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Board 67: Implementation and Impact of Design in Higher Engineering Education: A Comprehensive Investigation of the UK Region

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Implementation and Impact of Design thinking in Higher Engineering Education: A Study of UK Practices

Abstract:

This study investigated undergraduate engineering education across 61 institutions in the United Kingdom, focusing on the integration of design elements within teaching methods and curriculum structures.

This research classifies design thinking into three distinct areas: processes, capabilities, and frameworks, and examines their integration within engineering curricula. It utilizes thematic coding of data to underscore the emphasis on design thinking components. The primary goal is to explore how design thinking education is distributed across different engineering disciplines, offering strategic insights that could guide curriculum development.

The research presents a detailed view of the current state of design components within UK engineering faculties, revealing how incorporated design thinking and design education methods are adopted. Adapting Kolmos's "Response Strategies for Curriculum Change in Engineering", a new framework, "Response Strategy for Design Thinking in Engineering Education" is developed. By adapting a strategy framework for curriculum change, this study lays the groundwork for future research into the integration and effectiveness of design thinking within engineering education.

1. INTRODUCTION

Engineering education is on the cusp of a paradigm shift towards a student-centered, flexible curriculum, personalized learning environments, and the transformation of learning experiences into capabilities for students [1, 2]. Project-Based Learning (PBL) is often heralded as a model for future curricula [3]. Within this evolving landscape, the integration of design thinking into engineering education presents a complex terrain filled with notable achievements and areas ripe for further inquiry. The growing recognition of design thinking's value is evident through its positive impacts on teaching and learning processes. However, the uneven application and comprehension of design thinking principles across various levels of engineering studies point to potential gaps in its curriculum integration. Matthews and Wrigley's study [4] focuses on design thinking in business and management higher education. However, there's a notable gap in research when it comes to engineering education, especially in the context of the UK. The practice of teaching design thinking through short-term courses and workshops has sparked debate regarding the efficacy of these condensed educational approaches[4]. The elective courses of design thinking in engineering curricula may be a missed opportunity to instill a design thinking mindset among engineering students[5]. The necessity to delve deeper into the characteristics and understanding of design and design thinking within higher education engineering programs becomes apparent.

This study aims to investigate the distribution of design thinking education across engineering disciplines and seeks to provide institutions with a strategy framework for responding to curriculum changes. By focusing on these aspects, the research aims to deepen the understanding and facilitation of design thinking within engineering education, highlighting its integration and effectiveness in fostering innovative problem-solving skills among engineers.

2. BACKGROUND

2.1 Design and design thinking

Several studies have highlighted that the concept of design and design thinking can mean different things in various fields of work [6, 7], which sometimes makes it a bit confusing when we try to follow a specific path or approach [7]. Design thinking is like a bridge connecting different areas of study, aimed at bettering how we approach designing and its positive impact on our world [8]. It's become a very popular way to innovate in businesses, arts, and organizations focused on social good [9]. It’s not just about adding new tools for designers to use, but it’s also about encouraging a way of working together that includes everyone’s ideas to find solutions that the society needs right now. When people who aren’t trained in design use design thinking, it shows how flexible and useful this approach can be in many situations [10]. The purpose of employing design thinking to design-related course is to assist students in not only improving their understanding of certain topics but also in enhancing their modes of thinking [11]. In this view, design is not a strict science but rather a practice that can be learned and expressed not just through the knowledge of subjects but in the ways design professionals do their work and present themselves [12].

In the realm of engineering education, design has been considered an integral component since the late 1980s [13]. Design thinking is regarded as a crucial mindset that necessitates cultivation and growth [14]. This approach merges the realms of creativity, technological expertise, and empathy into the essence of “design”. Dym et al. [15] describe engineering design thinking as a multifaceted cognitive process. This process encompasses the integration of diverse perspectives, systemic thinking, the navigation of uncertainty, and effective collaboration. It employs a method that is centered around humans and adaptable, aimed at addressing challenging and multifaceted issues. Design thinkers engage with problems and potential solutions by considering all related elements and connections.

