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A Bibliometric Analysis on Critical Thinking Enhancement in Engineering Laboratory Context

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ABSTRACT

BACKGROUND & CONTEXT

Critical thinking (CT) is one of the keys 21st century attributes to be developed in engineering graduates, even from engineering laboratory education. Engineers need CT while designing and testing systems or solving complex problems. Some studies show CT can be enhanced through challenge-, project- and problem-based learning with proper scaffolding. Assessment of students, at a University in the Middle East, revealed lack of CT in laboratory context and this finding is supported by other studies.

PURPOSE

This research aims to investigate whether laboratory education adequately fosters CT and to examine trends in CT research in engineering education and highlight appropriate strategies and frameworks to be used in laboratory education to enhance CT.

METHODOLOGY

A bibliometric analysis was conducted using Web of Science and Scopus with keywords such as “critical thinking,” “enhance,” and “engineer.” Data were analysed using VOSviewer to generate network, density, and overlay visualisations. The study also identified key strategies for enhancing critical thinking through laboratory instruction and highlighted major contributors and frameworks within engineering education.

OUTCOMES

The findings show the under-utilization of laboratory education for enhancing CT. It identifies environments such as collaborative and problem-based learning in enhancing CT. There is indication that Paul & Elder Framework of CT, aligned to Facione's CT definition is suitable in this context. Argumentation and use of concept/argumentation maps are found to be the most widely used techniques for CT enhancement.

CONCLUSIONS

The results will guide engineering educators to include CT enhancement techniques in a laboratory setup, which is at present underutilized. It suggests utilizing argumentation strategies and use of concept maps, in a collaborative laboratory setting. It suggests using Paul & Elder framework of CT. A systematic literature review using PRISMA is recommended to validate and guide future research.

KEYWORDS

Engineering laboratory, Critical thinking, Argumentation, Paul & Elder Framework.

Introduction

With the 4th industrial revolution taking center stage, we are in the midst of a global reskilling emergency (Vesselina Stefanova Ratcheva & Guillaume Hingel, 2020). There are other agencies and studies which also point out to an inadequacy among the engineering graduates when it comes to graduate attributes (King & Australian council of engineering deans, 2008; Nair et al., 2009). There have been regular workshops and discussions regarding realigning engineering education to meet the challenges of the future (Beagon et al., 2022; Lasi et al., 2014). Training in skills rather than content is emphasised in many reports about engineering graduate attributes (Litzinger et al., 2011; Royal Academy of Engineering, 2018). As engineering educationists, it is an important part of our job to create engineering graduates armed with industry-ready skills. A balanced educational strategy with focus on critical analysis, design, experimentation and professional skills is recommended (Sheppard et al., 2008),

World Economic Forum reports the relative importance of different skill groups with growing demand. As per the surveyed employers, they identified Analytical thinking as the most important skill in their 2025 report with 69% of the surveyed employers suggesting its importance (World Economic Forum, 2025).

Definition of Critical Thinking

There are many definitions to CT. Many social scientists give importance to skills and dispositions when it comes to explaining CT. Since there were many definitions, American Philosophical Association involved experts in the field to come up with an acceptable set of definition to Critical Thinking. At the heart of all inquiry one finds fundamental reasoning skills such as (1) analysis, (2) interpretation, (3) inference, (4) evaluation, (5) explanation and, most important, (6) reflective self-correction. (P. Facione, 1990; P. A. Facione & Facione, 2013; P. A. Facione & others, 2011)

Cognitive Graduate Attributes in Engineering

Washington Accord (Washington Accord, 1989), of which most engineering accreditation bodies are signatories, specifies application of knowledge, problem analysis, design/development of solution, and investigation as the engineering graduate attributes in the cognitive domain. Engineers are expected to solve complex problems in all these domains. Investigation of complex problems using research-based knowledge and experimentation is one of the major graduate attributes in the cognitive domain and guides the laboratory learning outcomes set by accreditation agencies. (International Engineering Alliance et al., 2021).

