develop their critical thinking further in alignment with these higher-order skills.

The underlying assumption of the CTA was that students would engage in higher-order thinking skills by relating the (theoretical) course content to a real-life experience. By specifically targeting and developing problem solving skills the CTA linked theory to practice through a contemporary situation in which the connection to Fluid Mechanics had not been previously disclosed or which might not be obvious to the student. The IDEAL model (Bransford and Stein, 1993) was chosen to promote the problem-solving skills of students (Bhadargade & Joshi, 2020; Gusau & Mohamad, 2020).

The structure of the CTA is outlined in Fig. 2 and has many commonalities with other models such as the Four Stage Model of Creative Problem Solving (Cropley, 2015). Here, the theoretical framework consists of five steps to solve problems: Identify, Define, Explore, Act, and Look (Fig. 2) which is in alignment with core elements of the development of critical and creative thinking (Nazzal and Kaufman, 2020).

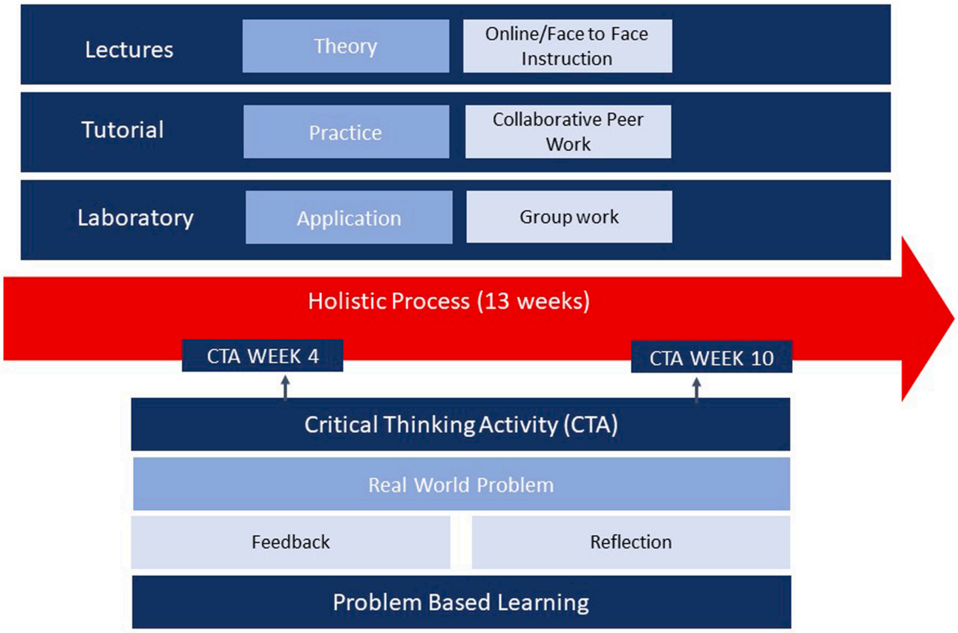

Fig. 1. Structure of the Fluid Mechanics Course from 2018 to 2020 incorporating the Critical. Thinking Activities (CTA).

Fig. 2. The structure of the Ideal Model applied to CTA.

Identify: In the first Step, students were required to identify and define the problem, the catalyst for this was an everyday situation such as a plane slowing down on the runway or the use of water jets for recreational sporting activities. This was one of the most challenging steps for students as the connection to the course content was made deliberately opaque (expressed in Fig. 2 above as the distance between Step 1 and the "Theoretical Background" arrow which represents the other course elements (Lecture, Tutorials and Laboratories).

Define: In the second Step, students had to select a strategy or concept from fluid mechanics that would enable them to solve the problem or identify whether it could be solved, for example the momentum equation, the hydrostatic equation, the Bernoulli principle etc. or a combination thereof.

Explore: In the synthesis phase (third and fourth step) students were required to calculate or execute their selected strategy. In Fluid Mechanics this often means students must perform calculations from the available data (for example, estimating /researching the touch down speed of an airplane on the runway.