2.2 The key features of design thinking in engineering education.

Expanding on the analysis of the key features of design thinking in engineering education, as outlined based on the definitions by Brenner, Uebernickel [16]. Three interconnected dimensions are categorized as a process, as a capability, and as a framework within engineering education. Each of these aspects plays a pivotal role in molding the educational experience to foster innovative engineers who can navigate the complexities of modern challenges.

Design thinking as the process within engineering education.

The review by Grönman and Lindfors [17] conducts a qualitative analysis of various models of the design thinking process, aiming to identify its components and phases. This investigation employs the framework initially adapted by Stanford University's School of Design (d.school), reformulating the original framework into a cyclical five-stage method: Empathize, Define, Ideate, Prototype, and Test. This cyclic process encourages a culture of perpetual enhancement, positioning failures as valuable learning opportunities that pave the way for superior solutions.

Design thinking as the capability within engineering education.

Design thinking as a capability within engineering education is recognized as a pivotal theme for curriculum aims, grounded in the design thinking competency model proposed by Razzouk and Shute [11]. In the face of the complexity and uncertainty of our ever-changing era, engineers increasingly require the innovative support of design thinking to assist in problem identification, resolution, and the systematic design of follow-up solutions. Design thinking promotes the development of well-rounded skills and an innovative mindset by emphasizing transdisciplinary, holistic, and problem-solving abilities [18]. Research indicates that incorporating design thinking into engineering education yields several positive outcomes, including enhanced creativity, sustainability, and career readiness[19]. Furthermore, it has been shown to improve students' leadership, algorithmic, entrepreneurial, and critical thinking skills, fostering a culture of design and creativity [20]. Graham’s study shows [21] design thinking enhances empathy, entrepreneurship, emerging technologies, material science, collaboration, and a human-centric focus. Traditionally, engineering education has heavily focused on critical thinking within technical realms, nurturing students' proficiency in managing tasks [22]. In contrast, design thinking aims to generate ideas and explore new possibilities. Design thinking provides concrete suggestions for communicating complex phenomena that are not overly abstract and are understandable for students while also being implementable for teachers. Thus, integrating design thinking into engineering education becomes a crucial consideration for future engineering [23].

Design thinking as the framework within engineering education.

Poursharif [24] contends that PBL, as a new teaching model, places students at the forefront and redefines the role of the teacher. Kuo [25] 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. Some studies [26, 27] reveal a positive correlation between students' design experiences and their intellectual development, and demonstrated the positive impact of PBL on innovation, professional skills, and hands-on abilities. In the context of higher engineering education, the Problem-Based Learning, Challenge-Based Learning, and Design-Based Learning are all PBL educational approaches aimed at engaging students and providing them with hands-on learning experiences and are considered here to be similar teaching methods.

The Conceiving, Designing, Implementing, Operating (CDIO) is an engineering education relevant pedagogical methodology that also incorporate elements of Design thinking [28]. Through practical projects and hands-on learning, CDIO integration in engineering education seeks to encourage students to apply their theoretical knowledge to real-world situations and foster active learning and problem-solving [29]. This approach frequently involves interdisciplinary collaboration, which helps students develop their communication and teamwork abilities. Furthermore, CDIO meets industry needs by presenting students with real-world engineering problems, which improves their preparedness for careers. Remarkably, several engineering institutions have already used the CDIO teaching style, realizing its ability to close the knowledge gap between theoretical knowledge and practical application. CDIO gives students the knowledge and attitude necessary for successful careers in the sector by fusing theoretical understanding with real-world experience [30].

2.3 Response strategies for curriculum change in engineering

In Kolmos's “Three Curriculum Response Strategies”[31], as shown in Table 1, a framework is presented for adapting curricula. This study's goal is to adapt this model specifically to design thinking education within engineering.