It can be observed that the accreditation agencies of countries who are signatories to the accord follow the directions of Washington Accord in their own contexts. Accreditation agencies like ABET (Corporate Author, 2024), EUR-ACE (EUR-ACE® Framework Standards and Guidelines, 2021), AHEP (The Accreditation of Higher Education Programmes (AHEP), 2020), (Board of Engineers Malaysia, 2020), and other agencies focuses on 'Application of knowledge', 'Problem Solving', 'Analysis' and 'Design' skills of students in the cognitive domain

Learning Outcomes from Engineering Laboratory

Accreditation agencies defines the learning outcomes from laboratories. "An ability to develop and conduct appropriate experimentation, analyse and interpret data, and use engineering judgment to draw conclusions" ABET (Corporate Author, 2024). 'Use practical laboratory and workshop skills to investigate broadly defined problems' (The Accreditation of Higher Education Programmes (AHEP), 2020). As can be seen from these agencies and other accreditation agencies (Board of Engineers Malaysia, 2020; EUR-ACE® Framework Standards and Guidelines, 2021), for undergraduate engineering laboratories, it may be concluded that problem solving is the major cognitive process which has to be tackled by engineers, especially

through investigations. The common factor in all these outcomes is critical thinking (Miller & Olds, 1994; Vaez Ghaemi & Potvin, 2021).

“Analysis”, “Interpretation”, “use of engineering judgement to draw conclusions” are the common cognitive processes expected from engineering laboratories. These skills are an integral part of critical thinking (CT) skills (P. Facione, 1990; Paul & Elder, 2013). Hence, it can be concluded that critical thinking skills such as analysis, interpretation and inference are the most important skills which need to be enhanced through engineering laboratory.

CT Skills in Engineering: Gaps

CT skills as evaluated from the student submissions in a university in the Middle East, presented that only 60% students achieved the satisfactory level and is of concern. The prevalence of such gap in other parts of the world was hence explored. It is found that students' critical thinking abilities lack the depth (Chavez et al., 2014; Tan et al., 2017). This is again supported by a detailed study (Orjuela et al., 2023), which reports weakness in students' ability in ‘analysis’ and explaining ‘solution suitability’. These studies point out the weakness of engineering graduates in their critical thinking capability.

Relevance of the Study:

Literature reviews in the field of CT were reviewed to find if CT enhancement strategies were employed in engineering laboratory environment. (Dong et al., 2023a; Nuryana et al., 2024; Yücel, 2025) were papers which used bibliometric analysis to identify various aspects of CT enhancement in higher education. Most of the papers present generic information such as the no. of publications and the keywords used most frequently. They also identify the countries/regions, institutes and authors who were the most productive. The publications with the most citations are also identified. Some of them were in the field of primary education (Aktoprak & Hursen, 2022). Some were generic and not field specific (Dong et al., 2023a; Yücel, 2025). Other bibliometric studies conducted were to observe the current status of CT studies in various fields of higher education such as physical education (Ridwan et al., 2022), teacher education (Hursen, 2023; Wang & Jia, 2023). A varied list of assessment strategies was also found (Nuryana et al., 2024).

However, the focus on CT enhancement through laboratories is not considered in any of the papers. A bibliometric study about CT, in the field of engineering was also not found in the WOS database. Further study in other systematic literature reviews (Ahern et al., 2019; Ismail et al., 2023) from engineering education, again presented a gap in study of CT in laboratory education. Hence this study becomes important and can establish this gap, guide engineering educators in establishing a framework which can be used in laboratory environment to enhance CT.

Research Questions

1. Is laboratory instruction utilized in developing CT among engineering graduates.
2. What are the widely used teaching and learning environment, strategies and frameworks to develop CT Skills for engineering graduates so as to implement in engineering laboratory education.

Methodology

Bibliometric analysis is considered an initial step in a systematic literature review. Software such as VOS viewer, CiteSpace and others analyse bibliographic data about co-authorship, co-occurrence, citation, bibliographic coupling and co-citation. The software reveals key indicators about countries, journals or authors active in a field, its chronological variation, productivity of journals, research trends and gaps in research. Since the quality of data depends on the search criteria used, it is important to provide clarity about the keywords, inclusion and exclusion criteria used in search, and the analysis details. The research process

in this study is outlined in Figure 1. It is to be noted that unlike SLR, the database selection does not need in depth scrutiny. Database selection was mainly Web of Science (WOS). However, both WOS and SCOPUS were used in answering the first and second objectives as listed above. The similarity of results obtained, supported the use of a single database for this generic study and hence duplicates were excluded. Data collection and search strategy was decided based on the research objective and are explained in the respective sections.