Act: In the fourth step, students extract meaning from their results that answers the initial question or problem as identified in Step 1 (e.g. determining the magnitude and direction of the thrust force, now acting as a breaking system rather than a propulsion force).

Look back and evaluate: In the final step, students were required to evaluate their result, i.e., is it meaningful and/or within expectations and physical limits and how would the result change if the boundary conditions were to change.

Feedback Loop: On completion of the CTA students were required to submit short responses (maximum length ~1.5 –2 pages) online with equations and diagrams to support their arguments. Integral to this process was an opportunity for students to resubmit a second attempt (Take 2) after their initial response (Take 1). Students received feedback within 72 h from a tutor on Take 1. This feedback included comments indicating how their solution could be improved by pinpointing where an assumption was either missing, incorrect or could be enhanced. Based on this feedback, students were able to re-submit a revised solution within 3 days to improve the marks received in Take 1 by incorporating responses to feedback and from their reflection on their answers in Take 1. Only the better score of the two submissions counted towards their final grade. Critical to this resubmission process was the timeliness of feedback (less than 72 h) that enabled students to reflect on their answer while still “fresh in mind”. This provided an opportunity to build a stronger connection between theorical concepts, the strategy they chose to solve the problem and to respond to the feedback through the process of reflection.

As outlined in Fig. 2, the CTA extends over approximately 8–10 days during which time they research, conduct experiments and gather data, the students then have ~3 days to submit their first answer (Take 1) after release of the problem., The submissions are then marked (2–3 days) and feedback provided after which students are encouraged to reflect on the feedback prior to submitting their final answer (Take 2) 3 days later. Although the CTA was designed to be completed and submitted as an individual assessment, teamwork was allowed. However assignments had to be submitted individually.

The submissions (Take 1 and Take 2) were marked by two tutors who were trained in marking and providing constructive feedback using the rubric provided. Turnitin was used to integrity check the submissions and because it allowed for customizing sets of feedback sets which guarantees consistency across the individual assignments and according to the marking rubric and solution key.

Throughout the semester, wo critical thinking activities CTA 1 (week 4) and CTA 2 (week 10) were implemented. Each of these incorporating two attempts, these“two takes” are labelled CTA1_1/CTA1_2 and CTA2_1 and CTA2_2 respectively hereafter.

A CTA template is provided in the appendix. Appendix A outlines an example problem set whilst Appendix B reflects a marked student response (Take 1) and the final submission after the tutor feedback was incorporated in the second answer (Take 2, Appendix C). The generic marking criteria used the mark the student answer is also provided in the appendices).

3. Methodology

3.1. Analysis design

Investigating the effect of the CTA required an approach that provides an in-depth understanding of the outcomes of the study and places these into context. This longitudinal case-study over a three-year period utilizes a mixed-methods -approach, examining both quantitative and qualitative data. Although, case-study research has been criticized for its lack of scientific rigor and the difficulties of generalizing it to broader research (Crowe et al., 2011) its credibility has arisen from its ability to explain, describe or explore complex events or phenomena in everyday contexts (Bhatta, 2018; Simons, 2006, Yin, 2014). Moreover, case studies are consistently the most common research strategy used in articles published in the Engineering literature domain (Malmi et al., 2018).

3.2. Evaluation instrument

Data from the Student Evaluation of Courses and Teaching (SECaT) survey was used to evaluate student perceptions of the impact of the CTA. From 2018–2020, students enrolled in Fluid Mechanics were invited to participate in the SECaT survey which forms part of the end-of-semester course evaluation and feedback system at UQ. The survey includes open-ended questions which aim to identify student perceptions of the course, including:

- Aspects that went well,
- Aspects that did not support their learning or that did not go well, and,
- What they thought could be changed or improved.

Those elements of the survey and feedback related to the CTA were qualitatively analyzed in an effort to provide information regarding student perceptions of their learning experience with the CTA.

