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Teaching Creativity in Engineering Schools: A review of the Literature*

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Creativity is an imperative catalyst for innovation within engineering education. This research undertakes a semi-systematic integrative literature review to examine various creativity teaching approaches within engineering schools across diverse universities. By analyzing 60 papers published or presented between 1995 and 2019, this study identifies distinct strategies employed in fostering creativity. One pivotal approach revolves around the decision to introduce creativity as a standalone subject or integrate it into the existing curriculum. Furthermore, the discussion extends to the timing of creativity instruction, whether it is incorporated at the outset or towards the conclusion of the four-year program. The results indicate a progressive increase in endeavors to cultivate creativity in engineering education over time, with a shift towards its integration within the core curriculum. This materializes through the introduction of creativity-enhancing tools, the adoption of Problem-Based Learning (PBL) methods, and the establishment of interdisciplinary environments in education. This study serves to enrich the landscape of creativity in engineering education by presenting a spectrum of teaching approaches from engineering schools globally, offering valuable insights to educators and researchers in the field.

Keywords: creativity; teaching philosophies; higher education

1. Introduction

21st-century engineers are expected to produce creative and innovative solutions to problems [1]. Governments are seeking creative and innovative thinking people because creative thinking "produces innovations, bringing new interpretations and valuable products" [2]. In this respect, engineers are expected to play important roles in dealing with these challenges; however, the question is how universities could contribute to educating creative engineers [3]. Engineering's uncertainties and complexities benefit from creativity to address these challenges as it motivates students to contribute to their field and society, while also enhancing engineers' problem-solving skills, and requires engineering faculty to nurture innovation [4].

Engineers need to be as good at creative thinking as they are with technical knowledge [5]. Creativity needs to be fostered throughout engineering education curricula to obtain innovative results from engineers [6]. Therefore, it is worthwhile to know what has been done in this field so far in engineering schools at various higher education institutions. This is particularly important to shape the future of engineering education by benefitting from best practices that are based on previously applied educational approaches.

It is not feasible to universalize the definition of creativity in our present world due to its intricacy. Researchers used different words to better describe creativity; "novelty" and "appropriateness" [7], "imagination" [8], "making the strange familiar" [9]. Different versions of creativity are described [10], namely, from the art, crafts, and invention perspectives. The current study is interested in the last one: "It is the creativity involved in solving practical problems, in engineering and in discovery. It is the creativity of invention, often associated with the fields of science and technology" [10]. Some [11] described creativity as "functional creativity" to indicate the importance of functional requirements in the engineering field. Creativity helps engineers deal with complexity, shape new knowledge, and find new solutions to problems [12].

Researchers [13, 14] agree that creativity is the basis for innovation. Creativity is "the act of coming up with original solutions relevant to problem-solving", and innovation is "the implementation of a creative solution" [15]. "Without creativity in design, there is no potential for innovation" [16]. This study uses the definition that was compiled in previous research conducted by the author: "Creativity empowers the engineer with ingenuity to tolerate the unconventional so as to generate original and non-obvious alternatives, which ultimately lead to better, innovative and worthwhile solutions to design problems" [17].

Creativity needs to be developed in engineering education for many reasons. First, creativity must be counted as a central aspect to design, engineering and problem solving [1, 6, 18]. Second, the creative skills of engineers should be enhanced to achieve innovative solutions to problems [19].

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Current employers demand that engineers have design and practical skills. However, students lack these skills due to the insufficiency of preparatory coursework focused on integrating the design process into the initial phases of students' educational trajectory [20]. Even though the goal is to teach engineering students how to be creative and innovative, the fast changes in technology and the growth of disciplinary knowledge leave insufficient time and room in curricula for implementing these concepts [21].

Traditional engineering curricula, that are mostly theory-based, are unlikely to satisfy the demands of current engineering accreditation criteria [22]. Traditional educators impart knowledge but neglect fostering students' creative-thinking abilities [2]. Within the realm of engineering projects, creativity is frequently viewed as a supplementary procedure that takes a backseat to the technical facets [23]. "Creating an ideal environment to develop creativity and innovation in engineering education is a real challenge" [24]. However, lately, to prepare students to become a driving force in the design industry, engineering education has extensively incorporated training in creativity [25].

This paper reviewed several educational approaches aiming to improve students' creativity and creative-thinking abilities in engineering education at several universities. This study aims to make a contribution to research in engineering education by presenting different types of teaching creativity approaches in engineering schools from around the world. The results of this study will provide insights to engineering educators and educational researchers who are seeking ways of enhancing creativity in engineering education.

2. Method

The aim of this literature review is to provide an overview of different approaches for teaching creativity in engineering education.

The approach of this study is "integrative review approach" as the purpose of the review is "not to cover all articles ever published on the topic but rather to combine perspectives and insights from different fields or research traditions" [26]. An integrative literature review aims "to assess, critique, and synthesize the literature on a research topic" [26]. As reviewing every single relevant article was not possible, the study adopts a "semi-systematic review approach" [26]. Besides the aim of overviewing a topic, a semi-systematic review aims to find and comprehend all research traditions that may be relevant to the topic being studied [26].

When the objective is to present a summary of a specific issue or research problem, literature reviews are valuable. Additionally, they assist in assessing the current understanding of a particular subject [26]. With this approach, this study reviewed 60 studies on creativity in engineering education. How the studies were retrieved and selected for inclusion are presented in detail.

First, a search was conducted on the following electronic collections and databases: EBSCOhost databases, ScienceDirect, Web of Science and Google Scholar. The keywords, titles, abstracts, and topics were searched for the keywords: "creativity" and "engineering education" together.

Apart from the abovementioned collections, the bibliographies of the retrieved papers were examined to reach different research papers and thus broaden the extent of the review. Although the initial aim was to involve only published journal papers, the author included conference papers after finding many quality conference papers about the practical applications of creativity teaching in engineering schools. Teaching creativity and creative thinking skills in engineering is an educational practice. In most cases, these studies were performed with educational purposes, not for research purposes. Therefore, the educators behind these papers might have preferred to share their experiences merely in conferences with other educators. The author did not want to miss these valuable experiences of such educators by restricting the search to journal articles. This approach not only helps enrich the review but also gives us the opportunity to follow some researchers in their future work by providing an extended bibliography.

The process of incorporating the papers was carried out by the primary author, who is a seasoned design educator and holds a PhD in the field of creativity in engineering education. The author read each paper to decide whether to include it in this study or not and only included the papers which showed the best evidence. To mitigate the effects of subjectivity and bias, certain inclusion criteria are pre-formulated.

The inclusion criteria of the research papers are described below:

- Only studies that took part at the higher education level were included.
- Only studies that took place in engineering schools were included.
- Only studies written in English and published/presented between 1995 and 2019 were included.
- The strategy was to include only studies published/presented since 2000 based on the connection between creativity and 21st century teaching and learning approaches. However, papers produced before 2000, until 1995, were also included

due to their small number and their diverse approaches in teaching creativity. The papers published between 2020–2023 predominantly centered on the impact of Covid-19 and mainly featured interventions carried out online due to lockdowns. As education is gradually transitioning back to face-to-face instruction following the pandemic, the papers published during that period were excluded.
- Only studies that describe conducted interventions in engineering educational environments with the aim of fostering, enhancing or teaching creativity/creative skills were considered.
- Only empirical studies were included.