Table 1 The conceptual framework for three systemic response strategies for curriculum change. [31]

Strategy	Curriculum
Add-on Strategy	Minor changes to existing curriculum structure, e.g., new electives
Integration Strategy	Competence integration in existing courses and high degree of coordination

Re-building Strategy	Crossing or merging disciplines with a high degree of coordination and management

2.4 The Research Scope of the Engineering

Engineers seek to create, develop and apply technology, processes and systems which enhance the lives of people and protect them from harm [32] and Engineering plays a central role in the development of essential modern infrastructures and technologies [33]. Broadly encompassing numerous scientific and technological areas, engineering is integral to various innovations and practical applications and to delivering equitable and sustainable solutions to pressing global challenges [32] The most recent standard in the UK is AHEP 4 which places increased emphasis on design as part of an Engineering curricula. Similarly, the latest QAA SBS (march 2023) [32] mentions the word design 26 times compared to 5 times in the previous 2015 standard.

The engineering field is traditionally divided into four main branches: civil, mechanical, electrical, and chemical engineering. Identified in the 1990 edition of the Encyclopedialike Britannica, these disciplines are often considered the foundational categories of engineering [34]. Modern approaches to Engineering education transcend these confines. The field is rich with a plethora of sub-disciplines and interdisciplinary areas, each intertwining aspects from these core branches, underscoring the dynamic and adaptive nature of engineering. This diversification reflects the field's responsiveness to emerging technologies and societal needs [34]. In this study, the engineering disciplines are broadly classified into five major categories and their respective sub-disciplines, as illustrated in Table 2.

The engineering field is traditionally divided into four main branches: civil, mechanical, electrical, and chemical engineering. Identified in the 1990 edition of the Encyclopedialike Britannica, these disciplines are often considered the foundational categories of engineering[35]. These “traditional” fields have given rise to many more specialized areas, each evolving from and expanding upon the core principles of these primary branches. Chemical, civil, electrical, and mechanical engineering are thus recognized for their significant influence within the engineering spectrum [36].

Table 2 Scope of Engineering Disciplines

Chemical	Civil	Electrical	Interdisciplinary	Mechanical
Ceramic	Architectural	Computer	Biological	Acoustic
Drilling	Construction	Control	Biomedical	Aerospace
Materials	Earthquake	Electronics	Bioprocess	Audio
Paper	Ecological	Microelectronics	Food	Automotive
Petroleum	Fire Protection	Power	Green	Manufacturing
Plastics	Geotechnical		Industrial	Marine
Process	Highway		Mechatronics	Nuclear

Production	Hydraulic		Neural	
			Pharmaceutical	
			Protein	
			Reliability	

2.5 Generic Design vs. Discipline-Specific Design Course

Mitchell, Nyamapfene [37]'s research indicates an increase in the number of integrated engineering courses in the UK. These courses aim to incorporate interdisciplinary elements and activities into specific disciplinary frameworks, thereby offering students a comprehensive engineering perspective. For instance, the University of Birmingham's School of Engineering has recently introduced an integrated design project as part of the discipline-specific study in the first year, aiming to provide students with the opportunity to learn collaboratively across multiple engineering disciplines [38]. Similarly, UCL has proposed a concept for a cross-faculty, multidisciplinary teaching framework [22].

There are two main reasons for choosing generic design courses:

Firstly, generic design courses focus on the development of designer skills, including user-centered design and human-centered design theories and methods, combining creativity, technical knowledge, and empathy to improve the world. Additionally, sometimes it goes beyond science and integrates with art and humanized design to solve complex engineering problems. This is beneficial for improving student retention rates. [39, 40]. This contrasts with the discipline-specific design courses aims inherent in various engineering disciplines, each tailored to meet unique sectoral challenges. Specific design courses aim to equip engineers with the specialized skills required for their respective fields. For instance, Electronic Circuit Design focuses on creating electrical circuits that perform specific functions. Software Engineering Design entails designing software systems and applications, focusing on architecture, algorithms, data structures, and user interfaces Structural steel design involves the planning and detailing of steel frames used in construction projects.

Secondly, according to Lawson [41], the primary subjects of study are students who will possess a strong and profound way of thinking and behaving as designers. Engineers must be able to work in diverse teams, and integrated courses provide a platform for students from different engineering disciplines to learn together [42]. Multidisciplinary design teams often produce better engineering designs because the team can draw upon a broader range of expertise. Therefore, while completing their engineering degrees, students need to become familiar with various engineering disciplines and work with students from many different departments [43]. Young's study suggests seeking educational development in specific subjects as a way related to academic interests might hide deeper problems about the lack of equal respect for teaching and subject-based research [44].