3.3. Qualitative data analysis

Thematic analysis was used to review the qualitative responses from the SECaT survey. Thematic analysis recognizes patterns within data, with emerging themes becoming categories for analysis (Fereday & Muir-Cochrane, 2006). Using a deductive approach (Adair & Jaeger, 2016) the survey responses were carefully read with constructs relating to only the CTA grouped and isolated from all other constructs and themes that emerged from the dataset. The responses relating to the CTA were then coded, by years. These were further synthesized to draw out key words that describe the student experience.

3.4. Quantitative data analysis

The statistical package SPSS was then used to analyze the responses from the thematic analysis of the survey data and the correlation between this and student scores on the CTA and their overall performance in the course. A descriptive statistic was used to estimate the mean response and establish the extent of different aspects of the course on the student experience. Student performance data in the CTA was exported to SPSS and cleaned by deleting students with 2 or less attempts. The mean score was then computed to explain the extent to which students’ final course grades (overall performance in Fluid Mechanics) were then correlated to their performance in the CTA, while the qualitative responses from the SECaT survey were used to explain the findings. Linear Regression was used to estimate the regression co-efficient, which explains the extent of the variables effect on student scores in the CTA.

4. Results

4.1. Quantitative analysis of CTA impact on final grade

The descriptive statistics shown in Table 1 demonstrate the significant central tendency, variability, and distribution of the CTA on students’ performance and their final grades in Fluid Mechanics. From 2018–2020 students’ performance in the CTA markedly improved from CTA1 to CTA2. For example, in 2018 the results indicate that a mean score of 51.3 ($N = 174$) achieved by students in Take 1 (CTA1.1) of CTA1 was improved after receiving feedback to a mean score of 69.8 ($N = 161$) during Take 2 (CTA1.2). Following this, the results from CTA2 also indicate a similar outcome in which the mean score 65.4 ($N = 149$) from students first attempt (CTA2.1) improved to 84.1 ($N = 120$) in the second attempt (CTA2.2) after receiving feedback. The difference between participating numbers between attempt 1 and attempt 2 in each of the CTAs can be attributed to the fact that students who obtained a high score in the first attempt chose not to participate in the second attempt. Data from the 2018 cohort indicates that 6 students did not participate in any CTA, and only one of those had a final grade of 5, the rest received grades of 4 or less. Although students’ mean score in the final grade was above 5.0 in 2018 and 2019, in 2020 the course was run online as a result of the COVID pandemic management by the university which resulted in lower student engagement and affected the mean score of the final grade for students in relation to the CTA. However, for those who effectively participated, a significant improvement can be observed in their performance (Table 1).

The Pearson correlation coefficient showed a very strong correlation ($p = 0.87$) between the number of attempts and students average score in the CTA (Table 2). The number of attempts on the CTA also strongly correlated with the students’ final grades ($p = 0.77$). This pattern of improved student learning and performance between each attempt in CTA1 and CTA2 is consistent across all cohorts (Table 2).

The statistical analysis shows that students who performed poorly in

Table 1
Mean distribution of CTA in relation final grade performance from 2018.

CTA	2018			2019			2020		
	Mean	SD	N	Mean	SD	N	Mean	SD	N
Final grade	5.10	1.19	202	5.57	1.11	167	4.97	1.36	156
CTA1_1	51.29	20.47	174	51.68	24.33	141	45.08	21.10	131
CTA1_2	69.80	22.21	161	84.38	18.74	136	80.89	17.17	118
CTA2_1	65.44	24.42	149	44.15	16.87	130	42.87	17.16	115
CTA2_2	84.06	18.83	120	62.32	17.22	125	78.19	16.52	116

Note: Statistics of student performance in the CTA are expressed in percentages whilst the Final grade is given using the grade scale in which 7 = 85%– 100%, 6 = 75%– 84%, 5 = 65%– 74%, 4 = 50%– 64%, 3 = 45%– 49%, 2 = 30%– 44% 1 = 1%– 29%)

Table 2
Relationship between CTA attempts, average score and final grade.