There were many valuable studies on creativity in engineering that were not included in this study. The exclusion criteria are as follows:

- Studies that took place in high school design, technology or engineering subjects were not included, because this paper focuses on studies that took place in higher education.
- Papers which merely inform about the current situation of educational institutions about creativity and do not implement any action were not included.
- Theoretical studies were not included. The reason for that was to understand the consequences of the educational practices.
- Studies conducted across universities were not included due to their comparative rather than descriptive structure.
- Papers on improving the creativity of engineering experts were not included because the foci of this review paper are engineering education and students.
- The papers about enhancing the entrepreneurship, problem-solving or design skills of engineering students were not included either. These are indeed crucial skills that need to be present in engineering education. However, this review is mainly interested in the connection between creativity and engineering education.

There are some limitations of this study:

In conjunction with the database search, several papers were obtained from the bibliographies of the reviewed literature. Despite not having been identified through the database search, these papers were included in the present investigation. Consequently, the total number of papers sourced from each respective outlet was not formally documented, as is customary in a systematic review. This may present challenges to the replication of this study. Furthermore, it is plausible that the search strategy implemented by the author may have inadvertently overlooked engineering courses that do not employ "engineering" or "creativity" as a keyword. It is worth noting that this study is limited by the fact that it only encompasses papers published up until 2019; however, this decision was made in a deliberate and conscientious manner, as outlined above.

It is imperative for readers to bear in mind that the efficacy of the examined interventions is predicated upon the information presented within the pertinent papers. It has been accepted that the authors of the analysed papers possess expertise in their respective domains, which enables them to evaluate and articulate the impact of their interventions.

The included papers were organized, summarized and presented in a table with the following headings:

The Authors: the reference number of the paper;

Year: the year the paper was published or presented;

University/Country: the institution where the study took place;

School: the school/department where the study took place;

Practical interventions: description of the actions and interventions conducted to teach/enhance creativity/creative thinking;

Date/Duration: the educational level where the actions and interventions were implemented; duration of the intervention;

Nature of Action: the means and the format in which the actions were executed; whether new subjects were designed, extracurricular activities were introduced, or creativity-related assignments were integrated in current subjects;

Approach/Tools and Methods: the type of assignments or training programs introduced; the teaching and learning approaches; the type of creativity tools and methods used;

Conclusion: the results of the interventions conducted.

The headings in the table were created during the data analysis process. While reading the papers, the variables were organized to gather demographic information and observe changes over time. The year, country, and school names were used for this purpose. The papers varied in terms of interventions aimed at enhancing creativity, which were influenced by the approach, tools, and methods used during the period. The date and duration of the approach were also considered to better understand its impact. A notable finding was the emergence of two distinct approaches to implementing creativity teaching, either within a single subject or throughout the entire program. Another noteworthy difference was the focus either on the first year of education or on the final year of teaching creativity.

This paper adopts a thematic analysis which is defined as "a method for identifying, analyzing, and reporting patterns within data" [27]. This type of analysis can be useful for detecting themes, theoretical perspectives, or common issues within a specific research discipline [27]. Although there is not a set rule, the overall objective of conducting data analysis within an integrative review is to thoroughly assess and scrutinize the literature, along with the key concepts and connections related to a particular topic [26]. Therefore, the reviewed papers were analyzed to detect main themes and to identify common approaches and issues.

3. Results and Discussion

Several approaches as shown in Fig. 1 were used in different higher education institutions to teach/enhance creativity in engineering education, such as using creative thinking tools, establishing a positive learning environment, encouraging group work, providing a discussion environment, learning by problem solving and implementing interdisciplinary studies. There are many papers written by researchers and educators about the new methods that they had tried in their classes. This section reviews the literature on these methods and demonstrates their results. Table 1 summarizes these approaches for teaching creativity in engineering schools.

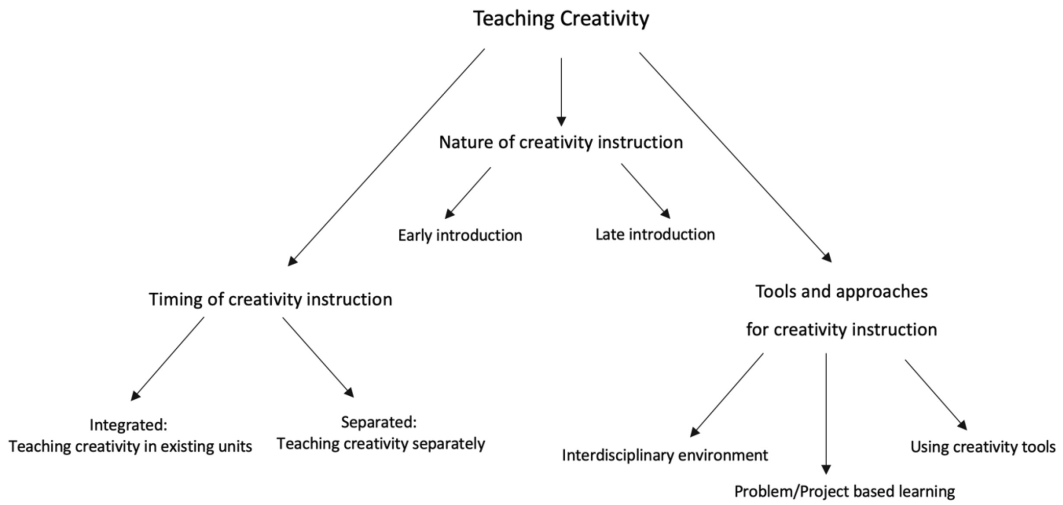

Fig. 1. Key approaches for teaching creativity.

Table 1. A Review of the Literature: Teaching Creativity in Engineering Schools

The Authors	Year	University/ Country	School	Practical Interventions	Date/Duration	Nature of the Action	Approach/Tools, Methods	Conclusion
44	1995	Prairie View A&M University/USD	All engineering schools	2 term Creative Engineering design sequence. 1st: Emphasizes solid modelling, drawing, engineering specifications. 2nd: Design unit requiring students to use the basic principles gained.	1st year 2 terms	New subjects integrated in 1st year curriculum	Participative learning method, teamwork, solution to a real-life engineering problem. Problem identification, preliminary ideas, design refinements, design analysis, implementation.	Increased the creativity and motivation of the students and helped their studies. Retention from 1st to 2nd year increased 50%, highly successful.
51	1996	University of Canterbury/ New Zealand	Chemical Engineering	"Strategies for Creative Problem- Solving Techniques" subject supported by interactive computer instruction.	3rd year	Integrated in a subject	9 one-hour sessions: Introduction to problem-solving, Problem definition, Brainstorming, Situation analysis, Problem analysis, Decision analysis, Potential problem analysis, Planning, Evaluation.	Students appreciated the problem-solving approach. Working in pairs found to be beneficial.
42	1997	University of Virginia/USA	Department of Mechanical, Aerospace, and Nuclear Engineering	As part of a major revision of the first- year curriculum: "Engineering Design" unit.	1st year 1 term	A new subject	Each week 50 minutes class, 90 minutes workshop: Design projects and case studies.	It has been valuable experience for students and it was successful in achieving its goals.
30	1997	Universidad Técnica Federico Santa María/Chile	Engineering	Designed 2 workshops in a creative teaching environment by using face- to-face cooperative learning techniques and divergent thinking methods.	1st year 1 term	One session per week Extracurricular voluntary activity	Face to face cooperative learning techniques and divergent thinking methods.	Students who took the workshops showed more effective learning and creative problem-solving strategies compared to the ones working under traditional schemes.