3. METHODOLOGY

The methodology employed in this study consisted of a review process of the course syllabi, encompassing a detailed examination of individual modules and course segments. The primary aim was to identify the presence of design thinking embedded within the curriculum. The initial phase of the review process involved a preliminary examination of the course content, facilitating the early identification of elements relevant to design thinking. In the coding phase, the accumulated data were classified according to predetermined criteria that reflected the implementation aspects of design thinking within the educational offerings.

The methodology adhered to a three-pronged search principle, focusing on:

Design Thinking as Process: This involved an in-depth analysis of course descriptions to understand the emphasis placed on design thinking as a systematic approach towards problem-solving in the educational process.

Design Thinking as Capability: The investigation delved into the objectives set forth by the courses to discern their intention in fostering design thinking as a key aim for student development.

Design Thinking as Framework: This segment of the analysis scrutinized courses for mentions of the CDIO framework or PBL within their educational frameworks.

3.1 Selection of the Institution

The investigation includes only those institutions listed on “The Office for Students Register of English Higher Education Providers”, in accordance with the provisions of section 3 of the Higher Education and Research Act 2017, ensuring that all entities considered are recognized universities. The process, as depicted in Figure 1, started with an assessment for official recognition by the Office for Students [45], which resulted in 166 institutions meeting the established qualification criteria.

Subsequently, the selection process excluded institutions without an engineering focus, identified by the presence of organizational units like Colleges of Engineering, Schools of Engineering, or Departments of Engineering. The scope of this study encompasses the five engineering categories in Table 2, focusing on institutions that offer at least two or more distinct engineering disciplines. This selection criterion ensures a comprehensive evaluation across a breadth of engineering fields, facilitating a more robust analysis of how design and design thinking are integrated within diverse areas of engineering education. This refinement narrowed the focus to 85 institutions. Further selection excluded small-scale universities with limited student bodies and faculty sizes. Additionally, universities that had merged various campuses within the same institution were considered as one entity, reducing the count to 63 institutions. However, two were later excluded due to technical issues that hindered access to their websites or detailed course information, leaving 61 institutions as the final subjects of this research. This approach aims to provide a comprehensive overview of design thinking's role within the UK's engineering education landscape.