CTA Attempts	*Final grade*	*Average Score*	*All Attempts*	*p-value*
Final grade	1	0.64 * *	0.77 * *	0.000
CTA1_1	0.42	0.49 * *	-	0.000
CTA1_2	0.57	0.69 * *	-	0.000
CTA2_1	0.49	0.49 * *	-	0.000
CTA2_2	0.53	0.74 * *	-	0.000
3 CTA Attempts	0.69	0.69 * *	-	0.000
Average Score	0.64	1	0.87 * *	0.000
All Attempts	0.77	0.87 * *	1	0.000

* * Correlation is significant at the 0.01 level (2-tailed)

Table 3
Impact of Critical Thinking Exercises on Final Grade (Regression Coefficient).

	Final Grades	Linear Regression Summary			
Year		*Coefficients β*	*Standard Error*	*t Stat*	*P-value*
2018	Intercept	3.145	0.180	17.473	0.000
	CTA1	0.019	0.003	6.425	0.000
	CTA2	0.011	0.002	4.637	0.000
	CTA1CTA2	0.028	0.002	11.494	0.000
2019	Intercept	3.318	0.204	16.251	0.000
	CTA1	0.019	0.003	6.823	0.000
	CTA2	0.013	0.003	4.433	0.000
	CTA1CTA2	0.033	0.003	11.734	0.000
2020	Intercept	3.192	0.233	13.693	0.000
	CTA1	0.016	0.004	3.990	0.000
	CTA2	0.011	0.004	2.997	0.003
	CTA1CTA2	0.027	0.003	8.342	0.000

both CTA1 and CTA2 also performed poorly in the course overall. This indicates that the CTA can be an indicator of students' learning progress in the Fluid Mechanics course and that, due to the significant correlation between the CTA and student final grades, they can be used to identify low performing students.

Furthermore, a statistical ANOVA (table in Appendix D) showed that significant effects of the CTA on final grades were recorded in 2018 ($F=68.09$, $p = 0.000$), 2019 ($F=69.71$; $p = 0.000$) and 2020 ($F=34.91$; $p = 0.000$). For example, in 2018, 14 out of 62 students who got less than 50% in CTA1.1, did not improve on their CTA1.2 score and also received a final grade of less than 5. Similarly, out of the 20 students who got less than 50% in CTA2.1, one student did not improve their performance in CTA2.2 and received a final grade of less than 5. In 2019, of the 49 students who got less than 50% in CTA1.1, 9 students did not improve their score during the second attempt (CTA1.2) and got a final grade of 5 or less. This was even more evident in CTA2, where 11 of the 65 students who performed poorly (less than 50%) in attempt 1 and did not use the feedback to improve their result in attempt 2 also obtained a final grade of less than 5. In 2020, of the 61 students who scored less than 50% in CTA1.1 only 6 were unable to improve their score in CTA1.2 and obtained a final grade of 5 or less. All 56 students who performed poorly in CTA1 but showed better scores in CTA2 received a grade of at least 5. The results indicate that if students did well in both CTA1 and CTA2 they achieved a final grade of 5 or more in Fluid Mechanics.

To better understand the extent of the impact of the CTA, the linear regression coefficient was calculated (Table 3). Results of the linear regression revealed that in 2018, CTA1 and CTA2 significantly impacted student final grades with a coefficient constant of $\beta = \beta = 3.145$. Thus, a unit increase in the final grade obtained by a student had a CTA1 contribution of $\beta = 0.019$ and a CTA2 contribution of $\beta = 0.011$. In 2019, with a coefficient constant value of $\beta = 3.319$, a unit mark obtained by a student in their final grade had a significant contribution from CTA1 with a value of $\beta = 0.019$ and CTA2 with a value of $\beta = 0.013$. The contribution of CTA1 to student final grades was consistently significant from 2018 to 2020.

