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CRITICAL THINKING TO EMBED SUSTAINABILITY IN ENGINEERING COURSES ACTIVITIES. A SYSTEMATIC LITERATURE REVIEW

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Abstract

This contribution presents the results of a systematic literature review, which tries to explore the current trend in engineering studies to include Sustainable Development (SD) in the curricula with the support of Critical Thinking Skills (CTS).
As future technical problem solvers, critical thinking (CT) development is considered essential for engineering students. Beside UNESCO announces CT as one of the key transversal competencies to insert SD into academic curricula, among others as, systems thinking, collaboration, normative competence, anticipation, self-awareness, strategy and problem solving. However, the way to embed sustainability in engineering education is uneven, and each academic institution or lecturer designs its own model for including sustainability in teaching.
After some years embedding SD in engineering curriculum, arises the need to know if lecturers actually implement models that contribute to inserting SD supported by the so demanded CTS according to UNESCO, and, if so, how are the adopted didactic designs. All it, with the aim to obtain a model to design effective training activities to insert SD in the engineering classroom through this key competence for engineering students. This work is considered an interesting study that combines the much-demanded need on the part of evaluation agencies to include SD and CT in engineering studies to train socially committed professionals according to the challenges and scenario of the 21st century.
The literature review was carried out systematically, according to the standards of the specialized bibliography. Nearly 40 articles obtained from the Scopus, WOS, and IEEE Xplore databases were analyzed. Its mains results show that there are fewer activities working on sustainability through critical thinking. In most cases, SD related PBL activities are carried out, and critical thinking is one of the ingredients needed for PBL process, which is developed transversally. Nevertheless, also interesting design has been found.
This paper shows the detailed results of the review, that is, the role of CT in analyzed papers and the description of teaching methodology used to embed both SD and CT. In addition, possible orientation is proposed to work critical thinking with sustainability activities for future lines of work are proposed.

Keywords: *Critical Thinking, sustainable development, engineering education, literature review*.

1. Introduction

UNESCO (2017) defines Education for Sustainable Development (EDS) as a transformative action to empower and motivate learners to become active sustainability citizens who are capable of critical thinking and able to participate in shaping a sustainable future.

According to this vision, among the learning objectives for achieving sustainable Development Goals (SDGs), UNESCO includes, in the aforementioned document, the Critical Thinking competence, as "the ability to question norms, practices and opinions; to reflect on own one's values, perceptions and actions; and to take a position in the sustainability discourse" (UNESCO, 2017, p.10).

Otherwise, CT is one of the principal competences for engineering graduates according to employers (Ahern, Dominguez, McNally, O'Sullivan & Pedrosa, 2019) that aid engineers in problem solving processes, especially in an increasingly rapid changing world (Adair & Jaeger, 2016).

About the need to insert CT and SD in engineering curriculums much has been written, below there is a brief summary of the most relevant highlighted ideas for the purposes of this research work.

1.1. Critical Thinking in engineering education

According to Lai (2011) the skills of CT consist principally in analyzing arguments, drawing inferences, judging or evaluating and taking decisions, with the object of guiding problem-solving; Ennis (1989) also includes metacognition among these elements. Besides Bezanilla-Albisua, Poblete-Ruiz, Fernández-Nogueira, Arranz-Turnes, and Campo-Carrasco (2018) go beyond, and include in the third domain level of CT skills, the action to transform the reality. Which fits with UNESCO vision of CT skills for SD.

In engineering education, where problem solving is one of the main activities, the CT skills acquisition seems essential; seen CT as a systematic thinking process transferable to different situations. Thus, in the criteria list of the most important engineering programs accreditation agencies, there are items clearly related to CT. They were analyses and classified by Malheiro, Guedes, Silva and Ferreira (2019) and some of them arouses and were classified as CT related skills. See Table 1.

Table 1. CT skills in Accreditation agencies criteria.

Competency	Body	Desired professional skill
Critical Thinking and Problem solving	ABET	Ability to understand the impact of engineering solutions (critical thinking) Ability to identify, formulate and solve engineering problems Ability to recognize the need for and engage in life-long learning
	EA	Ability to undertake problem solving, design and project work Ability to display critical reflection Capacity for lifelong learning and professional development
	UKEC	Ability to critically evaluate, make judgements, and frame appropriate questions to achieve a solution to a problem Ability to manage their own learning
	ENAEE	Ability to do judgements, identify, formulate and solve engineering problems as well as to manage complex technical or professional activities Ability to engage independent life-long learning

Source: adapted from (Malheiro et al., 2019, Table 1); ABET (Accreditation Board for Engineering and Technology): USA; EA (Engineers Australia): Australia; UKEC (Engineering Council):UK; ENAEE (European Network for Accreditation of Engineering Education): Europe.

