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Board 72: How to Develop Engineering Students as Design Thinkers: A Systematic Review of Design Thinking Implementations in Engineering Education

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How to Develop Engineering Students as Design Thinkers: A Systematic Review of Design Thinking Implementations in Engineering Education

Abstract: Since the 21st century, the concept of design thinking has gained increasing attention from engineering educators. Design thinking is an interdisciplinary and experimental learning process. Currently, some of the world's leading engineering education institutions have begun to make significant changes to cultivate students to apply design thinking to solving complex engineering problems. However, training engineers who can deliver practical and creative design solutions is still an ongoing challenge for traditional engineering education due to the diverse practice approaches offered by different educational institutions and the inconsistency between its theory and practice.

This study, therefore, aims to conduct a systematic literature review on design thinking embedded in an engineering curriculum in higher education to understand the current landscape and existing theories as well as practices of applying design thinking in engineering education. It has summarised and synthesized 87 relevant papers published in the last 20 years with the systematic review method and meta-analysis (PRISMA) process. Four themes were identified and the key factors, including curriculum setting, curriculum framework, and student learning outcomes, are examined based on the co-occurrence analysis. It also provides instructional guidelines and directions for future design thinking cultivating research opportunities.

1. INTRODUCTION

Design thinking is a problem-solving approach that prioritizes innovation, human-centeredness, and the utilization of multiple disciplines [1]. It is an iterative and non-linear process that allows for multiple iterations and involves testing and refining the solution to ensure it is effective and meets user needs [2]. This approach emphasizes user comfort and unmet needs, balancing the psychological and emotional aspects of design with the technical and economic feasibility of engineering solutions [3]. Engineering design thinking is particularly effective for solving complex problems because it encourages creativity and provides a comprehensive problem-solving framework [4]. Recent years have seen leading universities such as Stanford adopt a new approach to engineering education, known as "design thinking," which combines creative and scientific cognition [5]. This approach imparts students with a sophisticated problem-solving method that mirrors how designers think and work [6].

Design thinking is a problem-solving approach that emphasizes transdisciplinary and holistic skills to develop an innovative and comprehensive skill set among students [7]. In today's rapidly evolving and technologically advanced world, integrating design thinking into engineering education has become a valuable strategy to prepare students for success [8][9]. However, despite the growing interest in design thinking, there is a need for a systematic review of the literature to explore its current state and identify future research trends. A review of the literature can provide a comprehensive overview of the research on design thinking in higher engineering education, identify the strengths and limitations of the current literature, and suggest areas for future research. In this paper, we will discuss the benefits of incorporating design thinking into engineering education and how it can prepare students for the challenges of the future.

1.1 The role of design thinking in engineering education

Engineering education has been characterized by a rigid and uniform approach that emphasizes individualistic thinking for an extended period [10]. The conventional model of engineering education comprises three fundamental elements: the instructor, classroom, and textbook [11]. This model prioritizes information transmission and treats the information presented as absolute facts. The instructor is often seen as the primary source of knowledge, and students are expected to absorb and memorize the material presented to them passively. Classroom activities typically revolve around lectures, and textbooks serve as the primary reference for students. Unfortunately, traditional engineering education undervalues the importance of the arts and humanities in fostering a well-rounded education [12]. This approach often leaves engineering students with a limited understanding of applying their theoretical knowledge to real-world situations [13].

Integrating design thinking into higher education has garnered significant recognition and acceptance among diverse engineering fields [14]. Engineering design and architecture [15], directly correlated with the design discipline, were among the pioneering engineering specializations to embrace this approach. We aim to cultivate engineers with refined design skills and the ability to produce human-centred technical solutions [16]. This necessitates a revaluation and revision of current engineering curricula and pedagogical approaches. However, achieving this objective will require a significant overhaul of the current pedagogical approach in engineering education, as it does not adequately equip students with the competencies required for success [17]. In the last 20 years, interdisciplinary learning [18]; education for systems thinking and design [19]; project-based learning [20]; and the development of STEAM [21] courses have all been calls for engineering reform.