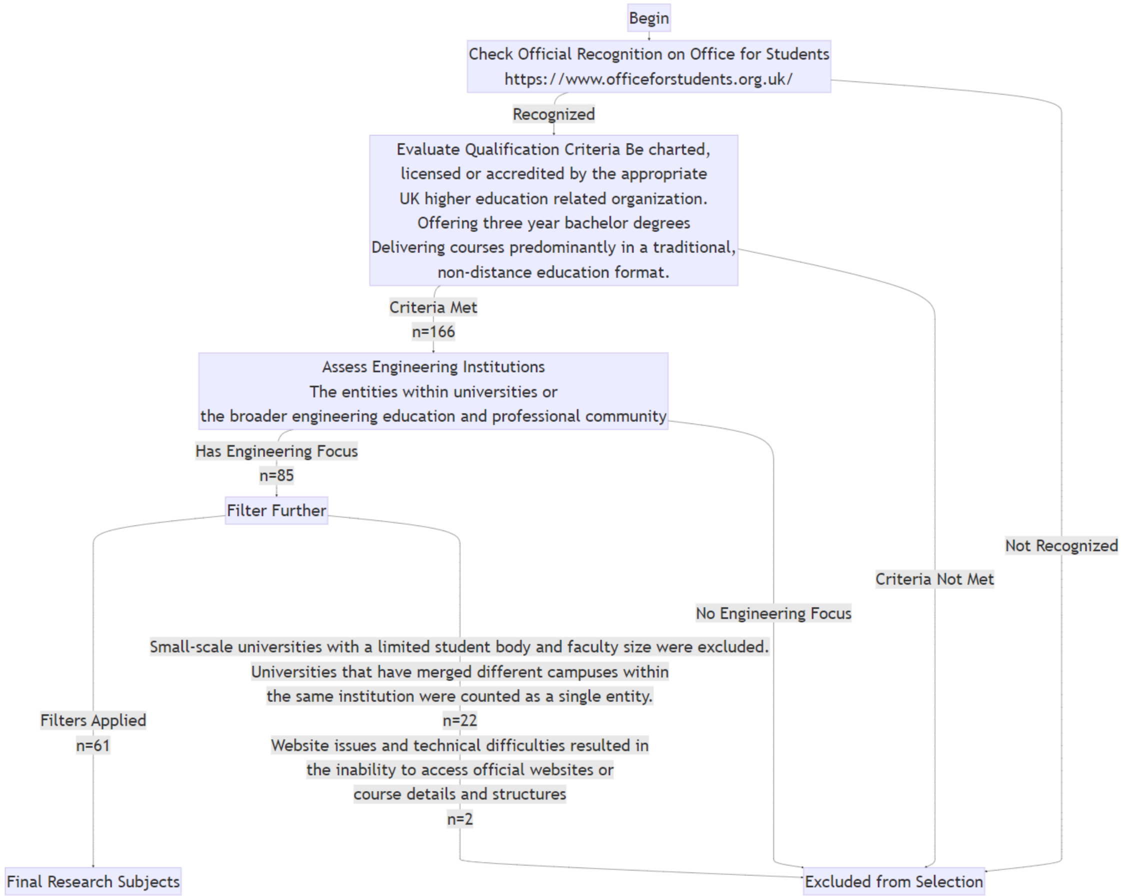

Figure 1 Selection Process Flowchart for UK Higher Education Engineering Institutions.

3.2 Selection of the Course

In this study, education plans, courses, units, and their contents at some universities were examined to understand how design and design thinking are imparted to engineering students in the UK. These courses, identified as general design courses, cover a wide range of design topics, and are mandated as required components of the curriculum.

As part of the search strategy, both general and specific criteria for inclusion and exclusion were established to refine the scope of the investigation:

2. The generic design courses selected for this study are required to serve students from at least two distinct engineering disciplines and designated as compulsory components of the curriculum.

1. The study focuses on institutions that offer a Bachelor of Engineering (BEng) program spanning 3 years and include it as a mandatory part of the study.

4. FINDINGS

The study examined the entire course syllabi, including module/course subdivisions, to identify instances of design thinking instruction within the curriculum. Following the review, data extraction, and coding, the findings were systematically categorized as detailed in Figure 2.

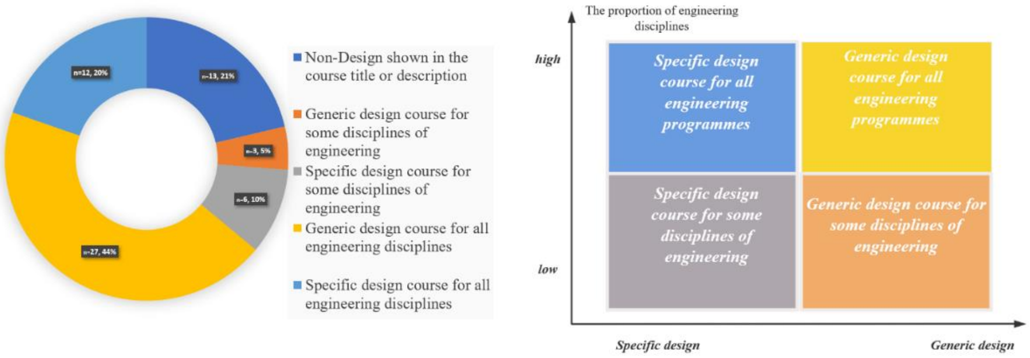

Figure 2 The distribution of generic design course and the 4 types of the courses.

Generic Design Course for All Engineering (44%): This significant proportion indicates a comprehensive approach where design principles are taught as fundamental to all engineering students, reflecting a trend towards an integrated engineering education. It suggests that these institutions value a broad-based understanding of design that transcends specific engineering disciplines, equipping students with versatile design skills applicable across various engineering contexts.