76	1998	University of South Australia/Australia	Engineering	Implementation of an undergraduate subject in Bachelor of Engineering degree with the goal of fostering and enhancing creative ability of students	Undergraduate	A new subject	Four components: Lectures (definition of creativity, role of the engineer, creativity in problem-solving, blocks to creativity), Educational counselling sessions, Case studies (focusing on creativity and innovation), Creativity project (to develop students' skills).	The program found to be successful in fostering creativity. Lectures helped to develop a theoretical creativity model. Counselling provided guidelines for improving skills. Creativity project allowed students to participate in a creative ability in a supportive environment.
77	1998	Sydney University/Australia	Mechanical Engineering	A new subject was designed "to enhance the thinking skills of the engineering students": "Professional Engineering"	1st year	A new subject	A variety of activities encouraged "group work, discussions, debates, role plays, competitions, interviews, presentations, communication exercises, industrial visits".	The seminar program is believed to have long term benefits to students in terms of developing creativity and innovation skills.
41	1999	University of Alaska Fairbanks/USA	Department of Civil and Environmental Engineering	Methods for teaching design to engineering students	1st year	Integrated in the subjects	Methods: Reverse engineering, Creating something useful, Full Scale Project, Small scale project, Case studies, Competitions, Non-profit project, Local project.	Reverse engineering is a preferred method. Teaching freshman design requires a shift in teaching. Lecturers should become mentors. It requires more resources than the lecture style model. There is a demand for additional faculty.
78	2001	University of Nevada/USA	Mechanical Engineering	Focused on product development, team skills and technical reporting.	1st year	Integrated in the subject	Worked in team-based exercises with hands-on approach. LEGOs were used to teach design, creativity and structured programming.	Team-based hands-on approach doubled the student enrolment. Lego provided excellent medium for teaching creativity.
79	2001	U.S Naval Academy/USA	Systems Engineering	Design competition: Systems Ball Vehicle Design	Capstone	Integrated in the subject	Teams of students come up with designs, develop engineering drawings and build the vehicle with the help of machinists. Then they compete with each other.	Systems Ball has been an effective and fun way to guide multiple student teams through the design process while stimulating their creativity for the last 10 years.
80	2002	Monash University / Australia	Bachelor of Information Management and Systems	Integrated in the subject: Bauhaus inspired studio-based teaching and learning model to inspire creativity and self-managed learning	1st year 1 term	Integrated in the subject	1. Redesign the physical space 2. Teaching staff directs the integration of subject materials across the levels. 3. IT facilities provided. 4. Students expected to develop portfolio	New physical layout of studio encouraged collaborative learning. Students were positive about their learning experience, however they found it difficult to self-manage.
68	2004	City University of Hong Kong/ Hong Kong	Electronic Engineering	InnovTech facility: teaching students to become professional engineers with society in mind and with creative and innovative flair in "Engineer for Society" subject	4th year	Integrated in the subject	Creative problem-solving processes and creative idea generation techniques (brainstorming, brainwriting, checklists, problem reversal, analogies, attribute listing, morphological analysis, 6 thinking hats), lectures, small group exercises, case studies from industry	The project found to be beneficial as it has enhanced the competency of students and employability. Students showed that they are very keen to become more creative.
81	2005	Yuan Ze University/Taiwan	Department of Industrial Engineering and Management	Curriculum reform program 3 courses were developed: 1. Engineering Communication 2. Creative Problem Solving Scientific 3. Research Methodology	1st year 2nd year	New subjects	1. Improve communication ability (speaking, reporting, writing, presentations, meetings) 2. Develop creative thinking skills (series of small group techniques to exercise creative problem-solving methods) 3. Develop scientific research concepts (lectures, data collection tools, data analysis and writing technical reports)	The proposed curriculum reform program improved students' creativity. However, it is necessary to observe students' creative performance in the following years.
69	2006	University of Toledo/USA	Engineering	Introduction to engineering design subject with TRIZ method	1st year 1 term	Integrated in the subject	First project was traditional idea generation method, second project was TRIZ.	TRIZ made easier to generate feasible concepts to design problems. Number of unique design concepts increased in TRIZ teams in comparison to non-TRIZ teams.
29	2008	University of Northampton/ England	Engineering	One-hour sessions per week for 21 weeks	1st year 2 terms	Extra hour	Analytical and creative techniques were used: Brainstorming, thinking aloud, meta plan, mindfulness training, meditation technique.	Students believed they got better in problem-solving. The authors suggest encouraging PBL in engineering through use of a suitable classroom environment, exercises, self-reflection and awareness.

43	2008	University of Massachusetts/ USA	Chemical Engineering	A creativity teaching module that can be integrated into an introductory engineering subject to maximise students' creative potential.	1st year	Integrated in the subject	Open-ended problems were given to students. Brainstorming, Lateral thinking, Synectics were used.	Concepts that were introduced in the module helped students become more comfortable with open-ended problems. Practice with creative exercises increase confidence in novel idea generation.
82	2008	Tecnologico de Monterrey/ Mexico	Mechanical Engineering	Experimental group and control group in the same class	1st year	Integrated in the subject	Using systematic creativity tools, challenge-based instruction and active learning methods. Introduction to TRIZ	The activities in the experimental group contributed to enhance creativity. However, the study does not prove that this type of instruction is better than a traditional approach.
83	2008	Vilnius University/Lithuania	Software Engineering	Modifying the teaching of "Human Computer Interaction" subject to foster student creativity and inventiveness.	Undergraduate	Integrated in the subject	User-centred design techniques were used; practical classes on user and task analysis, usability, goals and evaluation, brainstorming sessions, prototyping. Critical review of solution examples, encouraging unconventional solutions.	Modifications in HCI teaching, especially good and bad design examples, brainstorming and creation of alternative solutions increased creative thinking. It needs additional improvement.
72	2009	Technical University of Lisbon/Portugal	Mechanical Engineering	Training in creative and systems thinking in entrepreneurship framework in an elective course "Product Development and Entrepreneurship".	Postgraduate	Integrated in the subject	Product development process is taught (planning, concept development, systems development, detail design, testing & refinement, production and presentation).	The course trains the future engineer in dealing with real-life, multiple solution and ill-defined problems, and contributes to young engineers' engineering skills.
84	2010	Technical University of Madrid/Spain	Agronomic Engineer Technical School	Cooperative Project-based learning (PBL)	Final year	Integrated in the subject	Merging different methods: "Activities inside and outside classroom, lecture, group activities, cooperative learning, online and face-to-face tutoring, project exhibits, competition among teams".	"Training in technical, personal, and contextual competencies, Real problems in the professional sphere are dealt with, Collaborative learning is facilitated through the integration of teaching and research".
11	2010	University of South Australia/Australia	Engineering	Engineering innovation class with theoretical lectures on creativity	2nd year 1 term	Integrated in the curriculum	Lecture content were focused on learning about creativity and creative activity. Second element was to design novel and effective model of a wheeled vehicle.	They suggest that for teaching students to be creative, "students must be informed about what is creative in their designs".
85	2011	Rajagiri School of Engineering & Technology/ India	Engineering & Technology	"Hour of creativity" modules: A tailor-made program to train the students of Bachelor of Technology	1st year	Separated, extra hour of creativity	Sessions included: History of engineering, introducing creativity enhancing methods, Initialization session (mind freeing activities, oriental yoga), Problem-definition session, Brainstorming session, Evaluation	Accomplished to a great extent. The hour of creativity will remain as the practical session of the subject.
70	2011	Aalto University/Finland	MSc in Chemical Technology	Health Technology Microbiology 7- week course designed 2 hours/ pw lectures and 3 hours/ pw group work	MSc level 7 weeks	Integrated in the subject	Focused on "learning by doing, cooperation and teamwork". Used tools were drawing, Legos, modelling clay, knitting machine, videos, movies, welding machine or music. Focus was on learning process.	Enhanced students' understanding in difficult topics, development in confronting complex teamwork situations.
63	2011	University of Ljubljana/Slovenia	Faculty of Mechanical Engineering	A new subject in the curricula: "Product Design and Development"	N/A	A new subject	Problem-solving process: Product and market analysis, product development, CAD modelling.	There has been an improvement in success, by using motivational approaches, but the unit needs additional improvement.
33	2011	The Royal Institute of Technology and Stanford University/USA	The Swedish Product Innovation Engineering Program	Workshop program to establish change in mindsets	5 days	Extra- curricular	Design thinking lecture, Innovation workshop, teamology workshop, instrumenting and measuring innovation and site visits to Cars-lab, IDEO, Google and UC Berkeley.	Resulted with the understanding of proposing any kind of change in in the mindset requires big effort.
56	2011	Universiti Kebangsaan/ Malaysia	Mechanical Engineering and Manufacturing Engineering	Creativity techniques and conventional engineering techniques are introduced.	4th year	Integrated in the subject	Brainstorming, Mind mapping, Synectics, Fermi approach, Morphology analysis, Pugh evaluation, TRIZ. Basic product design methods (problem identification, design objectives, concept generation, detailed design)	Results show that creativity level can be enhanced through teaching and learning. It is proposed that students are exposed to creativity techniques combined with standard engineering design methods for generating ideas.

