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A literature review of critical thinking in Engineering education

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A review of critical thinking in engineering education

Developing optimum solutions to engineering problems typically relies on structured and complex thought processes that require evaluation, interpretation and opinion. Well-developed critical thinking (CT) skills are essential for dealing with the multi-dimensional nature of these problems. CT in an engineering context is well reported in teaching and learning academic literature. However, much of this is framed within theoretical and conceptual frameworks. Practical approaches of how CT skills are best promoted in engineering curricula are less common. A state-of-art review of practical interventions that target the development of CT in engineering students is presented. The review draws on 25 selected peer-reviewed journal articles in established engineering databases and focusses on teaching strategies where their effects in promoting CT skills in students are measured. Considerable variability in the reviewed literature was apparent. CT interventions and strategies are often reported, but metrics of their success in enhancing students' CT is often limited to qualitative, subjective inferences. To more robustly and holistically ensure that CT is clearly embedded in university curricula, there needs to be well-funded research programmes that allow different methods to be developed and trialled over extended periods in higher education engineering programmes.

Keywords: critical thinking; skills; dispositions; engineering; intervention; assessment

Introduction and context

A recurring recommendation of international education bodies, such as the Accreditation Board for Engineering and Technology (ABET) concerns the importance of embedding critical thinking (CT) instruction, along with other generic engineering competencies (otherwise known as soft skills), in engineering curricula (Nainpally et al. 2012). As part of the CRITHINKEDU¹ project, focus groups were conducted with engineering employers (Dumitru et al. 2018a), and the gap between the CT skills required in new graduates, and the CT skills actually exhibited by them, was identified

¹ <http://crithinkedu.utad.pt/en/crithinkedu/>

as an issue. In these focus groups with engineering employers, it was emphasised by employers that CT skills are vitally important for engineering graduates but that these skills are often not engendered in graduates. It was also identified in those focus groups that while students have strong technical skills, their CT skills were not addressed sufficiently. A previous study by Ahern et al (2012) has found that CT is seen by engineering employers and academics as a vital graduate attribute. However, Ahern et al (2012) also found that engineering academics were less sure than academics in non-technical disciplines of how to define CT and that the definitions and opinions they held regarding CT were less concrete and more abstract. According to Ahern et al (2012), engineering academics found it hard to verbalise what they meant by CT. For this reason, it is important to understand what universities are doing to try to bring CT to students and to identify if engineering faculties are introducing instructional strategies for CT.

Through a systematic review of the literature, this work intends to answer the following main question: What are the teaching strategies currently used in engineering to promote CT and how effective are these strategies? The objectives are to: (i) improve the understanding of how CT is being developed in EE; (ii) identify best practice for CT teaching and evaluation; (iii) highlight the challenges and barriers found by teachers in the adoption and implementation of CT educational practices and, (iv) present recommendations for addressing knowledge gaps in the current literature.

This paper presents a review study that identifies and describes at a practical level the teaching approaches, methods, resources and assessment strategies that are currently used to promote CT in engineering education.

Relationship between Problem solving and CT

In engineering, one of the skills valued by the job market and by employers is the ability of the engineer to solve problems in the workplace (Jonassen et al. 2006; ABET 2014; Claris and Riley 2012; Dominguez et al. 2015). The problems that engineers may have to face at work may be of different types, such as technical problems and other related to interpersonal relationships.

For example, Jonassen et al. (2006) explain that the workplace problems are ill-structured and complex because they possess “conflicting goals, multiple solution methods, non-engineering success standards, non-engineering constraints, unanticipated problems, distributed knowledge, collaborative activity systems, the importance of experience, and collaborative activity that rely on multiple forms of problem representation”. As Longren and Svanstrom (2015) stress, addressing wicked sustainability problems, such as climate change, poverty, and resource scarcity has shown to be challenging for engineering students. They lack of the appropriate tools for dealing with the complexity, uncertainty, and value conflicts that are present in these situations.

Itabashi-Campbell et al. (2011) state that in engineering, problem-solving is as much a social process as a technical exercise. The technical skills, interpersonal skills, social skills, leadership and motivation are important for the dynamics of engineering in problem solving and in the creation of knowledge (ibid).