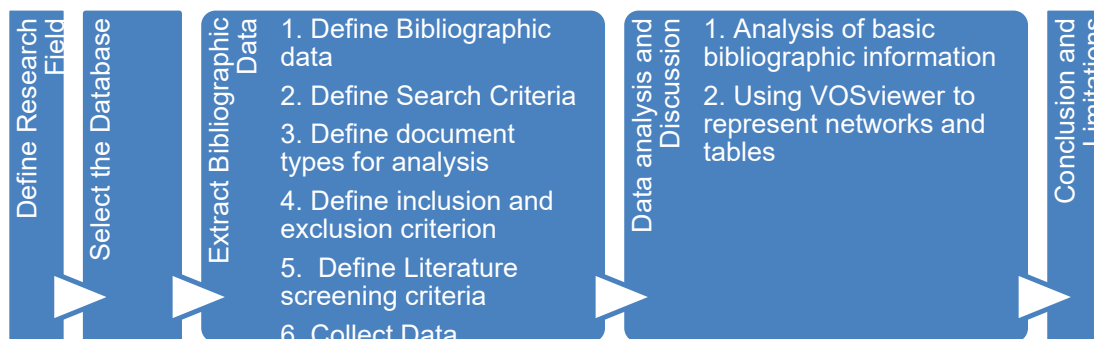


Figure 1 Research Process

Various features of the VOS viewer software (Eck & Waltman, 2023) prepared by Nees Jan van Eck and Ludo Waltman, associated with Universiteit Leiden, was utilized to provide network, overlay and density visualization maps and provide co-occurrence and linkages tables which could give clarity to the field being studied.

Findings

Research Question 1 : Identification of utilization of laboratory instruction, in developing CT in engineering graduates

To do this study, the following search procedure was carried out.

Table 1: Search Strategy

Category	Criteria	No: of articles
Research Field	Field: CT in Engineering	
Database Selection	Web of Science	
Search Criteria	Abstract: "critical thinking" OR "critical-thinking" OR "thinking skill*" OR "higher order thinking skills" OR higher-order thinking skills" OR "hots"	21,301
	All fields: engineer*	3599
Years	2000-2025	3457
Document Types	INCLUDE: Proceeding Paper, Article or Review Article	3391
Language	INCLUDE: English	3338
Keywords	EXCLUDE: keywords with less than 10 occurrences	
Literature Screening	No abstract screening was performed due to the no: of articles collected and as purpose of search was to get a larger view of the study.	

Web of science query Link: <https://www.webofscience.com/wos/woscc/summary/f8846898-35b9-4b4c-b427-cb955dac188f-01620159cf/times-cited-descending/1>

The thesaurus file option was initiated in VOS viewer to replace similar keywords to the same terminology as sampled in Table 2. It was done by providing the author keywords(labels) identified by the software and providing the alternate keywords, as defined by the researcher.

Table 2: Sample of thesaurus file to combine similar words in VOSviewer

label	replace by	label	replace by
critical-thinking	critical thinking	critical thinking ability	critical thinking
CT	critical thinking	critical reflection	critical thinking
critical thinking skill	critical thinking	critical thinking dispositions	critical thinking disposition
critical thinking skills	critical thinking		

The network visualization of keywords associated with CT is as shown in Figure 2.

