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Teaching and learning resources trends for engineering design courses: enhancing civil engineering education

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Abstract

As engineering education evolves, traditional pedagogical methods are increasingly inadequate to meet the demands of current learners; this requires a transition to more technologically enhanced approaches. This study explores how cutting-edge teaching and learning tools can enhance the educational experience within engineering education. New solutions and approaches are needed to address the critical issues of the role of innovative technologies in the development of essential professional skills of engineering students. Indeed, engineering design educators must examine trends in both technological and instructional resources for teaching and learning.

What are the current trends in technological and instructional resources employed for the teaching and learning of engineering design? What is the impact of innovative technologies on the development of professional skills within civil engineering education? Engineering educators need to understand how innovative teaching and learning resources enhance the engineering educational experience. Exploratory studies examining the impact of innovative technologies on the professional skills of engineering students are imperative. Through a comprehensive review of recent literature, this study examines innovative resources in civil engineering programs for engineering design courses. Our findings reveal a significant positive impact on student engagement, comprehension, and overall performance, highlighting the transformative potential of these educational innovations. In addition, the use of innovative resources enhances key skills required for the construction industry (e.g., teamwork, problem-solving, leadership).

This work not only underscores the importance of adapting to these educational advances, but also paves the way for future research on effective strategies for integrating emerging technologies into civil engineering curricula.

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Keywords: *design skills; engineering design education; teaching resources; learning resources.*

Resumen

A medida que evoluciona la enseñanza de la ingeniería, los métodos pedagógicos tradicionales son cada vez más inadecuados para satisfacer las actuales demandas de enseñanza de la ingeniería. Se requiere una transición hacia enfoques apoyados tecnológicamente que motiven a los estudiantes y faciliten el aprendizaje. Este estudio explora las herramientas de enseñanza y aprendizaje para mejorar la experiencia educativa dentro de la educación en ingeniería. Se necesitan nuevas soluciones y enfoques para abordar las cuestiones críticas del papel de las tecnologías innovadoras en el desarrollo de las habilidades profesionales esenciales de los estudiantes de ingeniería. De hecho, los educadores de diseño de ingeniería deben examinar las tendencias en los recursos tecnológicos e instruccionales para la enseñanza y el aprendizaje.

¿Cuáles son las tendencias actuales en recursos tecnológicos e instruccionales empleados para la enseñanza y el aprendizaje del diseño de ingeniería? ¿Cuál es el impacto de las tecnologías innovadoras en el desarrollo de habilidades profesionales dentro de la educación en ingeniería civil? Los educadores de ingeniería deben comprender cómo los recursos innovadores de enseñanza y aprendizaje mejoran la experiencia educativa de ingeniería. Es imprescindible realizar estudios exploratorios que examinen el impacto de las tecnologías innovadoras en las competencias profesionales de los estudiantes de ingeniería. A través de una revisión exhaustiva de la literatura reciente, este estudio examina los recursos innovadores en los programas de ingeniería civil para los cursos de diseño de ingeniería. Nuestros hallazgos revelan un impacto positivo significativo en la participación, la comprensión y el rendimiento general de los estudiantes, lo que destaca el potencial transformador de estas innovaciones educativas. Además, el uso de recursos innovadores mejora las habilidades clave requeridas para la industria de la construcción (por ejemplo, trabajo en equipo, resolución de problemas, liderazgo).

Este trabajo no solo subraya la importancia de adaptarse a estos avances educativos, sino que también allana el camino para futuras investigaciones sobre estrategias efectivas para integrar tecnologías emergentes en los planes de estudio de ingeniería civil.

Palabras clave: *habilidades de diseño; educación en ingeniería; recursos de enseñanza de diseño; recursos de aprendizaje de diseño.*

1. Introduction

Engineering design is a crucial activity of civil engineering education. The design process typically involves a sequential and iterative decision-making approach comprising three major phases: identifying design requirements, conceptualizing the system, and performing the structural design

(Wight, 2016). Traditional engineering education models often emphasize theoretical knowledge over hands-on practice, which can leave graduates less prepared for real-world challenges (Akili, 2010). As civil engineering evolves, education must effectively prepare students for the multifaceted challenges they will encounter in their professional careers. The global job market requires engineering graduates to possess a diverse skill set that includes technical proficiency, an interdisciplinary understanding of engineering design, the application of technological resources, and soft skills to enhance their professional development (Huffman, 2014; Jahnke et al., 2016).