28	2012	Swinburne University of Technology/Australia	Mechanical Engineering	Projects in Machine Design and Engineering Management that required documentation of a creativity tool to solve an identified problem.	3rd year 1 term	Integrated in the subject	List of creativity tools were provided for problem-solving (6 hats, Morphological Analysis, Synectics)	Resulted with the understanding of that "engineering students need to be taught more than creativity", such as how to combine creativity with their knowledge of engineering theory.
34	2012	Valparaiso University/USA	College of Engineering	3 days creativity instruction: "Inspiring Creativity"	NA	Separated extra sessions within a subject	"Team teaching approach": Educators from inside and outside of the faculty did a site tour, brainstorming sessions, engineering scavenger hunt in a theme park.	There has been an "improvement in students' confidence, their creativity perceptions and their ability to use and lead a creative process"
35	2012	Brigham Young University/ USA	Technical Engineering: Manufacturing Engineering, Industrial Design, IT	2-day Boot camp Instructional program: "Innovation Boot Camp" to encourage students experience divergent thinking	Undergraduate 2 days	Extra- curricular	Principles of innovation through solving real problems: "Idea finding, idea shaping, idea defining, idea refining, idea communicating".	Bootcamp found to be successful as the curriculum encouraged students to work in multidisciplinary groups by providing them a hands-on experience and to increase innovation during the design process.
54	2012	University of Massachusetts/ USA	Mechanical Engineering	Comparative experiment between 1st and 4th year by giving students a design problem	1st and 4th year	Integrated in a design subject	Innovation enhancement techniques then, C-Sketch and 6-3-5-method.	First year students generated more original concepts, but there was no difference in quality. Need for additional studies on innovation capabilities during design.
31	2012	Northwestern University/ USA	Design for America, studio	Extra-curricular design-based learning model in interdisciplinary student-led studios anchored in universities	6 weeks Summer studio	Extra-curricular	Students practiced innovative solutions to authentic, pro-social, and local challenges by blending elements from "project-based learning, design-based learning, service learning and situated learning to provide hands-on innovation".	The model positively influences students' skills and beliefs in ability in innovation related tasks.
53	2012	University of Moratuwa/Sri Lanka	Computer Science and Engineering	A new subject is designed: "Software Engineering Project"	3rd year 1 term	A new subject	The unit started with a workshop by asking 'if only' questions to students. Brainstorming was done. Former students were invited. Then students were expected to defend their ideas in front of their lecturers.	It has been successful. Positive changes were observed in students' approach. Students' level of confidence increased in software development.
86	2012	Lulea University/Sweden	Mechanical Engineering	A workshop to improve students' creative and sketching abilities	6 hour in 2 days	Extra hours	Educators from Innovation and Design Department held a workshop designed in five steps: "1. Warm-up, 2. Speed exercises, 3. Readability, 4. Creative exercise, 5. Reflection".	Simplifying the tasks and focusing on sketching as a creative tool improved the outcome of students' projects.
87	2012	Swinburne University of Technology/Australia	Product Design Engineering	Sketch fest: Use of free-hand drawing	Final year	Integrated in the subject	Open ended projects allowing quick ideation sketching.	Students reported that their sketching skills are increased.
14	2012	Aalborg University/Denmark	Medialogy	A creativity training program is carried out in PBL environment to foster creative engineers	5 days	An extra separate program	Training involves mix of lectures, workshops and discussion sessions: Theory of creativity, idea generation methods, brainstorming, checklist exercises, mind mapping.	Program was successful in terms of gaining project work skills, creative concepts and confidence of being creative and understanding of creativity. However, only five days of training was not enough for learning skills in PBL.
15	2013	University of Arkansas/USA	Interdisciplinary (Engineering, Business, Psychology, Art)	3 project-based subjects were developed: Strategies for Innovation, Design Skills, Innovation Project	Undergraduate programs A subject per term	New subjects	Tools: Global and Specific Abstractions, Random Words, Mind mapping, SCAMPER, Rephrase the Problem, Multiple Perspectives, Force Field Analysis, Making Novel Combinations, and Da Vinci's Technique.	Creativity and innovation skills must be dispersed through the whole curriculum. Use of interdisciplinary teams help engineering students to have multiple perspectives.
22	2013	ITESM Technologico de Monterrey / Mexico	Mechanical Engineering	Capstone activity to enhance student creativity while developing their senior design project	Capstone	Integrated in subject	Project oriented learning approach with computational tools (CAD, CSM, CFD, FEM). Project: Solar powered boat for Solar Splash Competition.	Computer software is an advantage for promoting and enhancing creativity in capstone projects.