1.2 Summary of relevant reviews

Implementing design thinking in education has been a topic of rising attention in recent years. Some review papers have examined research examining the application and results of design thinking in k–12 education [22] and higher education [11]. Rusmann [23] creates a design competence framework based on the literature as he explores the capabilities that students use and develop during the design process. To further our understanding of the benefits, and effects of bringing design thinking into education, Berggren [24] investigates the objectives of employing design thinking at various levels and in diverse contexts beyond engineering education. McLaughlin’s [25] review examines the implementation of design thinking in health professions education at the tertiary level, while Bilotta’s [26] study focuses on the application of design thinking in tourism education. Both studies demonstrate how educators in diverse disciplines often make disciplinary adjustments to adapt to the unique requirements of innovation and design.

A comprehensive review of the literature on the topic of design thinking in engineering education was conducted. Here we present four representative reviews of the literature. These literature reviews emphasize the advantages of integrating design thinking into engineering education and the significance and superiority of such an approach. Dym [11] conducted a review of the history of design in the engineering curriculum and highlighted the most used educational model for design thinking, Project-Based Learning (PBL). Lor's research [27] recognizes the benefits of incorporating design thinking in education through empirical evidence. The findings show that the integration of design thinking in the curriculum leads to improved student satisfaction and a broader set of skills. Pank [28] examines the advantageous qualities of design thinking and its implementation in various academic settings, including medical and business schools in addition to engineering schools. Freeman's [29] meta-analysis provides evidence of the effectiveness of active learning in enhancing the academic performance of STEM undergraduates through a comprehensive review of relevant literature, thereby establishing it as a preferred and scientifically verified pedagogical approach in regular classrooms.

Due to the customization and variety of curriculum design, the implementation of design thinking in higher education, particularly in engineering education, has not been thoroughly researched [27]. It is necessary to examine the utilization of design thinking in engineering education programs. However, the ill-structure in design problems leads to varying approaches to implementation. A more comprehensive overview of design thinking practices in higher engineering education is required.

2. METHODOLOGY

In this study, we followed the Meta-Analyses (PRISMA) protocol [30] for systematic reviews to screen scholarly articles that met our requirements. Our objective was to search the literature for relevant studies on the implementation of design thinking methods in higher engineering education curricula. To ensure that we covered a broad range of research, we searched the Web of Science (WoS) and SCOPUS databases using keywords. We limited our search to peer-reviewed conference articles and journal articles and found a total of 848 articles published between 2000 and 2022, 375 from Web of Science and 473 from Scopus. Firstly, we removed repetitive papers from two databases by comparing the titles. This reduced the number of studies to 691. We then screened the papers based on their titles, abstracts, keywords, and conclusions, removing irrelevant studies, and reducing the number of relevant studies to 406. Finally, we thoroughly read the remaining articles and assessed their relevance to our study. This resulted in 207 papers being reviewed in our systematic evaluation. We also applied the snowball sampling [31] and found eight additional publications in the form of research papers, bringing the total number of reviewed papers to 87. Fig. 1 illustrates the specific screening steps.