Specific Design Course for All Engineering Programs (20%) and for Some Disciplines of Engineering (10%): Collectively, these segments show that institutions are dedicating resources to specialized design education, recognizing the importance of tailored design training for the diverse needs of different engineering disciplines. Particularly in electronics and civil engineering, the focus on specific areas such as electronic design and construction design emphasizes the precise standards and skills required in these sectors. This approach allows for a more in-depth technical understanding and specialized design competencies that align closely with industry demands.

No Design Shown in Course Title or Description (21%): Some courses do not overtly feature “design” in their titles or descriptions, which might suggest that design principles are nonetheless integrated within the engineering curriculum, albeit under different terminologies or as part of broader subject areas. This absence in explicit naming could be due to several reasons such as elective versus core course structuring, curricular constraints, or the interdisciplinary nature of design that is woven into the fabric of engineering education without being singled out. Consequently, while design remains a crucial aspect of engineering, its presence in the curriculum may not always be immediately visible or labeled as such.

4.1 Design thinking in Generic Design Course

Process

In the context of a generic design, the integration of design thinking, despite being a popular term, might not be frequently visible in course descriptions, as shown in Figure 3. Although direct references to “Design thinking” may be scarce within course titles and descriptions, the underlying methodologies, and principles characteristic of design thinking process— encompassing projects, practical exercises, procedural steps, challenges, and developmental stages, as well as specific techniques such as sketching and prototyping — are often integrated into the educational content. The presence of these elements within the curriculum, and their prevalence as indicated by their frequency in course outlines, can offer insights into the subtle ways design thinking is embedded within the course structure. This integration suggests that while not always explicitly labeled as “Design thinking”, the essence of this approach is nevertheless present and emphasized through the practical application of its strategies in developing the curriculum.

In this regard, design thinking could be viewed as an hidden component in education, underpinning the creation of learning experiences without always being an explicitly taught standalone topic. For instance, a project involving a comprehensive engineering challenge might require students to employ design thinking through interdisciplinary collaboration, creative problem-solving, and iterative design, even if the course descriptions do not directly employ the term “Design thinking”.

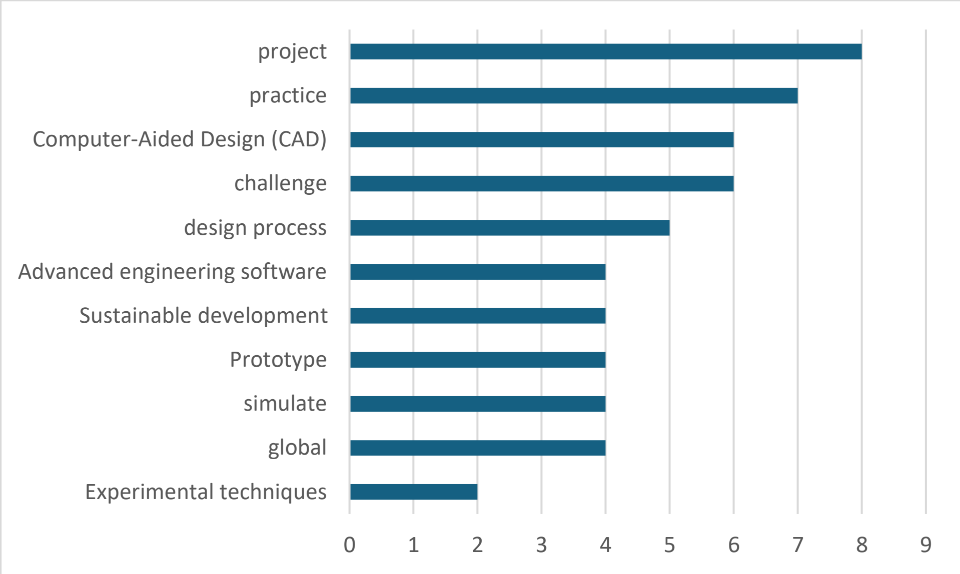

Figure 3 High frequency keywords for design thinking process.