64	2013	University of Minho/Portugal	School of Engineering	Integrating different disciplines in "Innovation and Entrepreneurship Integrated Project" to develop teamwork, initiative, creativity, decision making and communication abilities.	4th year and Master	Project integrated in the curriculum	Project Based Learning: students compete against each other in developing products	Students' technical and soft skills (project management, teamwork, communication) are improved. They acquire multidisciplinary knowledge.
2	2013	Federal University of Goias/ Brazil	Computer Science	Provide pedagogic alternative for teaching and fostering creativity in two subjects: Human Computer Design and Introductory Programming Subject	Undergraduate	Integrated into two subjects	Dialogic framework: The educator focuses on dialogic processes for promoting creative programming activities. 2 case studies: Programming Study and the Interaction Design Study.	The framework has the potential to allow students explore creative strategies collaboratively and creatively.
52	2014	Chalmers University of Technology/Sweden	Software Engineering	Weekly modules: A subject in mathematical modelling and problem- solving process with the aim of acquiring students with real-life problem-solving skills in science and technology.	2nd year 1 term	A new subject	Inquiry based learning approach: Focus is on PBL: 30 realistic problems were designed to be solved in pairs in a workshop setting under Socratic supervision.	Students' modelling and problem- solving skills developed. This kind of subjects or teaching should be present in the engineering education.
48	2014	Polytechnique Montréal/ Canada	Engineering School	12-hour workshop: "Creativity yes we can"	PhD degree	A new subject	Class discussions, games, a few creativity approaches (Mind mapping, 6 Thinking hats, SCAMPER), warm up exercises. First, individual artistic project, then, group engineering project.	The presented training "could eventually become part of the curriculum of all engineering programs".
21	2014	US Military Academy West Point/USA	Electrical Engineering and Computer Science	"Disruptive Innovations" to understand the nature of and identify potential disruptive and innovative technologies, develop critical thinking, creativity and innovation skills.	Upper- division Undergraduate	A new elective subject	Interactive engagement between students and that employ Socratic method as the pedagogical method. Tools, activities: Reading texts, doing research, class discussions.	Successful in achieving its goals. In a Socrative dialog format, keeping the student numbers small is important. Diversity of students' disciplinary backgrounds provides diverse perspectives.
65	2014	Lawrence Technological University/USA	College of Engineering: Architectural, Biomedical, Civil, Electrical and Computer, Mechanical	Combining discipline-specific courses into a multi-discipline course and to foster entrepreneurial mindset in engineering. 1 hour general multi- disciplinary, 1 hour discipline-specific course.	1st year 2 terms	Combined 5 subjects into 1	Project based design and build approach in a design studio.	Interdisciplinary introduction to engineering subject found to be successful. The project allowed students to express creativity due to its open endedness. It teaches problem-solving and design while instilling the entrepreneurial mindset.
75	2014	Georgia Institute of Technology/USA	Engineering	"The Invention Studio" a free-to-use maker space: A student run design-build-play space.	Capstone	N/A It's a venue.	The facilities at the Invention Studio encourages hands-on design-build education to stimulate innovation, creativity and entrepreneurship in engineering.	The Invention Studio is changing the culture in the institute.
88	2014	University of Alabama/USA	Electrical and Computer Engineering	Introductory course that has lecture and lab components. 4 laboratory modules are created to provide students on experience in design and build products with function and aesthetics attention.	1st year	Integrated in the subject	Creative process is introduced in design lab by stages; brainstorming, forming a construction plan, producing schematic representations, implementing design.	Creative lab was valuable and did raise awareness of the creative process.
67	2015	University of South Adelaide/ Australia	Engineering	15-week Introductory subject on engineering creativity: 1 h lecture, 1 h tutorial, 2 h practical activity every week	1st year	A new subject	Exercises related with creative thinking (such as Egg exercise, Spaghetti exercise)	A curriculum for engineering creativity was developed as an example/ guide for faculty.
89	2015	University of Calgary/ Canada	Engineering	Use gamification as a method of expanding opportunities for creativity and to engage student innovation	All years	Integrated	Conducted in stages: 1. Incorporating games in first year design course. 2. Expanding games in first year design course. 3. Using gamification for more advanced technical design. 4.Gamification education curriculum has been expanded for use in a 4th year electronic design automation course.	Gamification is a valuable method of introducing creativity and innovation into design education. Students were able to learn about the design process and technical challenges while still feeling motivated and engaged.

20	2015	California State University/ USA	Mechanical Engineering	Re-designed "Machine Design" subject to support with creativity needed for idea generation and help students in decision making.	Foundation 1 term	Integrated in the subject	Included intensive writing as a reflective piece, presentations with critical feedback sessions. Expect students to submit "ideation report" during the semester and get feedback for final submission.	This approach is found to be successful in preparing students for their senior design projects and for their professional life. Allowing enough time and effort in the initial steps of design process will shorten the overall project time and will result with more efficient process leading to a final product.
90	2016	National Taiwan Normal University/ Taiwan	Engineering	Analyse the effect of TRIZ on students' creative process and products. Students assigned to experimental or control groups.	1st year 6 weeks	Integrated	Apply TRIZ procedure, tool sets thinking approach.	TRIZ has positive effect on students' ability to analyse problems, to generate, select and execute a strategy. TRIZ has positive effect on producing creative products and on creative process especially on selection of strategies.
25	2016	Pennsysylvania State University/USA	Introduction to Engineering Design Course	Developed concepts for a design task that have different structures. 3 different problems. (Focus groups for research purpose)	1st year 8 week (half semester)	Integrated in the subject	1. In class design session. 2. Individually sketching for concept development. 3. Brainstorming as a team to develop concepts.	Reduction in creativity during design process and student abandonment of novel concepts. Creativity during the idea generation and concept selection phases don't necessarily reflect to the creativity of the final conceptual design.
91	2017	Ecole Nationale Superieure d'Arts et Metiers/France	Postgraduate Engineering School	Introduce creativity and development techniques through 150 h program "Product Engineering". 10 session hand-on project	8 weeks 150 hour program	New Program	Introducing creativity techniques to choose and apply (such as Brainstorming, Analogies, Bullchart, TRIZ, Mindmapping, Personas and etc.). Students complete workbook about their progress during creative process.	The tools to be used need to fit the type of design problem and individual preferences. Use of workbook was very useful to understand students' creative process.
92	2017	Universidad Europea de Madrid/Spain	School of Engineering	Project based learning; each grade all students participate in a capstone project integrating the contents and competencies of several courses.	1 Academic year	Development of engineering capstone Projects using PBL methodology	Connection with the real world. Coordination meetings with the teaching team. Integrated capstone projects linked to industry with the aim of designing new curricula established on PBL	Students' motivation increased. Cooperation, interactivity, creativity and innovation and global vision are developed in the projects.
66	2017	Tatung University/Taiwan	Material Engineering	Project based pedagogy with interactive learning courses and training	3rd and 4th year	New subjects integrated into the curriculum as elective course	Two design-based course modules are merged into the original curriculum as 'Project Laboratory 1 & 2' to promote creativity of students	Students became more confident in dealing with laboratory problems, more able to analyse their experimental process from different perspectives, to discuss their research with other and to present professionally.
93	2017	Transylvania University of Brasov/Romania	Faculty of Electrical Engineering and Computer Science	Replacing the classic Computer Interfacing laboratory with the new experimental lab procedures.	4th year	Integrated in the subject	Novel laboratory concept allowing students to develop their own lab projects	This procedure established competitive and collaborative environment which stimulates student imagination and creativity.
94	2017	La Laguna University/ Spain	Bachelor of Engineering	Workshop in engineering graphics subject	1st year	Integrated in the subject	Workshop aiming to promote creativity in students through use of three stages: 3D scanning, 3D digital mesh edition and 3D printing.	Creative competence can be improved through specific activities such as 3D scanners, 3D printers and computers with 3D software. Students value the activity positively towards the development of creativity.
24	2018	University of Santiago de Compostela/ Spain	Bachelor and Master of Chemical Engineering and Environmental Engineering	Application of Game storming methodology	4 different academic years	Integrated in subjects	In 3 subjects, product development and process design problems are given. Games are used in the process of brainstorming to develop students' creativity and teamwork.	Game storming methodology can be used as a mechanism to foster students' creativity in the progress of teamwork toward decision making process.
23	2018	Polytechnique Montreal/ Canada	Engineering	45-hour creativity course created in applied sciences and engineering	Undergraduate Postgraduate 1 term	New subject (elective)	Warm-up exercises, conference, short projects (engineering problems), logbooks, scientific reading texts, group discussions, in-class participation	The results of CEDA (Creative Engineering Design Assessment) show that students' creativity was increased after the course and it enabled a better understanding of creativity and how to foster it.