Traditional pedagogical methods are increasingly inadequate to meet the demands of today's learners, highlighting the need for innovative teaching strategies and technology-enhanced approaches that bridge the theory-practice gap in engineering design. Technological advances have significantly changed the landscape of engineering education, providing new tools and methods to improve learning outcomes. Incorporating hands-on design experiences throughout the curriculum, from introductory courses to capstone projects, significantly improves student understanding and retention of core concepts (Masters et al., 2008). Design projects that focus on sustainability principles (Rogers et al., 2012) and real-world problem-solving (Huffman, 2014) engage students and teach them to consider economic, environmental, and societal impacts, as well as project management and teamwork skills. These hands-on approaches ensure that graduates are not only technically proficient, but also equipped with the critical thinking and adaptive skills necessary for professional development in civil engineering (Gallet et al., 2022; Osman et al., 2020).

This article examines current trends in technological and didactic resources used in the teaching and learning of engineering design and their impact on the development of professional skills within engineering education. Five major clusters of teaching and learning resources and their benefits in engineering education have been identified.

2. Methodology

This study followed the Joanna Briggs Institute (JBI) literature review protocol. This protocol outlines a systematic bibliographic review process that includes the following clear and predefined steps: defining a review question, developing a search strategy, assessing the relevance and quality of studies, extracting data, and synthesizing the evidence. In this way, the study ensures comprehensive coverage of the literature, minimizes bias and provides reliable evidence for conclusions (The Joanna Briggs Institute, 2015). A final sample of 37 documents was identified and selected following the PRISMA flow diagram suggested by the JBI protocol (see Figure 1).

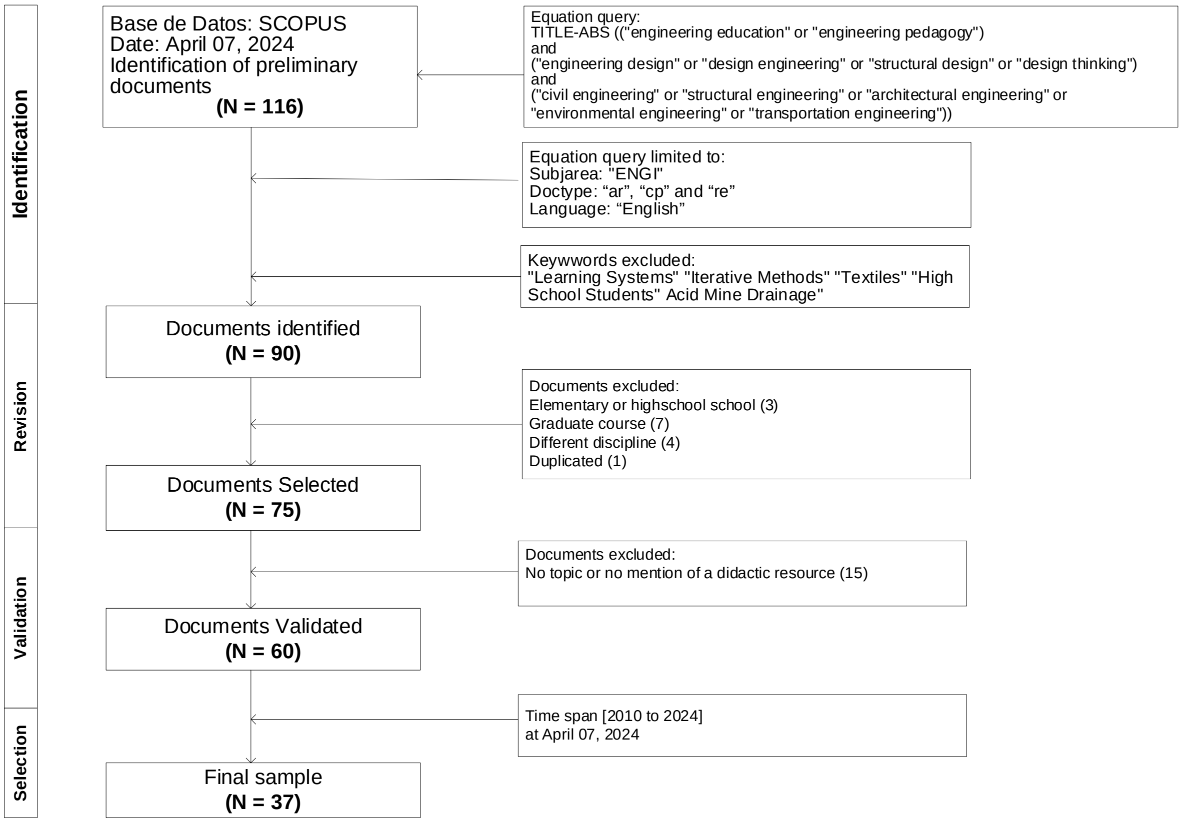

Figure 1. PRISMA flow diagram adapted (Joanna Briggs institute, 2021)