From the perspective of Trevelyan (2007), coordinating technical work with other people and cooperation are very important aspects of engineering practice, and it is necessary to develop a systematic approach in engineering education that promotes the development of the needed skills.

Due to these characteristics of the problems at the workplace, Jonassen et al. (2006) recommend that in engineering education, the programmes should consider the characteristics of real problems and encompass problem-based learning strategies and environments.

The connection between CT and problem solving in engineering is a recurring theme in the literature (Saiz and Rivas 2008). It involves the assessment of available information and subsequent evaluation of decisions taken. Despite the clear importance of CT in engineering education, there are still relatively few studies relating CT in engineering. Instead, discussions about CT in engineering are usually associated with pedagogical approaches that relate to problem solving, decision making, experimental achievements, and the impacts of technology on society (Claris and Riley 2012).

However, together with a more systemic thinking (Longren and Svanstrom 2015), engineers need to develop critical thinking skills to deal with a changing world (Aidar and Jaeger 2016). The quality of thinking of engineers, and how they think, determines the quality of what they design and produce. In this sense, teaching/learning critical thinking involves articulating assumptions in problem solving, selecting appropriate hypotheses and methods for experiments, and structuring open design problems (ibid.), as well as developing, through the interpersonal interactions critical thinking dispositions.

CT education practices in engineering

Facione (1990) describes CT as a “purposeful, self-regulatory judgment which results in interpretation, analysis, evaluation, and inference, as well as explanation of the evidential, conceptual, methodological, criteriological, or contextual considerations upon which judgment is based”. In this context, CT can be considered from two perspectives, namely, skills and dispositions (Angeli and Valanides 2009). CT skills are

characterised as a set of capacities, such as analysis, evaluation, interpretation etc. (Abrami et al. 2008), which require monitoring to evaluate the quality of thinking, and capacity for self-correction (Behar-Horenstein and Niu 2011). CT dispositions are understood as characteristics or predispositions of the individual, such as curiosity, openness of mind, prudence in making decisions etc.. (Facione et al. 1994).

This set of cognitive skills and CT dispositions can be developed through specific pedagogical strategies that promote their acquisition (Facione 2011; Tiruneh et al. 2014) and CT skills may be developed through teaching interventions (e.g. case studies, PBL, argumentative debates, etc.), but still require further development (Dwyer et al. 2014). Interventions that develop CT dispositions have been given less attention, possibly due to the complexity in addressing intrinsic characteristics such as student motivation, personalities, etc. There is a clear need for methods that show how these dispositions can be promoted and developed more systematically in engineering students in a continuous way (Cruz et al. 2017; Dumitru et al. 2018a; Dumitru et al. 2018b). In this sense, instructional methods are essential for students to engage in CT learning activities, and educators need to be sensitised to the adoption of teaching approaches that promote understanding of CT (Dominguez et al. 2015).

Instructional design and assessment for CT

Although there have been increased efforts in recent years to apply different instructional design principles that can better foster the acquisition and transferability of CT skills, the challenge lies in knowing which instructional strategies are most effective (Halpern 1993; Tiruneh et al. 2014). Some of the recurrent pedagogical strategies in the literature include FRISCO (Ennis 1996), the guidelines of Elder and Paul (2003), the 'IDEALS' technique of Facione (2011), Lecture-Discussion Teaching (LDT), Problem-Based Learning (PBL) (Ennis 2016), as well as problem solving (inquiry), lecture

discussions (argumentation), group work, role-play, self and peer-assessment and context-based learning (Dumitru et al. 2018b). Dwyer et al. (2014) also suggest that providing and constructing maps with structured arguments improves students' critical thinking. According to Ennis (1989), there are four distinct modes of CT instruction, namely, *general*, *infusion*, *immersion* and *mixed*. These modes describe how explicit the instructor is when teaching CT; selecting the appropriate approach is an important issue that requires consideration.

One of the biggest challenges for educators is how to evaluate the students' CT level (Aidar and Jaeger 2016), as there is little consensus on how it should be measured (Liu et al. 2014). Designing an assessment method for CT requires a careful collaboration of various specialists of domain content and psychometrics of university. Each plays a distinct role in ensuring that the evaluation method is valid, reliable and connects to key principles of undergraduate education (Liu et al. 2014). This is supported by Dwyer et al. (2014), who notes that there is little clarity in the relationship between how CT is taught with how it is assessed.