Nevertheless, in a literature review about CT in engineering education, Ahern et al. (2019) concluded that in general, there is not ensured that CT training is embedded across engineering programs; the activities to learn CT skills are isolated and short, and mainly are centered in problem-solving and real-world situations. They also stated that in the majority of papers CT aspect could be inferenced, although there is not specified the CT framework or definition.

1.2. Sustainability for engineering students

According to SD, currently, there is a global process for the holistic insertion of SD in higher education institutions, which includes also action plans to insert ESD into their academic curricula (Lozano et al., 2014). This is happening too in engineering syllabus with the inclusion of sustainability competencies (Sanchez-Carracedo et al., 2021). In this EDS inclusion context, engineering programs are special for some institutions which see engineering as "vital" change actor, and claim the necessity to form future engineers to address the mitigation and adaptation to climate change and the reduction of poverty (Walk, 2010; Engineering Council, 2021).

According to Duarte et al. (2020) engineers must be trained in the practice and awareness of sustainability. That is, students must take awareness about how their profession impacts the environment and the society and must know that they would have to actuate toward sustainability in their future career.

The accreditation organizations identify among others some aspect of sustainable development that must be address in engineering education courses. Duarte et al. (2020) made a comparative analysis between worldwide accreditation agencies to show how sustainability is present in the accreditation requirements of ENAEE, ABET, or NAE (National Academy of Engineering) an also for UNESCO. The result are summarized in Table 2.

Table 2. Sustainability related skills.

Organization	Strong technical scientific background	Interdisciplinary	Work in complex teams	Improve the quality of life for all	Rational usage of global resources	Social Responsibility	Environmental Responsibility	Develop Sustainable Societies	Environmentally friendly technologies	Cultural Responsibility
UNESCO	✓	✓	✓	✓	✓	✓	✓	✓	✓	
ENAEE	✓	✓	✓	✓		✓	✓	✓		✓
ABET	✓					✓	✓	✓	✓	✓
NAE	✓			✓	✓	✓	✓	✓	✓	✓

Source: Duarte et al. (2020)

In the described scenario, it looks interesting to include SD in engineering education with the support of CT; not only to include sustainability driven activities but to achieve EDS transformative objective in engineering graduates. Thus, with the aim to know what is going on currently on pedagogical interventions in engineering education that combine SD and CT, a systematic literature review has been conducted. The main research question of this work is: What are the teaching activities in engineering education supported by CT to embed ESD in the syllabus? And the pretended objective is to detect good practices to include SD in engineering education with a transformational perspective aided by CT.

2. Methodology

The systematic review of English language literature was conducted according to the method designed by Ahern et al. (2019), who analyzed CT in engineering education. Ahern's procedure is an adaptation of the general method proposed by Borrego, Foster and Froid (2014) for systematics reviews in engineering education. Considering the porpoises of this research, the procedure established by Ahern et al. suited perfectly in this research, so the methodology was replicated. Nevertheless, not having this research a quantitative analysis, instead of five, only four steps were conducted (see figure 1).

2.1. Phase 1: Identification of relevant literature

The search was limited to articles published from 2017 (year of the publication of UNESCO report linking CT skills and ESD) in SCOPUS, WOS and IEEE Xplore.

The keywords were:

Critical Thinking, Critical Thinking Skills

Sustainable development, sustainability, sustainable developments, sustainable development goals, SDG, SD

Engineering education, engineering.

The search algorithm was: (critical thinking" OR "critical thinking skills") AND ("sustainable development" OR "Sustainability" OR "sustainable education" OR "sustainable development goals" OR "SDG" OR "SD") AND ("engineering education" OR "engineering").