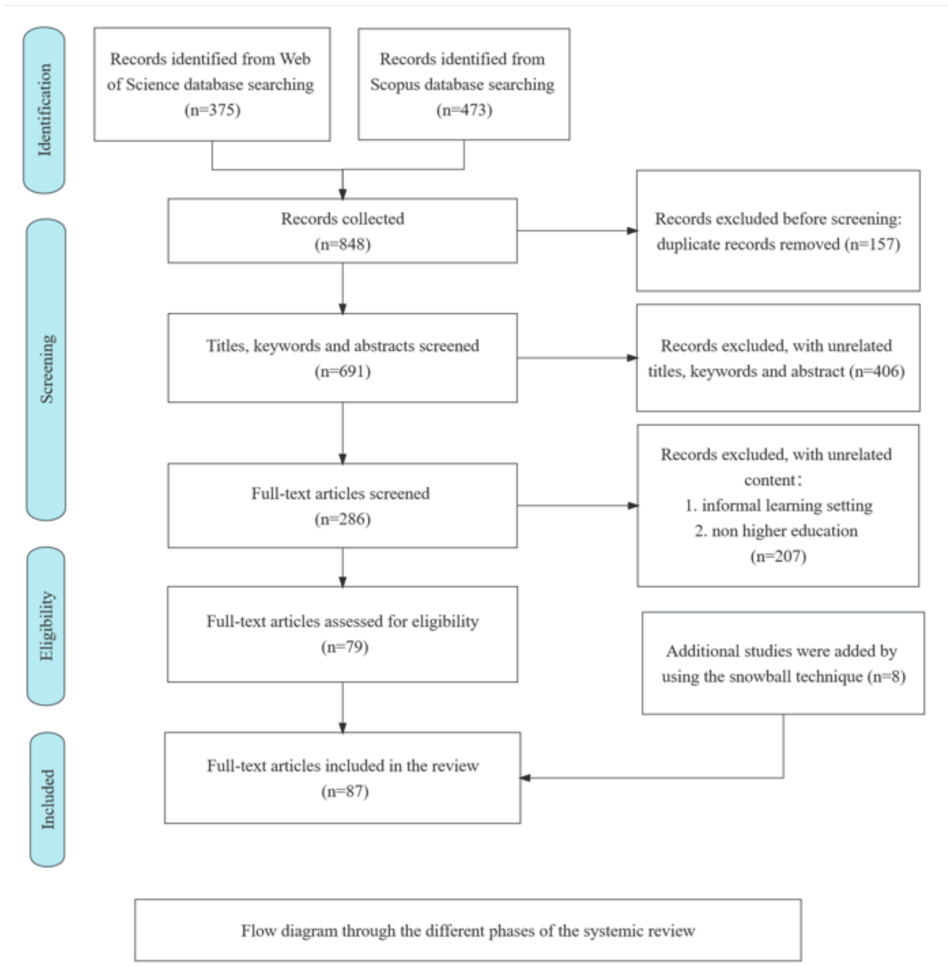

Fig.1 PRISMA diagram for systematic evaluation

2.1 Co-occurrence analysis

Callon [32] mentioned the keywords serve as indicators of the research topic of a given article and provide a summary of its content and the scope of knowledge it encompasses. The co-occurrence analysis method aims to evaluate the connections between these keywords based on the frequency of their occurrence together. The frequency of links between keywords reflects their significance, and the font size of the nouns symbolizes the importance of the topic [33]. The proximity of the keywords indicates the existence of categorical clusters, and the thematic relationships established by these clusters provide guidance for conducting an analysis of the primary literature [34].

This study employed a text-mining approach to perform a topic term co-occurrence analysis on 87 selected publications. The noun terms were extracted from the titles, author keywords, system supplementary keywords, and abstracts. The co-occurrence analysis was performed using the natural language processing algorithms of the VOSviewer software [35]. The results revealed that the main keywords were "process", "experience", "project", and "model". Other keywords were "challenge", "technology", and "methodology". According to the keyword clustering results presented in Figure 2, current research on advanced engineering design thinking has mainly cantered around learning methods. processes, experiences, curriculum models, and implementation, project-based learning, and technology.