32	2018	National Engineering School of Tunis/Tunis	Engineering (Industrial, Electrical, Civil, Mechanical, Hydraulic and ICT)	7 workshops depending on Tempus program i-Cre@ Formation project (Innovation, Creativity, Action and Training).	Undergraduate Grad PhD	Extra workshops	Egg's Drop Game, the International Innovation Week, 48 hours of innovation, Fabrication labs, 3D printing, CAD module	The implementation of FabLab was a success. The objective of the project has been achieved: development of new courses, introduction of innovation platforms, support education and research on design and innovation management.
73	2019	National Cheng Kung University/Taiwan	Computer Science and Information Engineering	18-week STEM IPBL (Interdisciplinary Project-based Learning) course designed and delivered through 4 phases of design thinking approach: Discover, Define, Develop, Deliver	Undergraduate Postgraduate	New subject design	Overview of design methods and process, design workshops, brainstorming sessions for idea development, design and prototyping, testing, presenting the works and final demo	STEM IPBL course empowers students from divergent backgrounds to participate in interdisciplinary collaboration help develop better products, improves the students' learning motivation and creativity.
95	2019	Afeka Academic College of Engineering/ Israel	Mechanical Engineering	Design, develop and 3D print devices using AM (Additive Manufacturing) technique. A pedagogical project- based learning module was developed to introduce AM approach.	Undergraduate 1 term	New subject	Introduction lectures, special topic lectures organized with industry and academic experts, laboratory training and final engineering projects.	Mechanical engineering education should adopt a multi-disciplinary PBL approach in order to encourage students' creativity, learning motivation and engagement.
96	2019	Swinburne University of Technology/Australia	Mechanical Engineering	Action research in Machine Design and in Mechanical Systems Design units to enhance creativity. Researcher worked in collaboration with the unit coordinators and tutors.	2nd and 3rd year 1 semester each subject	Integrated in the subject (research purpose)	Introducing creativity tools to apply. Expecting students to do sketching in idea generation time. Expecting students to present their concept solutions. Extra creativity assignment. Extracurricular peer creativity assessment.	Enhancing creativity among engineering students is not possible until the engineering instructors understand and value creativity practice. Instructors should emphasize the importance of design process for better creativity.

An analysis of the data collected from the literature showed different approaches. First, the literature is almost divided into two: whether to teach creativity in new subjects or to integrate creativity in existing subjects in the curricula. The other point is about the time to teach creativity in engineering education: in the beginning or towards the end of the 4-year curricula. The other commonalities among the teaching and learning approaches include introducing creativity tools, using the PBL approach and creating an interdisciplinary environment while enhancing creativity.

3.1 Creativity Teaching: Separated vs. Integrated

Within the domain of engineering education, fostering creativity and creative thinking is a critical pursuit. This section explores two primary approaches adopted to enhance creativity in engineering education: integration into existing curricular subjects and standalone teaching of creativity in new subjects. This debate raises important questions about the most effective way to nurture creativity among engineering students. The "Nature of the Action" column in Table 1 shows the two main reported approaches for enhancing creativity in engineering education. The review shows that among the 60 studies, 31 reported to have integrated creativity and creative thinking in existing subjects, and 16 reported the design of new subjects focusing on creativity and creative thinking by redesigning subjects or reorganizing the curricula.

Institutions can indirectly promote creativity by understanding how engineering students confront creative challenges, enriching the learning experience [28]. Alternatively, some researchers/educators reported to attempt teaching creativity and creative-thinking skills separately through additional hours, workshops, creativity training, or extracurricular programs [14, 28–35].

A group of researchers has experimented with the "hour of creativity" approach in engineering education [29, 30] and a study [1] is performed in the Rajagiri School of Engineering and Technology. This approach involves dedicated "hour of creativity" workshops where students generate and implement creative ideas for assigned projects [1]. The Universidad Técnica Federico Santa María has implemented a "one session per week" strategy to enhance creative problem-solving skills in first-year engineering subjects [30]. Their approach involves creating a creative teaching environment using face-to-face cooperative learning techniques and divergent thinking methods, but it remains voluntary for students. However, such short-term implementations come with limitations, as exemplified by the five-day creativity training program at Aalborg University [14]. This program was found to be insufficient for students to fully understand and apply creative techniques, highlighting the need for a continuous, long-term approach to creativity training. Therefore, creativity training should be a continuous, long- term plan ensuring that students will apply the skills they have learned in the long term [14].

The debate surrounding creativity in engineering education, whether through standalone subjects or curriculum-integrated units persists [36]. Some, like creativity expert de Bono [37], advocate for separate teaching of creative-thinking skills. However, separately designed creativity subjects present challenges such as limited implementation time and additional faculty effort [36]. Moreover, the impact of stand-alone creativity subjects may take a long time to manifest and prove challenging to measure its efficiency.

The author of this paper [17, 96] conducted action research at Swinburne University of Technology with the goal of enhancing creativity in engineering design, specifically focusing on Mechanical Engineering design units. The researcher initially chose to integrate creativity into existing units because creating new units would necessitate curriculum changes and involve more extensive approval processes. However, the outcomes revealed that addressing creativity in only two design units within a four-year curriculum was insufficient to significantly enhance creativity in an engineering discipline. Moreover, when engineering units are already saturated with technical content, instructors find it challenging to make room for creativity and creative thinking within their courses. As a result, it is argued that a more practical approach would be to undertake a comprehensive redesign of the existing engineering curriculum to seamlessly embed creativity into the existing units. This approach remains more practical than creating entirely new units within an already tightly packed curriculum [17].

The literature affirms that a limited number of creativity-related subjects are insufficient to fully develop students' creative potential [19]. Others advocate a holistic approach, asserting that addressing creativity in engineering education should extend beyond individual courses to encompass the entire curriculum. Creativity is best nurtured through systematic redesign of the entire curriculum [36]. Given the technical nature of engineering education, it's evident that design and innovation skills cannot be imparted into just one semester. In view of the diverse array of topics to cover, a smooth integration of design projects across the entire curriculum is recommended, making them an integral component of both technical and non-technical courses [38]. Nevertheless, it's vital to recognize that while creativity is inherently linked to design, a mere increase in the inclusion of design-related subjects in the engineering curriculum doesn't guarantee a proportional enhancement of creativity. Importantly, as the emphasis on design subjects intensifies, students are likely to encounter more open-ended challenges that foster creative thinking.