2.2. Phase 2: screening the title and abstract

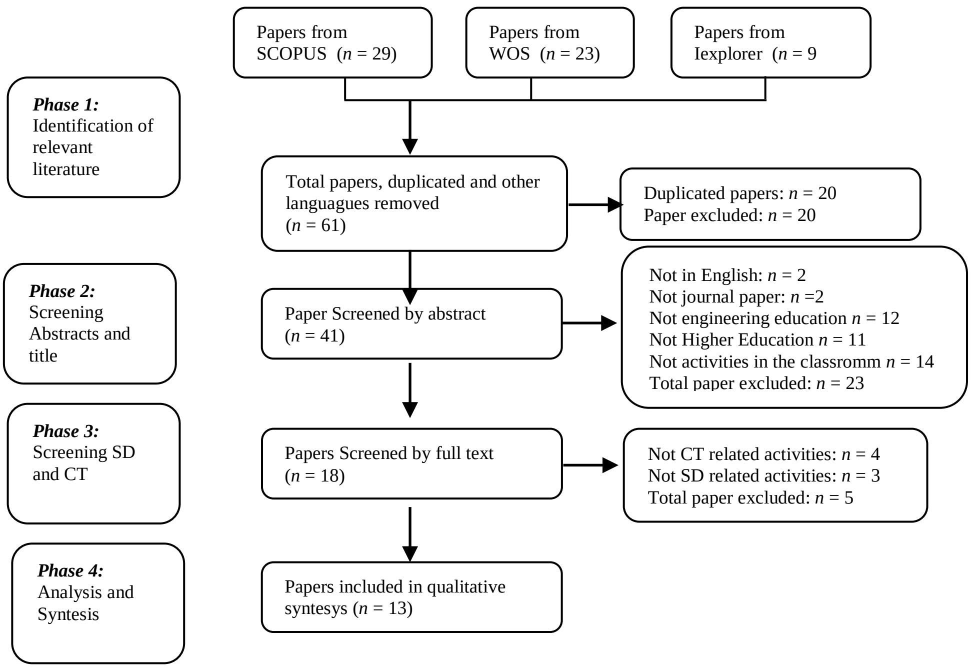
Potential 61 papers were identified, and 20 duplicated papers were eliminated. Finally, the abstract and titles of 41 paper were reviewed.

To be included in the study the papers had to describe applied activities in engineering courses (in higher education) were sustainability and critical thinking were developed. After this first screening, 18 papers passed to the following step.

2.3. Phase 3: screening methods CT and SD

18 full tests were reviewed. Only were accepted finally those that described the followed methodology to develop in the classroom scenarios or activities related to sustainable development that make explicit the intention to develop Critical Thinking skills and Sustainable Development. Five were removed for not achieve the admission criteria.

Figure 1. Research procedure.



2.4. Phase 4: review process, data extraction and analysis

In this phase data extraction of 13 full tests was done, de obtained information was about: (a) engineering courses and level; (b) intervention length; (c) applied approach or methodology; (d) way to integrate SD; (e) way to integrate CT; (f) assessment method of SD; (g) assessment method of CT.

One paper was removed, because the same intervention was described in two papers. The 12 analyzed papers are listed in table 3 with their identifiers.

Table 3. Finally analyzed papers.

ID	Reference
ID_5	Hoople, G. D., Chen, D. A., Lord, S. M., Gelles, L. A., Bilow, F., & Mejia, J. A. (2020). An integrated approach to energy education in engineering. *Sustainability*, 12(21), 9145.
ID_7	Membrillo-Hernández, J., J Ramírez-Cadena, M., Martínez-Acosta, M., Cruz-Gómez, E., Muñoz-Díaz, E., & Elizalde, H. (2019). Challenge based learning: the importance of world-leading companies as training partners. *IJIDM*, 13, 1103-1113.
ID_9	Gupta, C. (2022). The Impact and Measurement of Today's Learning Technologies in Teaching Software Engineering Course Using Design-Based Learning and Project-Based Learning. *IEEE Transactions on Education*, 65(4), 703-712.
ID_15	Pradhananga, P., & ElZomor, M. (2023). Developing Social Sustainability Knowledge and Cultural Proficiency among the Future Construction Workforce. *Journal of Civil Engineering Education*, 149(2), 04022011.
ID_19	Ocampo-López, C., Castrillón-Hernández, F., & Alzate-Gil, H. (2022). Implementation of Integrative Projects as a Contribution to the Major Design Experience in Chemical Engineering. *Sustainability*, 14(10), 6230.
ID_23	Rodriguez-Dono, A., & Hernández-Fernández, A. (2021). Fostering Sustainability and Critical Thinking through Debate—A Case Study. *Sustainability*, 13(11), 6397.
ID_29	Colmenares-Quintero, R. F., Rojas, N., Kerr, S., & Caicedo-Concha, D. M. (2020). Industry and academia partnership for aquatic renewable energy development in Colombia: A knowledge-education transfer model from the United Kingdom to Colombia. *Cogent Engineering*, 7(1), 1829805.
ID_30	Khandakar, A., Chowdhury, M. E. H., Gonzales, A. J. S. P., Touati, F., Emadi, N. A., & Ayari, M. A. (2020). Case study to analyze the impact of multi-course project-based learning approach on education for sustainable development. *Sustainability*, 12(2), 480.
ID_33	Malheiro, B., Guedes, P., Silva, M. F., & Ferreira, P. (2019). Fostering professional competencies in engineering undergraduates with EPS@ ISEP. *Education Sciences*, 9(2), 119.
ID_34	Gatti, L., Ulrich, M., & Seele, P. (2019). Education for sustainable development through business simulation games: An exploratory study of sustainability gamification and its effects on students' learning ouCTomes. *Journal of cleaner production*, 207, 667-678.
ID_35	Baillie, C., & Male, S. A. (2019). Assisting engineering students along a liminal pathway and assessing their progress. *Australasian Journal of Engineering Education*, 24(1), 25-34.
ID_38	Gallego-Schmid, A., Schmidt Rivera, X. C., & Stamford, L. (2018). Introduction of life cycle assessment and sustainability concepts in chemical engineering curricula. *International Journal of Sustainability in Higher Education*, 19(3), 442-458.