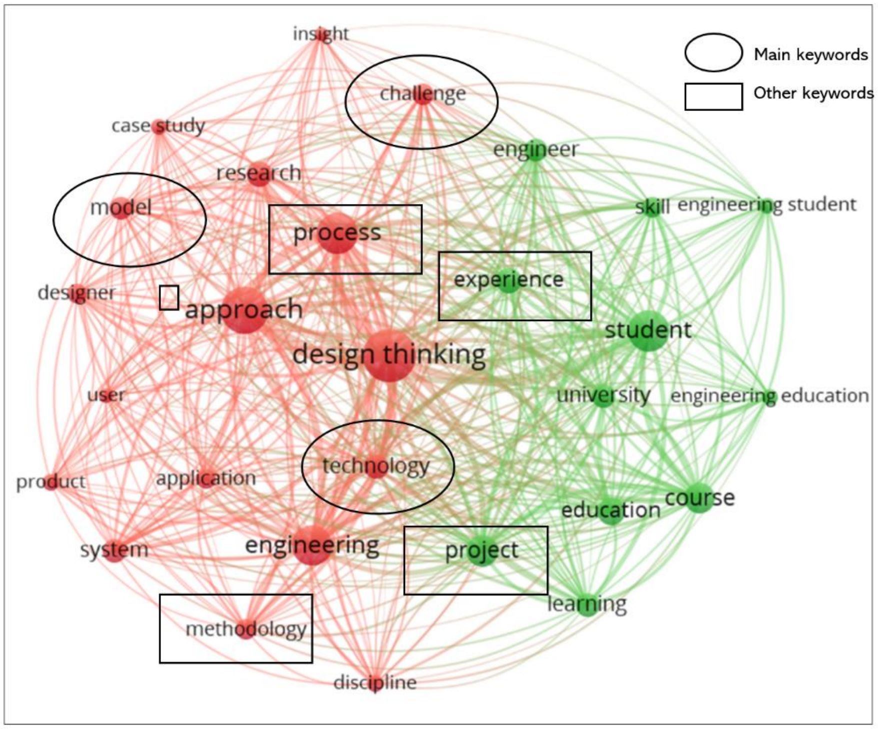

Fig.2 Co-occurrence map of emerging themes

3. FINDINGS

3.1 The current status of research on design thinking in higher engineering

Based on an analysis of selected articles, it was found that most research on design thinking in higher engineering education is practice oriented. Studies have focused on curriculum and case development, experiential activities in subject-specific courses, and teaching practice through case studies.

To provide a thematic analysis of the literature on design thinking in higher engineering education, this study improves Panke's [28] classification of the application of design thinking in engineering education.

Specifically, this research related to engineering design thinking was categorized into three aspects: a model or method, a process or approach, and a goal or outcome. This categorization allowed the existing literature to be grouped into four thematic categories, summarized: Roots for educators, Catalyst, Vehicle, and Goal for students. The study concentrates on these four distinct categories of themes focusing on both teacher-centred and student-centred perspectives.

3.1.1 Root

Cultivate educators' design thinking:

Brink [36] proposes using design thinking as a modelling tool and the organization of training and development programs for teachers to improve or redefine the engineering profession's traditional and outdated curriculum structures. Dym [11] underscores the importance of enhancing the creative thinking skills of leaders of engineering programs, educational quality managers, and curriculum leaders [37] through the adoption of an iterative design thinking approach. Integrating resources and disciplines is crucial to guide and improving curriculum programs. Moreover, pre-service teachers [38] and prospective teachers [39] should also strive to improve their design thinking skills.

Build the teaching platform:

The widespread use of design thinking in the business sector provides a valuable framework for teachers to use when designing and delivering educational content for students. According to Henriksen's [34] studies, incorporating design thinking into teaching can create more comprehensive and effective projects to support engineering education. For instance, design-based research methods have been established to aid in the development of online learning tools and platforms [40]. Additionally, design thinking can play a critical role in developing innovative and unconventional learning tools, as it helps to guide the creation of logical and effective instructional strategies [41].

3.1.2 Catalyst

Academic achievement:

The utilization of a design thinking approach amalgamates various components of the curriculum, providing guidance to students through a scientific approach to knowledge acquisition and exploration. It holds promise in enhancing student performance in specialized subjects. [42]. The advantages of integrating Design Thinking into the curriculum are twofold. Firstly, students receive a clear transfer of knowledge [43]. Secondly, the design process emphasizes developing problem-solving skills, including understanding complex problems, applying problem-solving techniques, and engaging in hands-on projects [37]. Lur [44] has successfully introduced the principles of Design Thinking into physics education.

Academic engagement:

Design thinking, which involves the integration of human-centred experiences into engineering education [45], has gained recognition as a practical framework for teaching students and designing engaging learning experiences. The integration of design thinking into education enhances the growth of emotional and motivational skills in students more effectively than conventional teaching methods. As an alternative to traditional teaching and problem-solving approaches, design thinking combines innovative teaching tools and methods to improve students' problem-solving skills and learning outcomes [46]. Evidence suggests that implementing design thinking increases student academic engagement [6], [47]. Research supports the effectiveness of design thinking in engineering education, as courses incorporating design thinking have been shown to stimulate student interest in problem-solving and improve performance and engagement [48]. Additionally, the application of design thinking has been linked to beneficial outcomes such as increased creativity and sustainability [49].