Comparing the average of CTA1 and CTA2 across all years showed a significant marginal contribution ($\beta = 0.028$ in 2018; $\beta = 0.033$ 2019 and $\beta = 0.027$ in 2020). Scores obtained in the combined CTAs (CTA1, CTA2) revealed a strong significant correlation (Corr.=0.630 in 2018 and in 2019 (Corr.=0.674) and a marginal correlation (Corr.=0.558) in 2020. Fig. 3 is a visual representation of the linear regression and the line-fit plots for each year demonstrate that there is indeed a linear relationship between performance in CTA and final grades.

4.2. *Qualitative analysis of survey*

Comparisons of cohort experiences from 2018 to 2020 (Table 4) revealed a number of similarities, including those where students expressed satisfaction, those where they expressed concern, and other recommendations worth considering. The broad emerging themes from the 2018 cohort highlights the extent to which the CTA improved their learning experience. The thematic summary included satisfaction with the CTA, relevance of the course materials and content to their learning, engaging and motivating activities, enhancement of their understanding of the topics, quality of the assessments and feedback to improve their learning, ability to apply theory and concepts to practical situations and how the CTA prepared them for their exams.

The relevance of the CTA to the course materials was helpful in enhancing the students' knowledge and understanding of the subject and enabled the students to digest the information more easily. More than 50% reported that, the CTA helped them gain a better understanding of what they learnt in class and were a good way for them to see how theories could be applied to solving problems. These views were also supported by the 2019 student cohort, who indicated that it was interesting to apply the knowledge they learnt in the course to real-world problems through the CTA.

Students from all three cohorts considered the integrated feedback loop in the CTA as beneficial to providing a deeper understanding of the topics. Students related this to the two attempts allowed and by explaining that it helped them fix errors made in their first response. The students described the feedback loop as thorough and helpful in closing their learning gaps, because they could see exactly where they went wrong, and what they could do to improve. In summary, the feedback loop between Takes 1 and 2 in the CTA provided them with an

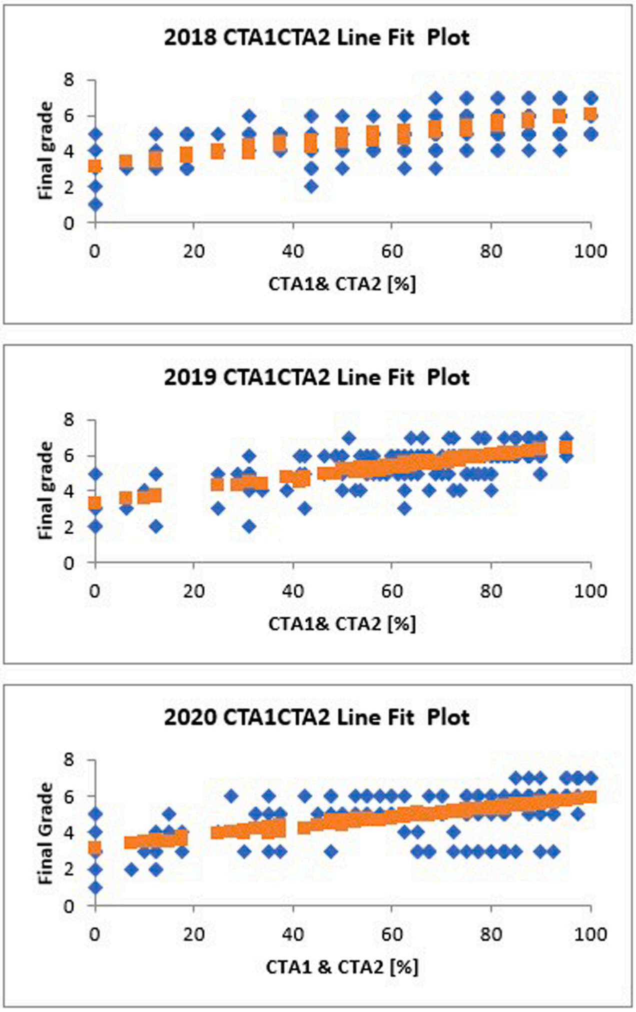

Fig. 3. Linear regression between the final grade and the CTAs. 2018 (top), 2019 (centre) and 2020 (bottom). Blue markers represent the final grade (out of 7) and orange markers depict the CTA results (%).