3. Results and discussion

The duration of intervention is declared in seven papers, all of them are short, only one (ID_15) was two semesters long; all interventions are isolated interventions in the curriculum, consistent with Ahern et al. (2019). Some of them are designed to be developed in more of one course (ID_15 and ID_19), and others have students of more than one engineering degree or master (ID_7, ID_9, ID_33, ID_38). According to the course type, three interventions are developed in sustainability related courses or modules (ID_34, ID_35, ID_38) and the rest are interventions in ordinary courses, or capstone project (ID_19, ID_33).

Adopted approaches in most of the cases (ID_7, ID_9, ID_19, ID_29, ID_30, ID_33) are challenge, project, problem or design-based learning approaches (CBL, PjBL, PBL, DBL) or their combinations; with open solution, real world and complex problem, project or challenges. However, in a good design it should be taken into account that as indicated Duarte et al (2020) a sustainability project is not only driven by sustainability, but to the achievement of the UN Sustainable Development Goals. Mainly, the declared aim of the adopted scenario is to develop SD and CT skills within a favorable environment, while a sustainability related problem is solved. Nevertheless, it is not the only option. In ID_23, ID_35 and ID_38 debates are raised, in ID_35 gamification and in ID_35 a service-learning activity.

Two insertions type of SD are differentiated. In ID_19, ID_29 and ID_30 interventions, students work on a SD related case, and it is considered that in this way sustainability competencies are already developed, indeed SD skills are not even evaluated. However, in the others, students work also on a SD issue to acquire SD skills. Which are evaluated separately through evidence from student's productions, or exams.

For the CT, something similar should be pointed out, in interventions ID_30 and ID_34 it is understood that the active method used develops CT skills, and CT is not evaluated. In the others, specific activities are designed or identified to develop CT and it is evaluated in all of them but in ID_38.

The activities that are specifically designed to develop the CT are mainly: reflective readings (in almost all of intervention); analysis/synthesis of issues related to SD from various approaches (in ID_5, ID_15, ID_38); debates (in ID_23, ID_35 and ID_38) and games (in ID_34). In those last cases, CT is evaluated by analyzing the documentation provided by the students, stands out a reflective diary (in ID_35), used with a transformational objective.

For the purposes of this study, the articles ID_35 and ID_23 stand out. In both cases, the CT is used to achieve EDS transformative objective.

4. Conclusions

The most adopted approaches are problem and project-based learning with sustainability related issues to solve, but they must be oriented towards the achievement of the UN Sustainable Development Goals.

The literature review conducted has been useful for the intended purpose: detect activities that serve to use the CT to achieve SD skills in engineering education.

It seems that intended designed activities to promote CT like debates, or reflective journals among others, can create the desired EDS transformative in engineering education.

Therefore, it seems that to achieve a transformation towards ESD in engineering, the way forward is as follows: create an active and trustworthy learning environment; design or agree with a social agent or company a sustainability problem to be solved; and design, make explicit and evaluate highly level critical thinking activities oriented to achieve SD skills.

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