2.1 Sample description

The final sample of 37 documents consists of 11% (4 out of 37) journal articles and 89% (33 out of 37) conference papers that underwent a blind peer review process. Sixty percent (22 out of 37) of the papers are from civil engineering, and the remaining 40% (15 out of 37) are from related disciplines such as architectural engineering, environmental engineering, structural engineering, and engineering in general. Eighty-four percent (31 of 37) of the sample reports studies in the United States, and the remaining 16% (6 of 37) report studies in China, Ireland, Malaysia, Mexico, and the United Kingdom.

3. Teaching and learning resources trends

Five major clusters of teaching and learning resources provide a comprehensive overview of the trends, strategies, and emphases in engineering design education discussed in the articles (see Table 1). The clusters highlight the importance of collaboration and multi-disciplinary learning, design course development, frameworks and methodologies, real-world experiences, and technology in preparing students for successful careers in engineering design.

Resource clusters	Documents	Percentage
Collaborative and multi-disciplinary learning resources	10	27%
Design course development resources	9	24%
Pedagogical strategies-based resources	7	19%
Project and experiential resources	9	24%
Technology-based resources	2	6%
Total	37	100%

Table 1. Resource clusters for engineering design course

The trend of publications shows that during the period 2010-2015, there was more interest in teaching and learning resources for engineering design education, and after 2015, the number of publications decreased significantly. Since 89% of the sample are conference papers, it seems that the topics are not yet consolidated. The topics that have attracted the attention of academics and researchers have been identified below, organized by interest groups or clusters (see Figure 2).

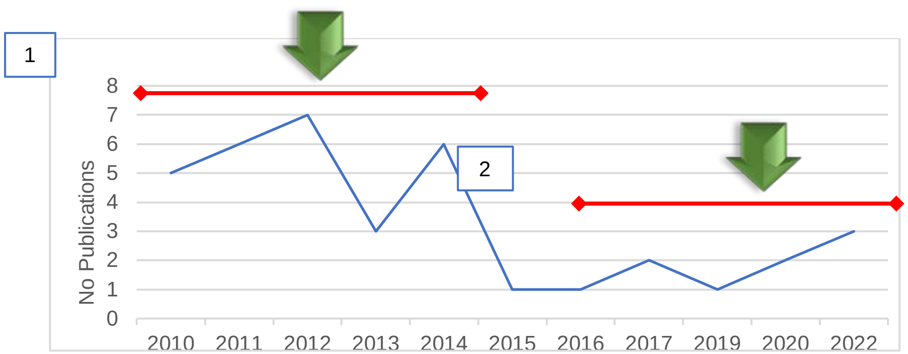

Figure 2. Resource trends for engineering design (n = 37)

3.1 Collaborative and multi-disciplinary learning resources

This cluster focuses on resources that promote collaborative and multi-disciplinary learning experiences in engineering design education (see Table 2). These resources expose students to diverse perspectives, encourage teamwork, and foster global thinking.

Article	Teaching and learning resource	Benefit
Art. 31	Interdisciplinary, project-based learning sequence: students work on real-world problems, incorporating green engineering and sustainability practices (Bauer et al., 2012).	Collaborative learning: Multi-disciplinary design
Art. 76	Multi-disciplinary capstone design: students from various disciplines to work with external clients on projects (Frank et al., 2014).	

Art. 88	Multi-disciplinary design project: students designed a biodiesel refinery, collaborating across departments (Mattingly et al., 2012).	
Art. 5	Collaborative community-based projects: students work with stakeholders to design (Cardenas, 2013).	Collaborative learning: Teamwork with community-Stakeholders of projects
Art. 57	Interdisciplinary international design: students consult with rural communities to design (Jahnke et al., 2016).	
Art. 78	Industry-driven capstone course: course involves practitioners in planning and teaching (Akili, 2013).	Collaborative learning: Practitioners-Practice
Art. 80	Collaborative learning with professional practitioners: to integrate practice into their education (Oerther, 2017).	
Art. 89	Capstone design course led by practitioner: students respond to requests for qualifications and prepare design reports under practitioner guidance (Fiegel & Denatale, 2010).	
Art. 64	International field study: students participate in on-site field studies at engineering locations around the world (Safai & Thompson, 2012).	Multi-disciplinary learning: international context
Art. 74	First-year environmental design project: students design a sustainable environmental engineering project, then install it in a rural Peruvian community (Montoya et al., 2013).	