While previous studies suggest that integrating creativity into existing subjects is advantageous, arriving at a definitive conclusion is challenging. To compare the benefits of integrated versus separated approaches, further research within the same institutional context is essential. Failing to consider these critical factors leaves the superior approach uncertain due to the inherent uniqueness of each educational setting. Integrating creativity into existing units is a more practical choice, only necessitating unit-by-unit redesign. Nonetheless, embedding these opportunities within the curriculum still demands a comprehensive program approach by the faculty or school. Whether creativity and creative thinking skills are to be introduced to engineering students, separated or integrated, both require substantial time and effort for preparation and design.

The majority of the literature [9, 17, 18, 39] emphasizes the importance of integrating creativity within the entire engineering curriculum, echoing the sentiment that "creativity will be fulfilled only if it is valued within culture" [8]. This holistic approach highlights the need for fostering creativity as an integral part of engineering education.

In summary, the debate between separated and integrated approaches to teaching creativity in engineering education reflects the complexity of nurturing creative thinking in students and the need for further research within diverse institutional contexts to determine the most effective path forward.

3.2 Creativity Teaching: First Year vs. Final Year

The question of when to best teach creativity skills in four-year engineering curricula, whether as part of existing subjects or separate courses, remains a topic of ongoing debate. Some researchers [40–45] argue for incorporating creativity and design concepts in the first year of engineering education, emphasizing that these skills are not effectively taught in a single course and should be introduced early in the curriculum. In contrast, a review paper on teaching engineering design [46] stress the importance of teaching creativity skills in final-year design courses to better prepare graduates for industry demands. Yet, some researchers [47] critique the efficacy of final-year design courses for imparting creativity, asserting that design and creative skills cannot be acquired in a single semester and should be integrated throughout the curriculum. Designing an accredited engineering curriculum that incorporates all these aspects is also a recognized challenge [15, 48].

One proposal [49] is to introduce design in the initial year of mechanical engineering, focusing on enhancing students' knowledge and engineering drawing skills in the first semester, followed by practical application in the second semester. However, the addition of units is often hindered by the extensive technical content within engineering programs, leaving limited space for non-technical topics [15].

Among the 60 reviewed papers, 20 reported to have focused on the first year of engineering education. However, if a university reported to have focused on first year, does not mean it is not teaching creativity in the final year. These numbers just show the educational level that the papers reported. There were also some papers that did not explicitly clarify the level of education on which they focused to teach creativity. 11 studies reported that they chose senior-year courses, such as capstone subjects, to introduce creativity. However, solely relying on senior-year courses for creativity has been criticized. Capstone design subjects, with their focus on a multi-dimensional approach to a topic, are not enough to make up for the lack of creativity in engineering education [47], but the addition of more units is challenging due to tight course schedules [50].

Several studies were conducted at other levels of education, such as the third year [51] and the second year [11, 52, 53]. These researchers may not necessarily advocate for creativity integration at the levels they studied, but rather attempted to integrate creativity into the subjects they coordinated or taught.

An experimental investigation [54] examined the innovation capabilities of undergraduate mechanical engineering students at the University of Massachusetts. The study compared first- and final-year students by giving them a design problem. The ideas generated by the first-year students were more original and innovative than those of the fourth-year students, as the authors had expected. However, there appeared to be no difference in quality or technical applicability. This suggests that engineering students may not inherently become more creative as they progress in their education, prompting the need for curriculum reforms to foster creativity and innovation throughout undergraduate education [54].

Torrance [55], the pioneer of creativity research, believed that students must be taught creativity before they start higher education. To become future innovators, engineering students need to be exposed to creativity early in their education because it is hard to change students' mindset once they are already in their final year [17]. To address this, introducing diverse thinking skills earlier is essential, as shown in previous findings [20], where an introductory subject enhanced creativity in a Machine Design unit by addressing the lack of prior exposure to design courses. This underscores the potential benefit of an introductory subject on enhancing creativity [5]. Alternatively, having a design course each semester may be the solution, promoting the development of design skills and enhancing creativity throughout students' academic journeys [17]. It is argued that introducing a design course every semester for engineering students can foster not only the development of design skills but also enhance their creativity throughout their academic journey and beyond. Consistent exposure to design, encourages students to seek innovative solutions, honing their creative thinking abilities, thus preparing them to become the creative thinkers of the 21st-century engineering landscape. Creativity levels can be enhanced through teaching and learning and therefore students should be introduced to the creativity techniques starting from their first year at the university [56]. Whether creativity is introduced in the first year or later in a four-year curriculum, fostering creativity in engineering education necessitates a comprehensive strategy involving a systematic curriculum overhaul [36].

A closer examination of the data underscores that introducing design education in the early years of the academic journey is the most effective approach for engineering students to grasp the design process, aligning with Torrance's [55] suggestion that creativity should be taught to individuals even before higher education. This implies that fostering creative thinking should commence before university. In essence, this study advocates for a holistic approach to integrating creativity into higher education and initiating this process as early as possible in the curriculum. If we envision our students as future innovators in the professional arena, it is imperative to instill the seeds of creativity within them beforehand. Anticipating that graduate engineers will suddenly become creative thinkers in their workplaces is unrealistic unless they have been exposed to creativity during their university education. Considering the body of research on the subject, the present study contends that the teaching of creativity ought to commence early in the educational process and persist throughout the four-year duration.

3.3 Creativity Teaching: Tools and Approaches

The findings suggest an approach to enhance creativity education by designing and integrating additional PBL subjects into the engineering curriculum, particularly in interdisciplinary settings and utilising various creativity tools.

3.3.1 PBL

Although many researchers distinguish problem-based learning from project-based learning, they are both "student-centered approaches to learning" [12] and have similar characteristics. Accordingly, in this research, PBL is accepted as both project – and problem-based learning, known for presenting open-ended problems within a collaborative learning environment. It is a powerful student-centered pedagogy that allows students to learn essential skills [57]. During PBL students work on "complex problem that does not have a single correct answer" [58]. PBL serves as the primary teaching and learning strategy in most design schools and offers exercises that can enhance creativity development [59, 60]. One of the common approaches of the reviewed studies is that they were conducted in PBL environments.

Aalborg University in Denmark holds the distinction of being the first higher education institution to adopt a project-based learning pedagogical approach [40]. However, despite its application in various engineering disciplines, its integration into the entire curriculum remains limited, typically being addressed in upper-level courses during final year projects [57]. A vast majority of literature [6, 12, 29, 61, 62] has been published on creativity in engineering education suggesting teaching creative thinking skills during the problem-solving processes.

Many studies emphasize the positive results of PBL and problem-solving processes when enhancing creativity [14, 17, 31, 35, 52, 63–66]. It is suggested [29] encouraging PBL in engineering by creating appropriate environments and giving students relevant exercises. These PBL projects should include designing, solving and improving solutions for real-world problems; by motivating students to identify and apply research concepts and information [64].

The PBL-focused bootcamp that was conducted [35] at Brigham Young University provided students a hands-on experience and increased innovation during the design process. The project-based design and build approach at Lawrence Technological University [65] instilled an entrepreneurship mindset into the students while allowing them to express their creativity. During PBL, students can experience self-directed learning and reflect on what they have learned [12]. PBL has been adopted as the primary teaching and learning strategy in many design schools, and PBL exercises can be used to develop creativity [59]. Given that engineering students develop their creativity skills through practicing problem solving [67], creativity training must be considered as a long-term project for integration PBL into curricula [14].