Interest of woman in engineering:
Design thinking pedagogy reinforces the recognition of the engineer's identity [50]. Some studies have demonstrated that female students participating in virtual engineering placements or design thinking-based modelling experiences significantly increase their confidence and engagement in engineering courses [51] [52]. For instance, the "CODING4GIRLS" framework [53], which teaches coding through a design thinking-based approach to the game design and development process, provides an adapted system that caters to the interests and motivations of girls to engage them in engineering subjects.

3.1.3 Vehicle

Interdisciplinary collaboration:
Repko [54] suggests that interdisciplinary research is the process of answering questions, solving problems, and addressing issues. With the escalation of the intricacy of tasks encountered by engineers, as observed by Lantada [55], the interdisciplinary character of engineering demands future engineers to assume a more prominent role in society as seasoned engineering and technical professionals. Thus, universities must emphasize interdisciplinary communication and collaboration through the implementation of a design thinking approach as an essential aspect of education. Thomas [56] states cross-disciplinary courses that extend beyond the confines of traditional disciplines enable students from different fields to acquire knowledge that can be utilized to address problems within their area of specialization, thereby facilitating their comprehension of the interconnections between economic, scientific, and social factors [55]. Single-subject learning has limitations, including the risk of promoting a reliance on stereotypical thinking and restricting thinking and behaviour by relying solely on one body of knowledge [56]. As such, future education systems must strive to move beyond isolated disciplines to mitigate these limitations [57].

New engineer quality:
Creativity, invention, and innovation are values championed as central pillars of engineering education [58] [59]. Engineering designers need good organisational skills, teamwork, critical thinking, social skills, and creativity [18]. By adopting design thinking pedagogy, students can learn about innovative business environments, comprehend the correlation between technical and commercial success [60], and acquire entrepreneurial skills to commercialize technology. Design thinking has been recognized as an effective tool for educating students on entrepreneurship and innovation, enabling them to tackle intricate social problems and find solutions [61]. In [42], Lynch examined the efficacy of employing design thinking as a pedagogical strategy in entrepreneurship education.

3.1.4 Goal

Design thinking is defined as a collaborative problem-solving process that involves defining a problem, generating potential solutions, constructing prototypes, testing and refining the solution [62] [63]. Furthermore, some educators argue that design thinking should be considered as one of the foundational sciences of engineering, alongside physics, chemistry, and biology [64]. The processes, practices, and roles intrinsic to design thinking are instrumental in promoting and fostering innovative product design [65]. Engineering designers should apply the principles of design thinking in their respective areas of expertise to solve problems effectively. [2] [66]. For instance, Corral proposes that computer science students' software engineering courses incorporate design thinking in their curriculum [67]. Moreover, ongoing efforts have been made to integrate design thinking into university engineering classrooms through reverse engineering activities [44]. Magana's research focuses on elicitation strategies to help engineering students develop design thinking skills in different ways [66].

Project-based learning (PBL):

Project-based learning, or PBL for short, is a collaborative learning process that rejects overly detailed sub-disciplines and teaching and values the integration and integrity of activities [67] [68] [69]. Challenging-based learning [71], problem-based learning [72], design-based learning [73] share similarities with project-based learning as educational approaches that engage students in practical, hands-on learning experiences [74]. Their primary objective is to promote students' creativity, sense of social responsibility, and practical skills through a student-centred pedagogy [75]. Thus, these teaching methodologies can be considered like one another.

PBL is a pedagogical approach that has gained popularity in academic circles due to its emphasis on integrated and cohesive learning activities [76]. Barber [77] contends that PBL, as a new teaching model, places students at the forefront and redefines the role of the teacher. Mills [71] reports positive outcomes of PBL in engineering education, demonstrating its effectiveness for both students and teachers over a decade-long evaluation. In engineering education, PBL has emerged as one of the most frequently used teaching methods, known for promoting design thinking. According to Van 's [79] study, an 'engineering experiential training' program has been introduced that focuses on engineering projects from inception to completion. PBL formats include Engineering design introductory course, Engineering design-based course, Real-life product design curriculum, Capstone project, Joint engineering-design degree programme, In-school lab practice and External cooperative internship training. The categorization of courses in the literature has been presented in Fig.4, based on the duration and class setting of the course project, which are represented on the coordinates.