Table 2. Resources for collaborative and multi-disciplinary learning

The teaching and learning resources in this cluster emphasize the importance of collaborative and multi-disciplinary approaches in engineering design education. Since 2010, these resources have enhanced learning by fostering collaboration between disciplines, involving teamwork with community stakeholders, integrating practical experience through practitioner interaction, and incorporating international field studies. These methods improve students' real-world project preparation, teamwork, communication skills, and global awareness, ultimately equipping them with the necessary skills for professional development in civil engineering.

3.2 Resources for design course development

This cluster includes resources that focus on curriculum, course, and program development initiatives in engineering design education (see Table 3). These resources aim to enhance the overall educational experience by integrating innovative teaching approaches and professional skills development.

Article	Teaching and Learning Resource	Benefit
Art. 19	Engineering case study: to understand professional practice, design team dynamics, construction processes, and ethical issues (Brady & Lawson, 2011).	Case studies-Review problems: improving knowledge
Art. 61	Inquiry-based case study: inquiry-based experiments in sustainability and green design (Luster-Teasley & Waters, 2011).	
Art. 81	Review problems: to reinforce concepts (Bruhl, 2020).	
Art. 20	External internships: to give students real-world experience under licensed professional engineers (Fries et al., 2010).	External Internship - Seminars:
Art. 53	Seminar on global construction: students present papers on labor-intensive construction and sustainable practices, helping them understand global construction needs (Koehn et al., 2010).	

Art. 59	SEEECS seminar (scholars of excellence in engineering and computer science): to work on interdisciplinary and enhancing leadership skills (Vernaza et al., 2012).	
Art. 10	Life cycle sustainability economics module: teaching engineers how to conduct economic analyses that include environmental impacts (Rogers et al., 2012).	
Art. 46	Engineering sustainable modules: offers sustainability modules, senior design projects, and internships (Sattler et al., 2011).	Modular activities: Portfolios
Art. 79	Project-based modules: to integrate engineering and design principles from the first semester (Kirschenman & Brenner, 2011).	

Table 3. Resources for design course development

The design course development resources articles were published in the early part of the 2010s. These articles discuss reforms in civil engineering curricula through methods such as project-based learning, problem-based learning, case studies, review assignments, interdisciplinary topics such as sustainability and economic concepts, peer mentoring, and integration of design courses with industry internships. These initiatives aim to enhance learning, creativity, problem-solving, communication, critical thinking, and analytical skills. In addition, integrating professional practice into design courses provides real-world experience, promotes career awareness, and facilitates student networking.

3.3 Pedagogical strategies-based resources

This cluster includes resources that focus on theoretical frameworks and methodologies to enhance engineering design teaching (see Table 4). These resources provide a foundation for designing effective learning experiences and evaluating student outcomes.

Article	Teaching and Learning Resource	Benefit
Art. 1	CDIO: conceive-design-implement-operate framework experiential learning model that incorporates teamwork and collaboration into the engineering curriculum (Cosgrove & O'Reilly, 2019).	Framework: CDIO
Art. 60	TRIZ: to solve complex engineering problems by improving problem identification, analysis, and innovative thinking through systematic methods (Mao-Guo et al., 2022).	Framewok: TRIZ
Art. 12	Peer review cycle: this method involves students in peer-reviewing each other's analytical content and written work. It improves constructive feedback and critical engineering skills (Barroso & Morgan, 2011).	Methodology: Peer review cycle
Art. 36	Inverse problem methodology: inverse problems is explored across various sub-fields of structural engineering education (Gallet et al., 2022).	Methodology: Inverse Problem
Art. 37	Flipped classroom: pre-class assignments and quizzes, short pre-class tasks help students prepare for a structural design of foundations course (Laman et al., 2012).	Methodology: Flipped Classroom
Art. 27	Math-related critical thinking theory: developed from professional practice, helps students justify engineering decisions using mathematical and critical thinking processes (Osman et al., 2020).	Theory: Critical Thinking

Art. 28	Creative thinking: a rubric based on the investment theory of creativity and the creative thinking value rubric, emphasizing divergent thinking and risk-taking (Husted et al., 2014).	Theory: Creative Thinking

Table 4. Resources based on pedagogical strategies

Resources based on pedagogical strategies include the implementation of CDIO (Conceive-Design-Implement-Operate) and TRIZ (Theory of Inventive Problem Solving) frameworks to integrate project-based, experiential learning with teamwork and collaboration, as well as problem identification, analysis, and innovative thinking. Methodologies such as peer review, inverse problem solving, and flipped classrooms promote constructive feedback, critical analysis of real-world problems, and student-centered learning. In addition, theory-based strategies focus on fostering critical and creative thinking, highlighting the interaction between critical and mathematical thinking in design practice and fostering environments that enhance students' creative abilities.