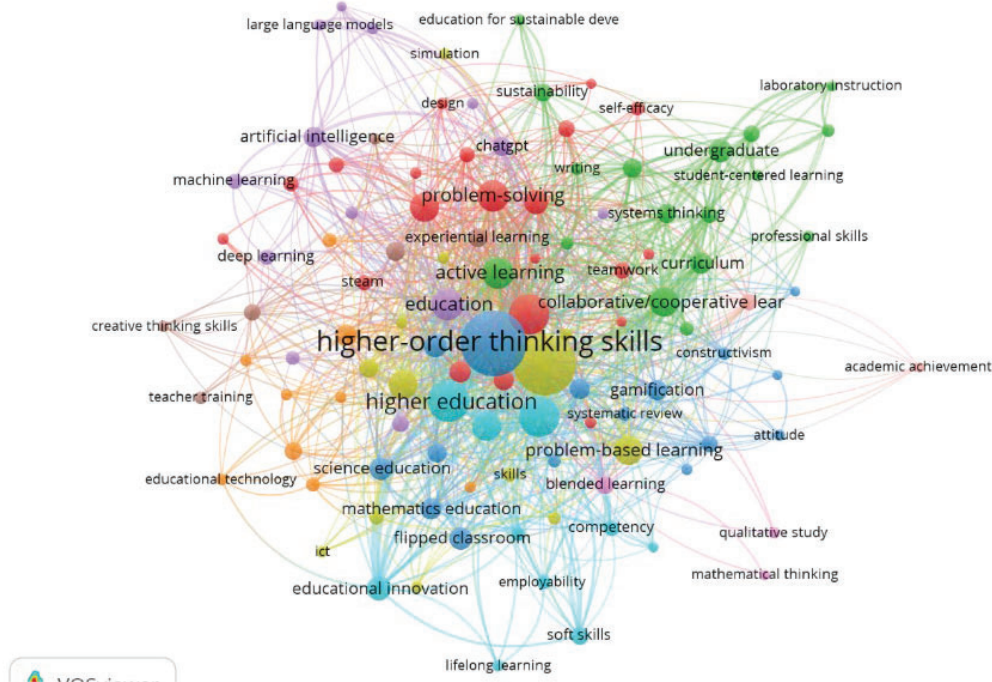


Figure 2: Keyword Network Visualisation: CT in Engineering

It can be observed that the plot is cluttered with the words used for the search. Many bibliometric researchers keep the 'search words' in the cluster of keywords presented (Aktoprak & Hursen, 2022; Dong et al., 2023b; Nuryana et al., 2024; Yücel, 2025). However, this clutters the keyword visualization and beats our purpose, which is to identify the main keywords which are related to CT in engineering undergraduate education. VOSviewer has the option to uncheck the keywords so as not to use it in the analysis. This was done by using the following strategy:

1. Keywords used in searching the WOS like "critical thinking", "higher order thinking", "engineering*",(which are obviously going to be the most occurring keywords)
2. Words like "undergraduate", "undergraduate education", "higher education", "education", "engineering", "engineering students" etc (which again does not add any value to the bibliometric study to identify the strategies and patterns used)
3. Words like "STEM", "STEAM" were removed as the focus is on engineering.
4. Any words like "chemical engineering" and other fields, which may provide linkages of CT in engineering are kept.

This criterion was used before the network map was re-generated using the VOS viewer. The visualization chart, Figure 3, shows the key areas which are active learning, collaborative/cooperative learning, problem-based learning, problem solving, computational thinking and project-based learning.

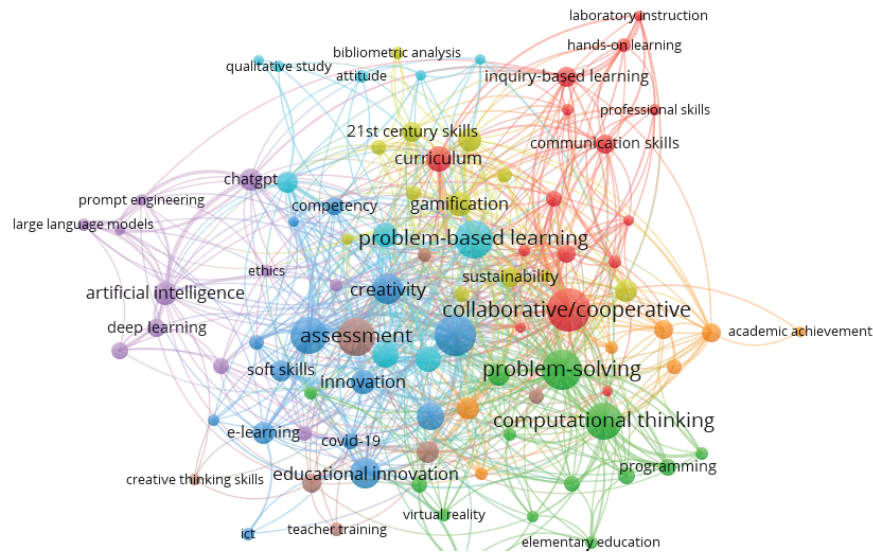


Figure 3: keyword network visualization: CT in engineering: regenerated

The main clusters formed:

1. Collaborative/cooperative learning, teamwork, student centred learning, Inquiry based learning, professional skills, communication skills which very well combine together. laboratory instruction and hands-on learning which is our focus are associated in this cluster
2. Artificial Intelligence, large language model, deep learning, chatgpt, machine learning, etc which are emerging trends, presents itself as a distinct cluster.
3. Computational thinking, problem solving, augmented reality, technology, robotics, programming are seen associated together in a cluster in computer related one.
4. Project based learning, active learning, creativity, educational innovation, flipped classroom, soft skills, are associated together in the third cluster.

A literature review of lab based CT activities shows a handful of CT enhancing activities. The strategies mentioned in those labs are: Instructor feedback and counter questions(Burkholder et al., 2021; Miller & Olds, 1994), Project based laboratory with real world design(Zhang et al., 2020), and Problem based laboratory sessions(Orjuela et al., 2023; Vaez Ghaemi & Potvin, 2021)

Key findings:

It can be visualized that laboratory instruction/hands-on learning is the furthest away from the critical thinking related keywords as presented in Figure 2 and Figure 3(Top right). These findings are further strengthened from the initial literature review. This suggests that laboratory instruction, even though is in the horizon of CT education, is under-utilized in CT enhancement studies. This is even when, the main learning outcome to be achieved by students from laboratory education is to demonstrate CT skills. This provides a gap and an opportunity for laboratory instructors to implement strategies in enhancing CT.

Research question 2. Widely used teaching/learning environment to enhance CT in engineering education

The learning environment suggested for CT enhancement in engineering laboratory can be visualized from the linkages which shows how collaborative/co-operative learning in a team based activity can support CT. Suggestions from literature shows alignment of Social constructivist theory as an effective strategy for CT enhancement(Burkholder et al., 2021; Cáceres et al., 2018; Giner-Navarro et al., 2022; Sasson et al., 2018; Vaez Ghaemi & Potvin,

2021). Students in teams can engage in Problem-Based Learning activities as required by the accreditation agencies. Cluster 1, presents a possible environment for CT enhancement and is a good indication on how laboratory education can be utilized in this context.

After identifying the appropriateness of using the laboratory environment, it is important to identify the strategies being employed in CT enhancement in the education community and not necessarily in engineering education. It is suggested that any strategy which works in other fields can also work in engineering. To develop this study, the following strategy as given in Table 3 was used to collect bibliographic data from both WOS and SCOPUS databases.

Table 3: Search Strategy CT enhancement techniques

Category	Criteria	No: of articles	
Research Field	Critical Thinking		
Database		WOS	SCOPUS
Search Criteria	Abstract: "critical thinking" AND (improve OR enhance OR train OR teach OR develop)	12468	13504
Years	2021-2025	12152	13032
Document Types	INCLUDE: Article	8189	7950
Language	INCLUDE: English	7634	7403
Keyword visualization	EXCLUDE: keywords with less than 20 occurrences.		
Literature Screening	No abstract screening as purpose of search was to get a larger view of the study.		

<https://www.webofscience.com/wos/woscc/summary/143d69fd-a61a-45c3-baec-c7750389fdc9-0160d8a620/times-cited-descending/1> . Use this query link to download the documents.

Similar search using SCOPUS database resulted in finding 7403 documents in English Journals. Analysis was done using VOSviewer for Co-occurrence of author keywords. The minimum number of occurrences of a keyword was set to 20 and 160 keywords met the threshold.

The Network visualization map was generated using downloaded data from both databases.. The findings from both maps(not presented) confirms the position of laboratory instruction farthest from CT supports the findings regarding RQ1. This similarity also indicates the necessity to use only WOS database for further studies.