Capability

In engineering education, design thinking capabilities enrich the curriculum by introducing students to a diverse array of skills, as shown in Figure 4. These include creative problem-solving that inspires innovation, the ability to work effectively in teams, and applying principles of sustainability to engineering challenges. Such capabilities ensure that students can not only devise inventive solutions but also collaborate successfully and approach their work with an environmentally and socially responsible mindset.

Furthermore, professional skill development is integral to this educational model. Through supplementary workshops and lectures, students learn vital presentation techniques and the nuances of technical report writing, which encompasses effective research practices and accurate referencing. These professional skills are crucial for communicating complex engineering ideas.

Another key part of the courses is learning to use advanced software for engineering tasks. This software helps students calculate, analyze, design, and test their ideas on the computer. This shows how important it is to make models and use digital tools in design thinking. It makes students ready to use technology in smart ways to solve problems.

So, by bringing design thinking into engineering courses, students get a wide range of skills. They learn not only about engineering but also about being creative, working with others, solving problems, and using technology. This prepares them for the many challenges they will face in their engineering careers.

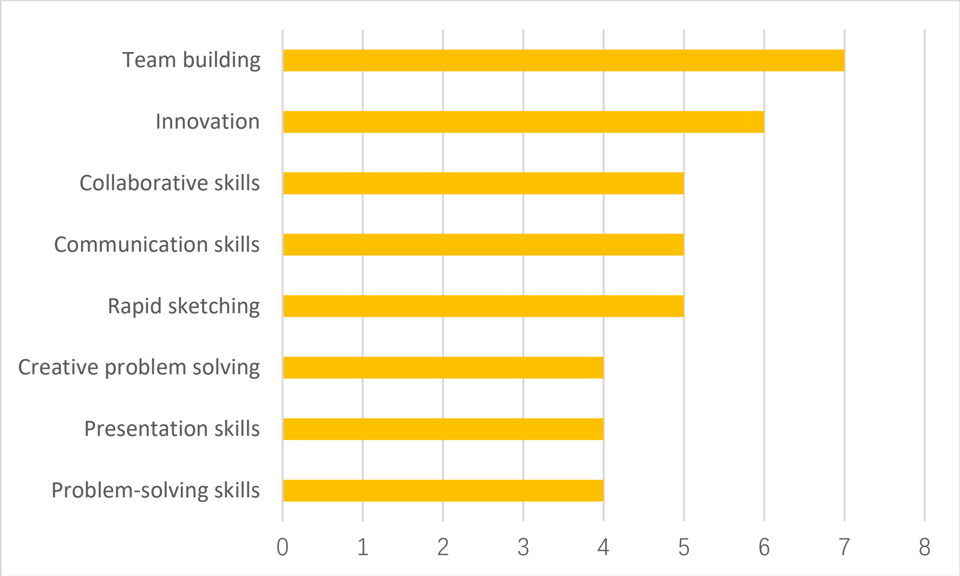

Figure 4 High frequency keywords for design thinking capability

Framework

The PBL framework has evolved and matured significantly within engineering education. Almost all engineering programs now incorporate PBL or project-based activities, either throughout the academic years or specifically in the final year as a capstone project.

Among the 61 institutions surveyed, about 12 explicitly mention the use of the CDIO framework. Some studies have suggested that CDIO requires more emphasis on the "Conceive" and "Design" aspects, rather than just on "Implement" and "Operate" to foster greater innovation among students. As Edstrom and Kolmos[28] have noted, advocates for design thinking recognize its necessity to be highly contextual and flexible, allowing the CDIO model to adapt more effectively to various conditions.

4.2 Respond Strategy

Based on Kolmos's "Response strategies for curriculum change in engineering" and the course survey discussed above, a Response level model for design thinking has been formulated. This model identifies different levels of design thinking integration within engineering curricula, as discovered throughout the data analysis process. The model, as illustrated in Table 3, details the levels, along with corresponding examples, characteristics, and the impact of each level of integration.