Table 4
CTA Theme classification and statistics (expressed as percentages).

Emerging themes	2018 N = 78 (n = 46)	2019 N = 66 (n = 46)	2020 N = 19 (n = 14)
Enhanced understanding/knowledge of topic	54.3	26.1	21.4
Enhanced Learning/performance/digestion of information	15.2	23.9	57.1
Encouraged/motivate learning	15.2	10.9	
Relating course material/content	8.7	23.9	
Enhanced Engagement – engaging	15.2	8.7	
Relating to Practical situation – application of theory	13.0	26.1	
Enhanced preparation for exams (Assessment)	10.9	26.1	21.4
Feedback/Solutions/Resubmission	17.4	32.6	42.8
Provide insight into learning progression	6.5	17.4	35.7
Relating to theory and concepts learnt (to real-life)	30.4	21.7	
Encourage independent practice of learning		10.9	

opportunity to identify how they were progressing in the course. The opportunity to resubmit their CTA allowed students to review and learn from their mistakes and gain greater understanding of the course content and theoretical concepts and areas where they need to improve.

Benefits of the CTA to learning progression were also identified by students who indicated that they were required to stay up to date with lectures and other course material to be able to undertake the CTA. Some students in the 2019 and 2020 cohorts proposed the inclusion of more CTAs, while a third of students in the 2019 cohort suggested that each topic in the course should have a CTA so that the understanding of all topics in Fluid Mechanics could be deepened equally. This reflects the general perception that the CTAs were a great way of applying theoretical concepts to solve real-life problems. A significant observation from the 2019 cohort was that some students (5) indicated that the CTA encouraged independent thinking and the application of learning that occurred during the lectures and tutorials. The CTA also encouraged high achieving students to critically assess and solve complex problems systematically. In addition, students appreciated the opportunity provided by the CTA to demonstrate the practical application of theories and concepts was valuable for future practice and helped them prepare for the Mid-Semester examination.

A small number of students (N = 3) expressed concerns about the consistency of marking for the CTA with marking perceived as either too easy or too strict. Some students also felt the rubrics used for marking were confusing, whilst others mentioned unclear or inconsistent feedback from tutors.

In summary, student feedback was consistent across the three-year period. Cohort responses centered around the helpfulness of the CTA to student learning, the relevance of the feedback to the improvement of their learning and performance, the opportunity to resubmit in an effort to improve their learning, the positive challenges the CTA provided to their learning and the ability of students to monitor their progression through the course. Generally, students described the CTA as ‘a good idea’, and ‘well structured’ in supporting their learning. The majority suggested that additional CTA would allow them to practice and work on their own, and to further improve their learning in the course. In addition, students suggested that greater weighting should be attributed to the CTA compared to the laboratories and the final exam.

5. Discussion

While research has indicated a number of interesting interventions to promote critical thinking, the impact of these interventions on student skills appears limited (Ahern et al., 2019) or does not have a lasting impact as reported in senior engineering students (Sola et al., 2017). The CTA reported in this study improved the student’s ability to think critically through the considered design of the activity. We found a strong positive correlation between performance in the CTA and student final grades. By using a problem-solving approach embedded in real-world oriented assessment, the CTA relates theoretical concepts to an everyday context and provides students with an opportunity to think outside the box. The use of CTA has provided clear benefits to student learning as reflected by their performance and has resulted in significant improvement in the student learning experience as described through the qualitative course feedback provided by students.