Tiruneh et al. (2014) note that the assessment of CT acquisition and transfer is difficult, as researchers adopt various types of measures that span a wide range of formats, focusses, and psychometric characteristics, depending on the conceptualisation and nature of the items involved in the evaluation. There are also limitations associated with the design of interventions, namely studies with short duration between the pre-test and the post-test (ibid).

Behar-Horenstein and Niu (2011) recommend that more than one measure should be used, combining quantitative and qualitative assessments, to assess changes in students' CT, as this provides a more accurate and comprehensive assessment of change in CT. Working in the field of health education, they report that the use of various

assessment tools such as open-ended questions, essays, interviews, observations, etc., can help researchers find and describe the practical meaning of treatments and identify factors which influence the development of CT (ibid). Some of the most common standardised instruments for CT assessment are: Watson-Glaser Critical Thinking Appraisal tool (Watson and Glaser 1964), Cornell Critical Thinking Test (Ennis et al. 1985), Motivated Strategies for Learning Questionnaire (Pintrich et al. 1993), California Critical Thinking Disposition Inventory (Facione et al. 2001), and the Halpern Critical Thinking Assessment (Halpern 2010).

Research Methodology

To meet the objectives of this paper, a systematic review of the English language literature was jointly conducted by two teams of the CRITHINKEDU project (Portugal and Ireland). The approach developed was based on the systematic review method by Borrego et al. (2014; 2015) adapted to the purpose of this paper presented through the acronym PICO:

P – Population: Students in Higher Education Institutions (1st and 2nd cycles) in Engineering programmes;

I – Intervention: CT-related learning strategies; Complete description of the strategy (goals/design/assessment of outcomes/...); Evaluation of acquired skills/attitudes;

C – Comparison: Reports on different teaching and learning strategies to compare;

O – Outcome: Effective teaching and learning outcomes and Increase in the CT Skills/attitudes.

The research methodology was structured in five phases following the work of

Bennet et al. (2005) as depicted in Figure 1.