CT enhancement strategies:

Keyword co-occurrence study was conducted to find the strategies used for CT enhancement using both databases. The strategies presented in literature, as per abstract review of a few of these documents are debate(Latif et al., 2018; Lin & Crawford, 2007), socratic method(Ho et al., 2023; Oyler & Romanelli, 2014), peer feedback(Hwang et al., 2023; Lynch et al., 2012) and argumentation. Occurrence of keywords collected presented the following results as shown in Table 4.

Table 4: co-occurrence CT strategies

keyword	SCOPUS		WOS	
	occurrences	total link strength	occurrences	total link strength
argument mapping	7	14	8	16
argumentation	52	115	58	124
debate	27	72	27	72
peer feedback	33	75	38	86
socratic method	7	20	6	20
socratic questioning	6	15	6	11

Both databases show the prevalence of argumentation as the most widely used strategy associated with CT. It shows around 55 occurrences, which is in concurrence with similar findings in similar CT studies (Dong et al., 2023b). Argumentation is found to be effective in many findings (Caratozzolo et al., 2019; Siverling et al., 2021)

Use of Argument maps/Concept maps is also highlighted in CT enhancement studies observed from Table 4. Further studies suggest using these as cognitive tools to train and assess CT(Barta et al., 2022; Si et al., 2019).

Framework Identification

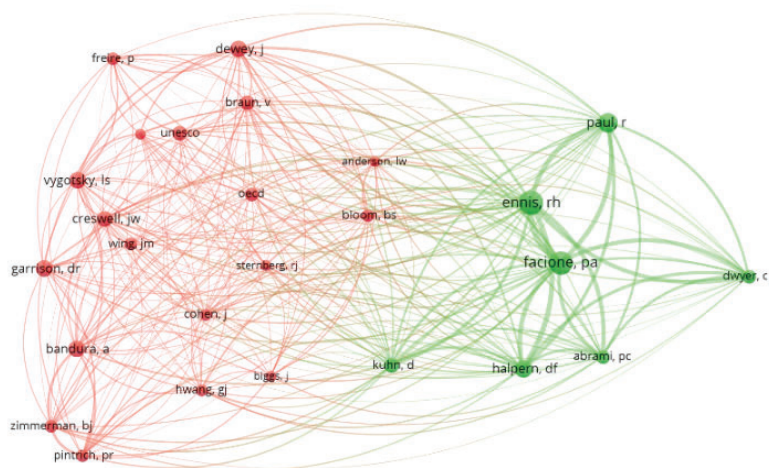


Figure 4: Co-citation network

Facione's CT definition was adopted after proper scrutiny. Hence, it is important to find the framework which matches Facione's school of thought. Further refinement of the above dataset was done in WOS by adding "frame*" in all fields. It resulted in a dataset of 2006 documents. A co-citation analysis was done with cited authors to identify any connection. Using a threshold of minimum 50 citations per author, 26 authors were identified and linked (Figure 4). Peter A Facione (237 citations and 1198 link strength) can be seen well connected with Robert H. Ennis (238 citations and 1331 link strength) and Richard Paul (155 citations and 709 link strength) On careful reading, it can be seen that Ennis RH was more into defining CT and Richard Paul along with Linda Elder had suggested a framework in Critical Thinking. As seen prominent in the co-citation network, and as found effective from other published work in engineering studies(Adair & Jaeger, 2016; chavez et al., 2014), it will be assumed that the framework of Paul & Elder be effective in developing CT in the engineering context.

Recommendations and Implications for Future Research

The study clearly established a gap in the utilization of engineering laboratory in the development of CT. This is when, CT is regarded by the engineering community as the skill to be utilized during investigation in labs in analyzing and interpreting results to reach conclusions. The study can guide engineering educators to develop and implement CT enhancement frameworks applicable in engineering education. The results points at using collaborative/co-operative learning in a team environment. The study also suggests the use of Argumentation and use of Concept/Argumentation maps using Paul & Elder framework to enhance CT.

The implication of the above results is expected to bring back focus into Laboratory Education in Engineering, which was visualized as being given very less importance in the development of CT. This could also overcome challenge faced in CT enhancement, mainly the availability of time with students as the lab environment provides ample time for faculty/teaching assistants with students.

Since Bibliometric studies are good in providing indications about further research, it is recommended that a systematic literature review be done and the findings be confirmed.

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