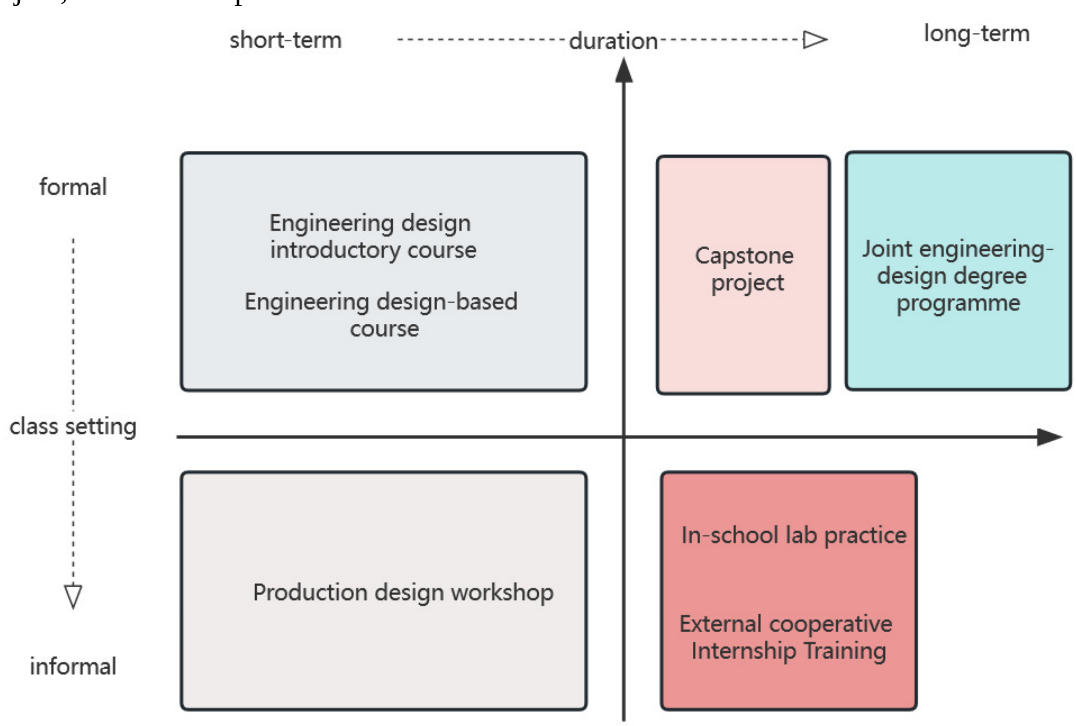

Fig.4 Course classification

First-Year engineering design introductory course

Castles [80]and Al-Qaralleh [81] suggest adopting a series of workshop laboratory sessions to acquaint students with the design thinking process. The focus of these sessions is on the first three stages of the process, i.e., empathy, definition, and conceptualisation [3]. Pre-course activities [82] are carried out to aid the students in developing their design awareness, understanding of design challenges, and knowledge building. These activities involve presentations [83], lectures, and text-based, gamified exercises [84] centred on the main themes contained in the proposed framework.

Engineering design-based course

The incorporation of project-based learning (PBL) into laboratory course design is becoming increasingly prevalent in engineering design courses, such as those focused on physics [44], electronic engineering [85], software engineering [86], and others. This approach integrates elements of design thinking and PBL into the learning experience, resulting in a more innovative and effective engineering teaching model that seeks to improve students' scientific process skills and creativity [2] [87].

Product Design curriculum

In the field of engineering education, the process of developing artefacts or products involves a synergistic combination of practical, real-world experience and the application of creative development concepts. This approach integrates both the theoretical foundations of engineering and the practical aspects of product design to produce innovative solutions that effectively address the needs and requirements of users [88]. By incorporating real-world experience into the design process, students gain a deeper understanding of the environment in which their product will be used [89]. It enables them to create designs that are both functional and user-friendly, providing a superior user experience.

Capstone project [90]

Cornejo-Aparicio's [91] proposed model for managing engineering capstone courses represents a significant step forward in engineering education. By emphasizing practical experience and the integration of engineering knowledge, this model provides a comprehensive approach to engineering education that prepares graduates for success in the professional world. Wan [91] proposes a two-semester senior capstone project that serves as a critical component of this model, providing a rigorous and comprehensive assessment of students' engineering competencies and ensuring that graduates are well-prepared to tackle the challenges of the modern engineering workplace [92].