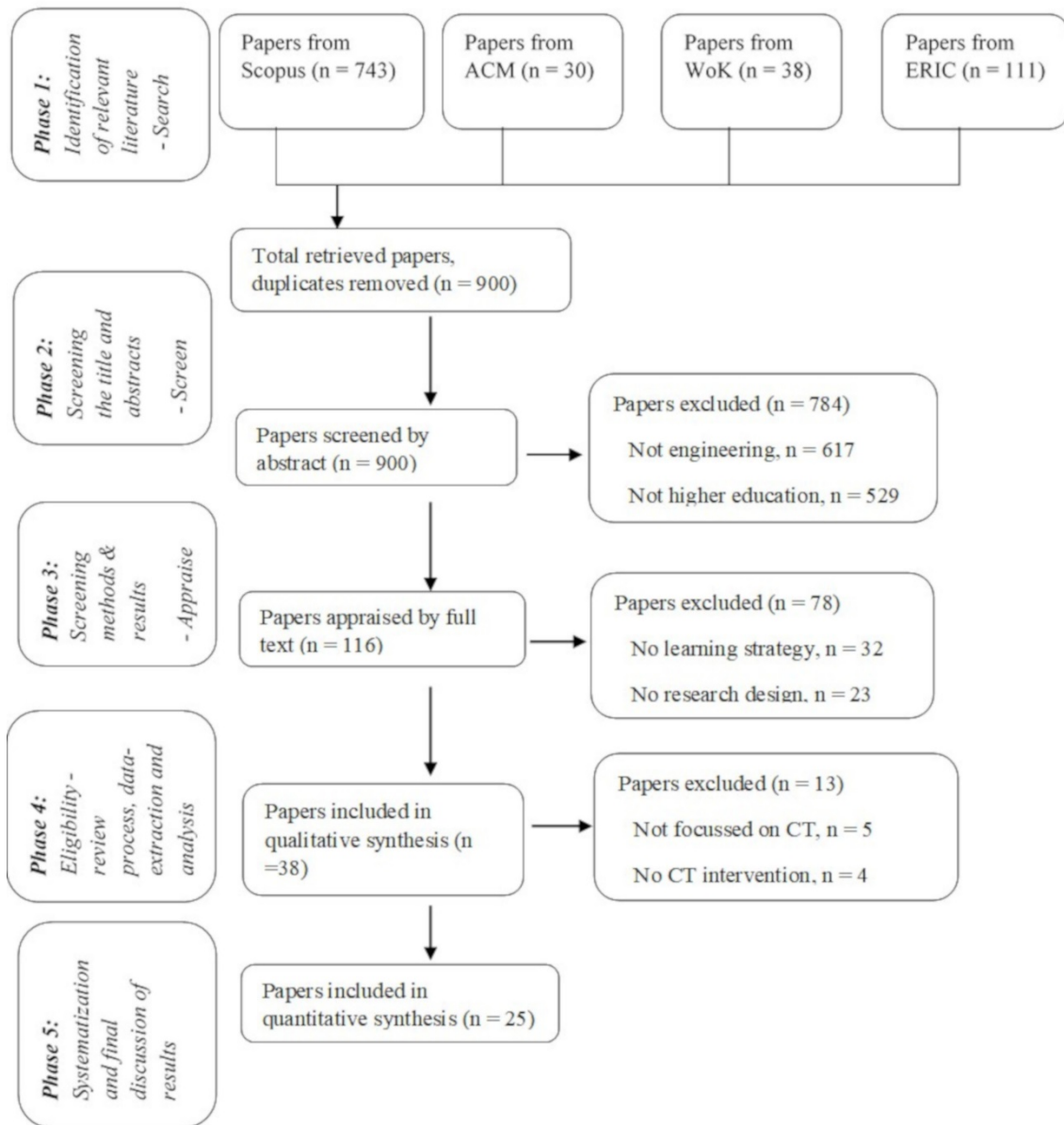


Figure 1: Work structure

Phase 1: Identification of relevant literature

The search was limited to relevant peer reviewed journal articles published since 2008 in the Association for Computing Machinery (ACM), Web of Knowledge (WoK), SCOPUS and Education Resources Information Center (ERIC) databases. The keywords used in searching the papers were:

- critical thinking/engineering reasoning;
- skill, ability, disposition, attitude;
- higher education, universities, faculties, tertiary education, college;
- interventions, strategies, practice, training;
- engineering.

In order to search the databases the above terms were searched for as followed:

(“Critical thinking” OR “Engineering reasoning”) AND (skill OR ability OR disposition OR attitude) AND (High* education OR universities OR faculties OR tertiary education OR college) AND (Interventions OR strategies OR practice OR training) AND (Engineering).

Phase 2: Screening the title and abstracts

The initial screening identified 922 potentially relevant papers. When duplicates were eliminated, 908 papers were identified. The abstract and title of each of the identified papers were reviewed independently by two authors.

Inclusion criteria required that papers presented an actual teaching intervention to promote CT and that the efficacy of the intervention was qualitatively and /or quantitatively assessed. In this phase 8 duplicates were found, and 784 papers were excluded, leaving 116 papers for the next phase.

Phase 3: Screening methods & results

The full text of each retained paper from the previous phase was reviewed independently by at least two authors. Papers were only retained if they showed a clear description of the learning strategy used; a clear description of the research design and method, and an evaluation of CT using effective assessment methods or instruments.

This resulted in the exclusion of 78 papers and 38 papers remained in phase 4.

Phase 4: Eligibility - review process, data-extraction and analysis

This phase required data-extraction and analysis of the 38 papers. The analysis of these articles utilised a rubric developed by CRITHINKEDU (a European project on Critical Thinking in Education) project members (Dumitru et al. 2018b). The developed rubric was informed by Abrami et al. (2008); Tiruneh et al. (2014) and Abrami et al. (2015) and was adapted to align with engineering practices. The rubric considered

- (a) the research goal/ question/ purpose of the study;
- (b) the research design and methodology
- (c) the study level
- (d) the field of engineering;
- (e) the research sample
- (f) the duration of the intervention
- (g) the CT skills and dispositions targeted [based on Facione (1990)]
- (h) the overall approach to CT [based on Ennis (1989)]
- (i) the specific type of interventions [based on Abrami et al. (2015)] / teaching strategies utilised [based on Ennis (2016)]
- (j) the learning activities and resources
- (k) a description of the CT assessment and the methods used for data collection
- (l) the analysis and identification of CT skills and dispositions assessed
- (m) the impact of the pedagogical intervention on CT
- (n) the reported challenges, barriers and difficulties in carrying out the research work
- (o) the limitations of the study identified in the paper.