Table 3 Response strategy for design thinking integration for engineering education

Level	Strategy	Description	Examples	Characteristics	Impact

Single Course	Add-on Strategy	Design thinking is introduced as an optional component through elective courses and workshops, offering students the opportunity to delve into this area without modifying the core curriculum.	Elective design thinking courses; Introductory workshops	High flexibility; Individual choice; Optional engagement	Enriches the learning journey by providing diverse choices and fostering the exploration of interests beyond the core curriculum.
Smaller Parts of Curriculu m	Integration Strategy	Design thinking principles are interwoven into the core curriculum, ensuring all students gain exposure and develop proficiency in these concepts and skills.	Integration in specific projects or modules within core courses; design thinking as part of capstone projects	Mandatory engagement; Core curriculum enhancement; Uniform exposure	Enhances holistic skill development and secures the wide applicability of new competencies across fields.
System Approach	Re-building Strategy	Design thinking is adopted at an institutional level as a core component of the curriculum, required across various academic levels and explicitly connected to the engineering education framework.	Institution-wide adoption of a design thinking pedagogy; Cross-disciplinary design thinking initiatives	Comprehensive curriculum overhaul; Interdisciplinary emphasis; System-wide implementation	Stimulates innovation in teaching and learning approaches, establishing a foundation for a forward-thinking educational model.

5. DISCUSSION

This study analyzed course syllabi across institutions to determine the integration of design thinking principles in engineering curricula, revealing various educational models. The study found the incorporation of generic design courses across all engineering disciplines, indicating a trend towards integrating design thinking in engineering education. This approach equips students with skills essential for addressing complex problems. The study observed specific design courses for engineering fields, recognizing the unique challenges of each discipline. These courses provide students with the technical knowledge and design skills for their sectors, such as electronics and civil engineering.

However, the study noted a gap where design thinking is not explicitly mentioned in course titles or descriptions, suggesting variability in its acknowledgment within the curriculum. This raises questions about the visibility of design thinking principles in engineering programs and the need for more explicit integration. The analysis of design thinking as a process, capability, and framework within generic design courses showed how these principles are integrated into the curriculum. Despite varied terminology, principles like problem-solving, creativity, collaboration, and sustainability are emphasized, indicating an understanding of design thinking as a component of engineering education, even if not always labeled as such. In response, this study proposes a "Response Strategy for Design Thinking in Engineering Education", adapted from Kolmos's strategies for curriculum change. This framework aims to guide institutions in integrating design thinking into their curricula, preparing students for the engineering profession.

In summary, design thinking is a component of engineering education in the UK, with variability in its integration and explicit inclusion in curricula. This research underscores the need for ongoing exploration and adaptation in educational strategies to enhance the integration of design thinking, aiming to prepare innovative engineers for the future.

5.1 Suggestions for Future Research

Given the successful application of design thinking in other disciplines such as business and healthcare [18], future studies should conduct cross-disciplinary comparisons. However, the lack of detailed information on the scope of courses and weekly learning activities available online poses a challenge for in-depth analysis and comparison between courses. This gap suggests a need for employing a tailored Respond Strategy for Design Thinking Integration to individually assess each course's approach to integrating design thinking.

Understanding the reasons behind the lack of adoption of design is also critical, as it may highlight challenges that must be addressed to propagate this educational approach more widely. Future research should delve into individual case institutions, conducting interviews or in-depth investigations to explore each engineering institution's specific goals for nurturing design, the tools, and thinking they employ, and how such education enhances students' employability and problem-solving abilities. These case studies could offer tangible insights into the benefits and challenges of integrating design into engineering education.

5.2 Limitation

The study has several limitations that should be acknowledged. Firstly, the study presents several limitations that need acknowledgment. This study reviews how design thinking is integrated by examining course outlines, learning outcomes, and the presence of specific keywords and concepts in course descriptions, analyzing secondary data. This approach might limit the depth of the review. Moreover, the term "Design thinking" may not appear in the descriptions of some institutions' courses, leading to an incomplete research scope. Additionally, this research focuses particularly on the UK context, limiting its applicability on a global scale. Future research should expand its geographic coverage to include various regions, offering a more comprehensive understanding of how design thinking is integrated across different engineering education landscapes.

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