Joint engineering-design degree programme [93]

To meet the demands of the modern engineering profession, joint programs that focus on skills development, challenge-oriented projects, and creativity have become increasingly important [94] [95]. The University of Illinois at Urbana-Champaign's College of Engineering has launched a dual degree program in Innovation, Leadership and Engineering Entrepreneurship (ILEE) [96], which integrates training in science, design, and leadership to prepare students for leadership roles in engineering and technology industries. Through this program, students engage in a rigorous and interdisciplinary learning experience that emphasizes innovation, problem-solving, and creative thinking.

In-school lab Practice

For instance, institutions such as the MIT Media Lab, Berkeley CITRIS, and Stanford D.school have established Innovation Labs as learning environments that focus on open-ended questions in the fields of science and design [97]. These Labs employ a unique and personalized learning process for students. The result is a space for the creation of innovative and cutting-edge technologies, as well as interdisciplinary research in fields like science, multimedia, technology, art, and design. This approach promotes breaking down traditional academic boundaries and encourages the integration of diverse areas of study, providing students with the opportunity to engage in cutting-edge scientific research and participate in the design of engineering projects.

External Cooperative Internship Training

Undertaking short-term project-oriented studies can be a valuable approach for students to gain practical experience while contributing to local companies, non-profit organizations in addressing real-world challenges [98]. Through such projects, students can develop new knowledge, gain an understanding of collaborative inquiry, and learn to identify and evaluate different options in making informed decisions [99]. Additionally, students can apply their conceptual knowledge to integrate problem-solving and develop sound solutions. In this way, students can acquire valuable practical experience and new skills while working towards solving real-world problems [100].

4. DISCUSSION

Design thinking applied to higher engineering education is founded on actual challenges, research, and solutions [101], merging interdisciplinary and collaborative methods in project-based learning that emphasizes the holistic comprehension and resolution of intricate problems and issues [11]. The utilization of design thinking as a pedagogical approach empowers engineering students to merge humanistic perspectives with their technical expertise, effectively addressing intricate real-world issues. This approach lays a robust groundwork for students to acclimate to the demands of lifelong learning and future growth. Based on the above literature review analysis, it is essential to embrace a new paradigm or carry out widespread educational reform to advance education significantly [16]. By incorporating design thinking, the emphasis of engineering education should be switched from only transmitting knowledge to developing skills and building a diversified learning environment that responds to the demands of Generation Z [17] [102].

To adapt to the intricate and unpredictable nature of changing times, engineers must employ design thinking to enhance their system design abilities, enabling them to identify problems, devise solutions, and innovate accordingly. Design thinking fosters a sense of self-driven and lifelong learning in engineering students, emphasizing cultivating creativity and design skills from the outset to facilitate the development of interdisciplinary, holistic, and problem-solving skills. In interpersonal and cognitive dimensions, design thinking helps students develop self-awareness, efficacy, and effective communication and networking skills [103]. Implementing design thinking can yield beneficial outcomes related to creativity and sustainability, thus preparing students with core skills and career readiness, critical thinking [104]. Additionally, design thinking enhances students' collaboration and communication skills, while scholars have demonstrated that it can improve engineering students' leadership, algorithmic thinking, entrepreneurial, critical thinking, creativity, and innovation culture [103]. Ultimately, design thinking exercises thinking skills and overall literacy, both during and after achieving learning outcomes [12].

5. CONCLUSIONS

This study first aims to classify engineering design thinking in curriculum design, analyse the characteristics and connotations of different introduction approaches, and establish a basic framework and methodology for the study of design thinking in the field of higher engineering education. Finally, the study concludes with a detailed analysis of keywords and key course types in design thinking in higher engineering education, laying the foundation for future research. The backbone of existing research is reflected in the case studies, individualised curriculum design, the connotative purpose of the curriculum, and superiority. As an emerging concept in recent years, academic research has rapidly grown into the processes and strategies for implementing design thinking in higher engineering education.

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