Of the 38 papers that were analysed through this rubric, 25 were accepted for the final discussion and 13 were excluded on the basis that they were deficient in some aspect(s)

of the established criteria. The final 25 were then passed to Phase 5.

Phase 5: systematization and final discussion of results.

For the final 25 papers included, the analysis from the rubric in Phase 4 was used to discuss and comment upon the CT interventions. These papers are listed in Table 1, along with the ID numbers that are being used to identify the papers in the results below.

Presentation and Discussion of results

The analysis of the papers selected for review was conducted as described below. It was possible to count some factors presented in the rubric. However, this proved to be impossible for all factors as papers were generally not explicit in terms of describing the factors in the rubric. Instead, the rubric allowed patterns to be identified as being common amongst the papers.

Approaches to critical thinking in engineering

In general, the approach to teaching CT in engineering courses places an emphasis on problem solving and the impact of real-world situations and/ or case studies on student ability to learn CT skills. The use of authentic situations (including case studies) was the most commonly described intervention, described in at least 8 of the papers. The majority of papers did not specifically define CT or use a CT framework, but aspects of CT could be inferred (for example in ID2_W; ID19_E; ID48_E): these aspects include problem solving, analyticity and evaluation. Other studies (such as ID16; ID9) clearly defined CT in the paper, in ID16 the definition of CT is based in Paul-Elder framework (Paul & Elder, 2009) and the conceptualization of Scriven and Paul (1987), whereas the ID9 CT definition is based in the work of Facione and Facione (1992), and also clearly

defined CT to the students.

Table 1 shows the approaches used in the papers. ID16 and ID9 employed an infusive approach and described how students in the programmes were taught about a particular CT framework. ID46 also described how students were provided a lecture on CT skills before commencing on specific exercises. Other papers, for example ID59 used a mixed approach.

Approach	# papers
Infusive	7
Immersive	7
Mixed Approach	11

Table 1: Approaches

Papers usually did not specify particular skills (for example ID10; ID18; ID14; ID5; ID2_W; ID20). It was however possible to infer the most common skills and dispositions from the papers, as shown in Table 2. These skills are most likely a reflection of the fact that a majority of the papers focussed on problem-solving, and many engineering papers frequently equate CT with problem solving (for example ID18; ID5). Some papers focussed very specifically on one or two CT skills: *self-regulation* was considered by ID57 while ID25 explored *argumentation*, in relation to ethics, for students.

Most commonly mentioned skills and dispositions	# papers
Analysis	7
Inference	5
Explanation	5
Evaluation	5
Interpretation	4
Inquisitiveness	5
Open mindedness	5
Analyticity	4

Table 2: Skills and Dispositions commonly mentioned in papers

The research methods described in the papers were quasi-experimental or experimental in all cases (for example ID10; ID5; ID2_W; ID16; ID). Samples were predominantly male, which is not unexpected given that engineering classes are more likely to include higher numbers of male students in most countries.

Types of intervention and teaching strategies

Most reported interventions (14 out of 25 papers) were short, typically 1 semester or less, and involved a lecturer or module coordinator making changes in a single module (for example ID10; ID2_W), as shown in Table 3. It was rare to find evidence of more co-ordinated or cohesive approaches to teaching CT skills across a programme or degree course. This confirms the need for a greater number of teaching interventions to develop critical thinking skills (Dwyer et al. 2014).