Overall, the reviewed studies highlight the effectiveness of PBL environments in enhancing creativity among engineering students through real-world problem-solving exercises and hands-on experiences, with PBL being increasingly adopted as the primary teaching and learning approach in design schools. Therefore, integrating creativity in curricula in PBL environments should be considered as a long-term project in engineering education.

3.3.2 Creativity Tools

In higher education, various theories and approaches are used to guide and coach students in their learning process through problem solving. Whether implemented in the first or final year of education and whether integrated into existing subjects or taught as newly designed subjects, many creativity tools and methods are introduced and used to enhance students' creativity and creative-thinking skills. The importance of providing adequate warm-ups for creative thinking by "mind-stretching" activities are highlighted a long time ago [55].

The trainings in the reviewed papers involved a mix of lectures, workshops, in-class discussions, projects and CAD modules. The tools used to enhance creativity included case studies, reverse engineering, divergent thinking methods, discussion sessions, role play, C- sketch [54], gamification, use of LEGOs, brainstorming sessions, mind mapping, competitions, reflective exercises, TRIZ and the 6-3-5 method. For example, the introduction of idea generation techniques within an Electronic Engineering course [68] empowered students to conceive highly creative and innovative designs that not only proved cost-effective but also effectively mitigated the risk of failure. In another study [69], the teams that used TRIZ experienced a higher number of distinct design concepts compared to the non-TRIZ teams. Action research [17] findings to enhance creativity in engineering education reveal that engineering instructors typically did not promote the use of creativity tools in the design process, primarily due to workload constraints that limited time for practicing with these tools. However, it is argued that engineering students should be introduced and encouraged to use fundamental creativity tools, similar to design students, in order to enhance their creative capabilities. Just introducing some of the creativity tools and expecting students to use them is not enough. Students should be properly taught how to apply these tools, and most importantly time should be allocated for this creative process [17, 96].

Merely engaging students in creativity-promoting environments and applying creativity tools are not enough to develop creativity [17, 36]; as these tools are limited when applied separately, they should be integrated in curricula. It is also recommended [60] applying creativity tools at least two or three times to learn them comprehensively. Integrating creativity tools in the curricula is not the complete solution for fostering creativity in engineering but a good first step [60]. Administering only certain kinds of exercises to promote creativity does not guarantee an improvement. Educators must prepare conditions that are appropriate for receiving the given material [60]. While facilitating these kinds of activities, educators need to integrate themselves into the learning environment and take responsibility [70].

To develop creativity in students, simply providing creativity-promoting environments and creativity tools is insufficient, and instead, educators should integrate these tools wisely into the curriculum and take an active role in facilitating and adapting to the learning environment.

The study recommends that educators should emphasize the use of creativity tools and demonstrate their application in PBL environments. The application of these tools should be integrated into the design process, contingent on instructors assigning value to them and encouraging their use during creativity sessions. Importantly, the introduction of creativity tools should not be postponed until the final year of the curriculum. This aligns with previous research [71] who proposed the comprehensive integration of creativity methods into the engineering curriculum.

3.3.3 Interdisciplinary Environment

Another point worth highlighting is the favour for interdisciplinary collaboration in problem-solving processes in engineering. 9 papers [15, 21, 31, 35, 64, 65, 72–74] stated how interdisciplinary work helped students in terms of enhancing creativity, providing hands-on innovation, equipping students with multiple perspectives and improving motivation. Educators deliver academic knowledge to students in discrete, clearly defined units of scientific information, however interdisciplinary knowledge is lacking in the universities [72].

The role of today's engineers is changing from being in manufacturing to being in the service industry. Presently, capstone design courses predominantly concentrate on constructing products or devices, which do not account for the significance of procedures and protocols in the service industry. To equip engineers with multifaceted perspectives, it is imperative to integrate interdisciplinary courses that facilitate collaboration among educators from diverse fields, and foster teamwork [15].

Polytechnique Montréal proposes a distinctive approach for developing a creativity course in engineering. The approach involves assigning an individual artistic project to the students initially, followed by a group task that involves tackling an engineering problem. Learning things in domains other than engineering, "which allows students to expand their knowledge hierarchy", is as important as developing a deep understanding of a certain subject [48].

Interdisciplinary courses empower students coming from different disciplinary backgrounds to collaborate and develop better products [73]. What they achieved at Lawrence Technological University [65] was combining many individual two-credit-hour discipline-specific subjects into a one-credit-hour multidisciplinary and one-credit-hour discipline-specific subject. The interdisciplinary subject successfully allowed students to express their creativity. A similar approach was conducted at the University of Minho. The researchers integrated subjects from different disciplines into the so-called Innovation and Entrepreneurship Project. Upon completing this project, the students obtained a comprehensive understanding of multiple disciplines that would have been unattainable through other means [64].

Engineering education should adopt a multidisciplinary PBL approach to enhance students' creativity, learning motivation and engagement [74]. Another learning objective that comes along with creativity is entrepreneurship. Many interventions conducted in universities [64, 65, 75] aim to teach creativity, innovation and entrepreneurship together as a package.

Studies show that, interdisciplinary collaboration is vital for boosting creativity, innovation, and motivation in engineering education. So, incorporating interdisciplinary courses and teamwork among educators from diverse fields is essential to prepare students for their future careers.

4. Conclusion

This study reviewed 60 papers on teaching creativity in engineering education from 1995 to 2019, conducted at various higher education institutions. The research contributes to the understanding of different approaches to teaching creativity in engineering education, informing curriculum development, and offering guidance to educators and researchers with a comprehensive summary of educational approaches to teach creativity.

It delves into the debate of whether creativity should be integrated into existing subjects or taught as separate courses, offering insights into the challenges and benefits of each approach. Additionally, the paper discusses the timing of creativity education within a four-year curriculum, whether in the early years or the final year, highlighting the arguments for and against each.

The role of creativity tools and approaches is examined, showcasing various strategies such as problem-based learning (PBL), interdisciplinary collaboration, and an array of creativity tools and techniques. The research emphasizes the importance of introducing creativity tools early and continuously throughout students' academic journeys, rather than as standalone solutions. The paper underscores the significance of interdisciplinary environments, showing that collaboration among students from different disciplines not only enhances creativity but also equips them with multiple perspectives and improves motivation.

Considering the discussion, the paper concurs with the practicality of integrating creativity into existing subjects but suggests the necessity for further research to compare the benefits of integrated and separated creativity approaches within the same institutional context. It emphasizes the importance of considering the unique characteristics of each educational setting when determining the most effective approach. Ultimately, this comprehensive analysis of creativity in engineering education advocates for a holistic approach, beginning creativity education as early as possible and integrating it throughout the curriculum. The paper also argues that creative thinking should be cultivated alongside technical knowledge to prepare future engineers for innovative problem-solving in the professional arena.

Based on the findings of studies on creativity teaching practices in engineering, it is suggested that integrating creativity during problem-solving practices in PBL subjects can enhance creativity in engineering education and teach creative skills to engineering students. This approach facilitates students' engineering problem-solving process by nurturing a creative mindset. Additionally, it is recommended to integrate creativity into interdisciplinary teaching and learning environments, as this approach enables engineering students to benefit from diverse perspectives. To equip engineering students with the necessary creative thinking skills alongside problem-solving skills, a variety of creativity tools and techniques should be provided. For optimal results, it is recommended to adopt a holistic approach to teaching creativity, which entails redesigning and redeveloping the entire engineering curriculum.

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