3.4 Project and experiential learning resources

This cluster includes resources that emphasize project-based, experiential, and hands-on learning approaches in engineering design courses (see Table 5). These resources engage students in real-world problems, laboratory work, and design challenges, promoting active learning and practical skill development.

Article	Teaching and Learning Resource	Benefit
Art. 6	Capstone projects: students engage in real-world projects guided by professional engineers and consulting firms (Huffman, 2014).	Project-based learning: Capstone Design Project
Art. 16	Capstone project-based learning: a hybrid PBL method to develop problem-solving, group work, and presentation skills (Gavin, 2011).	
Art. 17	Capstone design course: students work on real-world problems in teams with industry professionals (Akili, 2010).	
Art. 68	Freshman engineering capstone project: students design and build a drawbridge that helps them grasp interdisciplinary teamwork and technical communication (Khorbotly & Reid, 2010).	
Art. 84	Architectural senior capstone: students work in groups on large-scale, multi-disciplinary projects, such as architectural, structural, mechanical, and lighting design (Megri, 2014).	
Art. 49	Introductory fabrication exercise: students build Archimedes-screw devices (Epstein et al., 2014).	Experiential learning: to understand principles
Art. 56	Tree mechanics: trees as multifunctional structures to teach mechanics, material science, and sustainability (Jawaharlal et al., 2017).	
Art. 13	Origami engineering course: teaching advanced design skills through origami models that align design thinking and entrepreneurship (Simon et al., 2022).	Hands-on learning: practical experience
Art. 38	Charrette sessions: collaborative, hands-on sessions where students build consensus through peer evaluation, teamwork, and technical analysis (Oswald et al., 2012).	

Table 5. Resources for project and experiential learning

Project-based learning in capstone projects varies from fabricated scenarios to real-world design projects and multi-disciplinary collaborations. These resources enhance students' exposure to real-world engineering design, improve long-term knowledge retention, facilitate learning industry software, and develop teamwork, communication, and project management skills. Experiential learning helps familiarize students with tools, materials, and techniques, aids in understanding structural concepts through real-world analogies. It enhances design thinking, team formation, leadership skills, communication, technical evaluation, and professionalism.

3.5 Technology-based learning resources

This cluster focuses on technology and software-based resources that support engineering design courses (see Table 6). These tools facilitate learning and understanding of design concepts and processes.

Article	Teaching and learning resource	Benefit
Art. 2	PENCAST technology: to capture handwritten notes alongside audio explanations, aiding students' comprehension of structural design foundations (Laman & Brannon, 2014).	Supporting learning process: technological aids
Art. 22	Topology optimization software: to visualize and improve structural design concepts (Sangree et al., 2015).	Enhancing design comprehension: structural design

Table 6. Resources for technology-based learning

The use of technology and software resources for teaching and learning engineering enhances the understanding of complex concepts. In the last decade, two notable resources have been identified for application in engineering design: PENCAST technology and topology optimization software. PENCAST, which captures handwritten notes and audio explanations, has proven effective in enhancing knowledge retention and supporting the learning process. Topology optimization software is used as a teaching resource to visualize and improve structural design concepts, thereby enhancing students' comprehension.

4. Conclusion

The articles reviewed in this study discuss various teaching and learning resources that enhance engineering design education, which can be grouped into five main clusters: collaborative and multi-disciplinary learning resources, resources for design course development, pedagogical strategies-based resources, project and experiential learning resources, and technology-based learning resources. Collaborative and multi-disciplinary learning resources, such as interdisciplinary project-based learning sequences, multi-disciplinary capstone design projects, and collaborative community-based projects, promote teamwork, real-world problem-solving, and engagement with stakeholders, practitioners, and international communities. Resources for design course development include case studies, review problems, external internships, and seminars that improve students' knowledge and understanding of professional practice, global construction needs, and sustainability. Pedagogical strategies-based resources encompass frameworks like CDIO and TRIZ, methodologies such as peer review cycles, inverse problem approaches, and flipped classrooms, as well as theories like critical and creative thinking, which enhance problem-solving, innovation, and decision-making skills. Project and experiential learning resources, including various capstone projects, hands-on exercises, and practical experiences, help students grasp interdisciplinary teamwork, technical communication, and real-world applications. Finally, technology-based learning resources, such as PENCAST technology and topology optimization software, support the learning process and enhance students' comprehension of structural design foundations and concepts.

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