Duration of interventions	# papers
Less than one semester	14
More than one semester	11

Table 3 Duration of interventions

However, one study stood out from other ones in that it was the only one taking a coordinated approach to teaching CT skills within a programme. Such longitudinal experience was described by ID16 which outlined the CT skills to be developed, as well as the approaches and assessment methods used. It described a program that adopted the Paul-Elder Framework to intentionally stimulate and incorporate CT in undergraduate engineering curriculum. The results of the program demonstrated a positive impact on the development of students' critical thinking abilities. Also, the authors described a plan for assessing results of the program. This assessment program is based on feedback loop (assessment, revision, implementation, assessment, etc.) which strengthened on-going strategies that assess ABET outcomes, and improved students' critical thinking skills.

11 out of 25 papers were found to be of longer duration, but there was considerable variation between these. For example, the studies described by ID18; ID5; ID21; ID19_S; ID48_S; ID57; ID13_S are based on a single intervention over the course of 1 semester. That intervention was then repeated over a number of years, meaning that each cohort of students experienced the intervention on one occasion only.

Teaching strategies employed most often included problem solving/problem-based learning, case-based studies and lecture discussions (for example ID2_W; ID18; ID45). Problem-based and project-based learning were the most commonly described

strategies (for example ID21; ID48_S; ID46; ID57; ID9; ID50). The use of case studies and real-life situations appears to be extremely popular in engineering as a means of encouraging students to develop CT skills, with authors feeling that engagement in real-life engineering problems allows students to gain a better understanding of the complexities that a professional engineer would experience in practice (for example ID17; ID9; ID13_S; ID23; ID45).

This shows also that the scientific and pedagogical community is concerned to develop skills that are valued by employers, namely the ability of an engineer to solve real problems of the workplace (Jonassen et al. 2006; Claris and Riley 2012; Dominguez et al., 2015; Aidar and Jaeger 2016).

ID46 describes how using problem-based learning allowed students to take on the types of roles that they might experience in the real world (for example as a structural engineer or as an architect) and that this would allow them to experience the stages of project management actually lived by real engineers, thereby encouraging them to develop CT skills.

Assessment and evaluation

In the studies considered in this paper, there is often some overlap between assessment of CT in the students and evaluation of the interventions. Assessment of CT is the measurement of the attainment of CT skills in students, as a result of the intervention. The authors of this paper consider evaluation of the various interventions in the context of their efficacy as a teaching tool to develop CT skills in students. Common to many of the reviewed papers, the assessment of CT was made using a quasi-experimental/experimental design with both control and experimental groups of students, each one exposed to different teaching strategies in order to compare their different effects. Examples can be found in the papers ID57; ID3_S; ID18; ID2_W. In

the case of ID57 and ID18, this involved students undertaking the module at the same time, but with different teaching methods and different instructors. Grades were compared including some form of statistical analysis of both cohorts of students (ID2_W). However, this method of evaluation has limitations (e.g. one class may be stronger than another), nor does it allow for other biases, including instructor bias. Other studies looked at pre-tests and post-test of the same students where students' CT skills were assessed both before and after a particular intervention (for example ID17; ID57; ID20; ID50; ID14; ID19_S).

Other overlap between evaluation and assessment is also evident: many papers described collecting feedback from students – sometimes by interview and sometimes by survey, in order to evaluate the impact of the teaching interventions on their CT skills (examples include ID17; ID46; ID10; ID36; ID50; ID45). It was rare for students not to express positive feedback about interventions. These questionnaires and surveys were, in some cases, also used to assess the CT skills of the students. ID46, in addition to grading the design projects submitted by students, used interviews and surveys of students to evaluate how a problem-based learning teaching approach impacted upon students' CT skills. ID9 was very explicit in CT skills assessment in students: it included an analytic memo where students were asked to reflect upon the impact of the problem-based learning intervention on their CT skills. This memo was used to both assess the students and evaluate the intervention. ID57 used a very particular type of survey – the Situational Motivational Scale at the task level and the Motivated Strategies for Learning Questionnaire at the course level– to evaluate the impact of integrated project learning (where engineering students are exposed to teaching from other humanities courses while working on projects) on CT skills, like self-regulation. ID16 also clearly describes a very detailed and well-defined quantitative method of

assessing CT skills, involving a number of lecturers and graders who received training in how to mark and assess CT using an engineering holistic critical thinking rubric based on Paul-Elder critical thinking framework. In this case, the assessment was designed and aligned to the CT interventions which had been introduced, through a critical thinking assignment for students. Each of the student artefacts (assignment) was scored by two engineering faculty (or three, if there was greater than a one-point discrepancy between the two faculty rater scores), using the holistic critical thinking rubric. Also, to assess the consistency of the paired faculty rater scores was used the intraclass correlation coefficient.