There is no consensus within the studies of how critical thinking should be measured most efficiently (Ku, 2009). However, we argue that at the most basic level and from the educator’s perspective the use of assessment activities such as the CTA provides an effective means of determining whether students have met the competency requirement of ‘critical thinking’ (critical thinking in a sense as defined and targeted by problem solving learning models (such as the IDEAL model described earlier). In addition, another significant impact of this assessment was that it also provides a very clear and effective means of differentiating students, allowing for more targeted support or extension activities to those that require it.

Based on our results the use of the CTA motivates students to learn in ways that traditional lectures and tutorials are unable to achieve. It does this by relating the concepts introduced to students during lectures and tutorials to real-word problems in a way that their significance to students is meaningful i.e. through their grades. By relating these problems to their everyday life or the work and problems that engineers encounter throughout their career, students are able to approach the theoretical lecture content from a different perspective which leads to a revelation in which these concepts can be applied to real world experiences. This revelation provides meaning and contributes significantly to students' motivation in the course and the ability to analyze and reflect critically which has been proven throughout the literature (Ahern et al. 2019, Gutiérrez Ortiz et al., 2021) and what has been coined "learner agency" in a recent study by Pisani & Haw (2023).

From our results and the feedback obtained we conclude that the CTA is correlated to improvements in the overall performance of students. We hypothesize that the impact of the CTA on student learning was sustained and carried through to the exam. Successful completion of the CTA is directly related to the ability of problem-solving activities to contribute to the development of sustained critical thinking skills in students. A significant part of the problem-solving activity, the feedback loop was considered by students as the best or one of the most useful features in enhancing their own learning and engagement. Feedback encourages reflection and is an important skill in the ability to think critically (Lynch et al., 2012). Although issues around the consistency of feedback were raised by some students, the vast majority thought that the feedback was helpful in allowing them to review their learning and to identify and understand where errors were made.

Based on our findings we recommend the use of CTA in undergraduate courses due to the importance of providing students with real-world learning experiences. and the impact that problem solving strategies can have on students' ability to think critically. However, when making any changes to instructional pedagogies there are a number of issues that exist. Firstly, incorporating activities such as the CTA should be considered from a course wide perspective or even across a program of study. Students may resent activities that are added ad-hoc and without significant alignment to the course learning outcomes and other activities therein. Secondly, resourcing issues are also manifested in activities such as this and careful consideration must be made to the workload of all teaching staff in the course – including the feasibility of tutors implementing the specified marking regime. A significant feature of 'quality' feedback is its timeliness (Chen et al., 2019; Sopina & McNeill, 2015). In an effort to provide the feedback required to stimulate students to think critically about their responses and resubmit the CTA, marking was effectively required twice. Therefore, special attention needs to be considered for large cohorts and any staff involved in marking, as it can be quite challenging to maintain the necessary time frames.

6. Conclusion

The rationale behind the implementation of the CTA in Fluid Mechanics was to encourage students to review their learning, apply insights gained by this reflection and to think critically about the fundamental concepts taught in the course. Despite the apparent difficulty in defining and measuring the process of critical thinking, these CTA have been implemented and evaluated over a three-year period and therefore provide a good record of how strategies and activities designed to encourage the process of critical thinking such as the CTA have impacted student performance and their learning experience as a whole. Different student cohorts consistently indicated that the CTA were helpful tools for their learning and prepared them for their exams. In particular, the CTA related to the course topics which helped to reinforce the lecture content. The feedback loop within the CTA provided significant reinforcement of student learning, as it enabled students to identify areas where they made mistakes and what they could do to improve. The CTA not only enhanced student knowledge and understanding of concepts, but also enhanced the evidence of learning and their overall performance in the course. The consistency of acknowledgement across all cohorts independently confirms the impact of the CTA on the student experience and their performance.

We recommended that as part of any further research the implementation of CTA should be encouraged and monitored in other (engineering) courses. By benchmarking CTA against the intended learning outcomes of the course and any graduate attributes the impact of these activities on students' employability can be more fully explored.

Declaration of Competing Intrerest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ece.2023.10.004.

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