The fact that specific CT skills were not always clearly defined at the outset of some studies, however, means that assessment was not always transparent. Therefore, making any general conclusions regarding the relative impact of different teaching strategies and interventions on the attainment of CT skills and dispositions in engineering is difficult: there have been few studies in the discipline that have clearly defined what is meant by CT or have clearly assessed CT in students, or evaluated CT interventions in a very quantifiable way. In fact, there is little consensus about how CT should be measured (Liu et al. 2014) in engineering.

For many studies, improvements in problem solving skills are identified and equated with improvements in CT (examples include ID48_S; ID14; ID50; ID57). ID57 found that students exposed to integrated project-based learning demonstrated improved CT skills and dispositions in their project work. ID50 found students exposed to PBL had improved conceptual learning.

Study limitations

The limitations encountered in this review largely relate to the methodologies of the research employed in the various papers. Several authors cited the limited sample (both

in size and composition) as a limitation of the studies (for example ID10; ID2_W). ID2_W also outlined that the use of questionnaires and feedback from students were not sufficient to be able to generalise the findings. In the majority of cases, studies were limited to one course and one university, which authors saw as a limitation (ID21). This is a criticism that could be made of many of the studies: they tended to describe relatively small experiments with limited cohorts of students and limited evaluation of the impact of the interventions. Therefore, reaching general conclusions about the success or otherwise of those interventions is difficult. Assessing the long-term impact on critical thinking skills in engineering students has not been conducted in most of the studies (with the notable exception of ID16). In addition, the studies generally do not make any allowance for instructor bias.

Conclusions and recommendations

The review of CT in engineering education was motivated by a perceived gap in the CT skills of graduates by employers, in particular in engineering (Dumitru et al. 2018a): it would appear that engineering employers do not feel that engineering graduates possess CT skills. While it is acknowledged that it is difficult to identify the most effective instructional strategies for critical thinking through a review of published studies, given the relatively low number of studies in existence, the review set out to identify the range of teaching interventions being used in engineering to improve the CT skills and dispositions of engineering students. While a number of the reviewed articles outlined different approaches and teaching strategies in engineering courses, these papers tend to be somewhat limited in that they typically focus on the impacts of interventions of students in single modules, in single universities. There is a need for a more cohesive approach to CT in engineering programmes, where skills are taught across the programme and where there are links and relationships formed across modules and

stages. While the authors have identified a number of interesting and laudable interventions to promote CT, the impact of these interventions on student skills appears limited by not being part of a more coordinated approach across a programme to teach CT, and to ensure that CT is embedded across a programme. It is also interesting to note that there is no consensus within the studies read of how critical thinking should be measured. This echoes recent reports on new engineering curricula (Graham 2018).

The studies described in this paper appear not to be externally funded and in the main, result from the efforts of individual instructors or groups of instructors to develop CT skills in the students they teach. To more robustly and holistically ensure that CT is clearly embedded in university curricula, there needs to be well-funded research programmes that allow different methods to be developed and trialled over extended periods in higher education engineering programmes.

Much of the research in CT is underpinned by theoretical concepts and conceptual frameworks which have been described extensively by researchers in the area. However, this review shows that from the educator's standpoint there is disconnect between CT theory and the practice of teaching CT in engineering: in engineering, it would appear that there is limited awareness of theories of CT. The CT described in many studies are subjective, and not underpinned by theory or CT literature. Therefore, there is a need to bring CT theory to engineering educators and practitioners and to do so in a way that is tangible, practical and understandable. Much of the CT literature does not seem to have permeated the consciousness of engineering educators.

While outside the scope of what is described in this paper, the focus groups conducted with engineering employers, and described by Dumitru et al. (2018a) as part of a wider project looking at CT in Europe, would indicate that there is also a

disconnect between employer's understanding of CT and educator's understanding of CT. There is a need for more analysis of these disconnects, between CT theorists and engineering educators, and between engineering educators and engineering employers.

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