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RESEARCH ARTICLE

Innovative interdisciplinary models in engineering education: Transforming practices across global universities

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ABSTRACT

The growing complexities of global challenges necessitate a transformative shift in engineering education, prioritizing interdisciplinary collaboration. This study explores innovative interdisciplinary models implemented by leading universities worldwide, including three European universities (University College London [UCL], Delft University of Technology, Aalborg University), three American universities (Stanford University, Princeton University, Massachusetts Institute of Technology [MIT]), and three Canadian universities (University of Toronto, McMaster University, and University of Waterloo). It examines and synthesizes talent cultivation frameworks in interdisciplinary engineering education, highlighting key challenges and providing actionable insights. The study also investigates the structural and cultural changes required for effective implementation, focusing on the delicate balance between preserving disciplinary depth and promoting cross-disciplinary integration. Finally, it offers practical strategies centered on leadership, institutional culture, and project-based learning to enable universities to build interdisciplinary competencies and sustain global competitiveness.

Key words: interdisciplinary engineering education, curriculum reform, project-based learning, collaborative innovation, challenge-based learning, higher education transformation, global challenges, sustainable engineering practices

INTRODUCTION

In the 21st century, the increasing complexity of challenges in large-scale engineering practices necessitates interdisciplinary collaboration to address global issues effectively. No single discipline can independently resolve the multifaceted problems presented by such challenges. This complexity arises, in part, from the convergence of specialized technologies across industries such as energy, transportation, communication, and medicine, fostering heightened interdependence within intricate socio-technical systems. Consequently, interdisciplinary teams are indispensable for tackling pressing global challenges, including climate change and societal pandemics. In the field of engineering, interdisciplinarity is not merely an option but an imperative. Therefore, engineering education must urgently shift its focus towards fostering talent equipped for interdisciplinary collaboration.[1–3]

WHAT IS INTERDISCIPLINARY EDUCATION?

Definition of interdisciplinary

The prevailing talent cultivation model in higher education remains predominantly traditional and discipline-oriented, wherein students acquire knowledge and skills specific to a particular professional field and subsequently pursue careers within that domain upon graduation. When engineering projects demand solutions

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spanning multiple disciplines—such as mechanical engineering, electrical engineering, civil engineering, and chemical engineering—the conventional approach is to assemble a multidisciplinary team comprising specialists from these respective fields. This method epitomizes the standard "multidisciplinary" approach. However, addressing complex, large-scale engineering challenges necessitates a more integrated strategy, one that synthesizes the diverse disciplinary knowledge, skills, and experiences of all team members into a cohesive "community of knowledge." This process requires individuals to transcend discipline-specific perspectives, develop new, holistic understandings by integrating various fields, and fully embrace this synthesized knowledge system as the basis for addressing intricate problems.[4] This methodology is referred to as "interdisciplinarity." In the modern era, the concept of interdisciplinarity has garnered widespread recognition and positive connotations, often being equated with notions such as "innovative research" and "comprehensive solutions".[5–6]

What is the difference between "interdisciplinary" and "multidisciplinary"? Taajamaa *et al.*[7] argue that in a multidisciplinary team, members work either in parallel or at different stages of a project, remaining grounded in their respective disciplinary bases throughout. While multidisciplinary teams benefit from diverse disciplinary knowledge, they do not create a new knowledge system. In contrast, interdisciplinary collaboration involves team members analyzing, synthesizing, and coordinating across disciplines to achieve an integrated final outcome. Members of an interdisciplinary team share a conceptual framework and focus on leveraging diverse disciplinary methods, theories, and concepts to address problems collaboratively.[6] The report *Facilitating Interdisciplinary Research*, jointly published by the US National Academy of Sciences, National Academy of Engineering, and National Academy of Medicine, provides a clear distinction between the two concepts (Figure 1).[7] Multidisciplinarity refers to disciplines A and B working together to solve a common problem, after which they separate without change. Interdisciplinarity, on the other hand, involves disciplines A and B collaborating to solve a shared problem, during which interaction leads to the formation of a new research field or discipline C.

What is Interdisciplinary Education?

Interdisciplinary Education is an educational process where learners draw knowledge from two or more disciplines to enhance their understanding of a particular subject or problem, ultimately reaching a level of comprehension that surpasses what any single discipline could achieve. Through interdisciplinary education, learners integrate and develop information, concepts, methods, and procedures from various disciplines to acquire new knowledge, understanding, and skills, enabling them to explain or solve problems effectively.[8] This form of learning is inherently active and self-directed.[9]

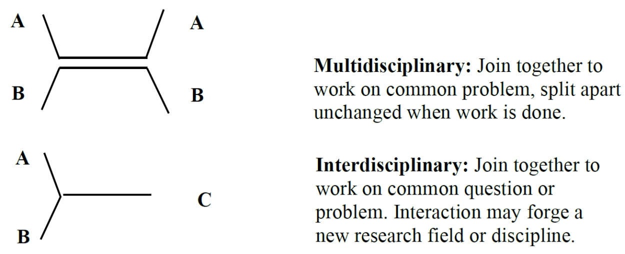

Figure 1. The difference between multidisciplinary and interdisciplinary.

Interdisciplinary education first emerged in the realm of higher education in the United States. As universities around the world have grown in number and scale, it has gradually developed into an innovative educational practice in countries such as those in Europe and North America. This evolution can be attributed to two primary factors. First, the widespread adoption of the internet (or, to some extent, the nature of modern technology itself) has unleashed unprecedented opportunities for combining ideas across disciplines. Second, the emergence of complex real-world challenges—such as climate change, sustainable development, and artificial intelligence (AI)—clearly demonstrates a level of interdisciplinarity that surpasses the traditional structure of most academic departments.[10]

Currently, there is no established methodology for implementing interdisciplinary education in the field of engineering education. However, interdisciplinary engineering education has garnered widespread attention from industry, academia, and the education sector. Several universities in Europe and North America have begun to make meaningful and proactive attempts in this area. Notable examples including the Integrated Engineering Program at UCL in UK, the Integrated Collaborative Innovation (ICI) framework at Delft University of Technology in Netherlands, the interdisciplinary Megaproject-based education at Aalborg University in Denmark, the Human-Centered Engineering for Global Solutions model at Stanford University, the Engineering + Humanities Model at Princeton University, the New Engineering Education Transformation (NEET) initiative at MIT, the Institute for Studies in Transdisciplinary Engineering Education and Practice at University of Toronto, the Pivot Program at McMaster University, and along with University of Waterloo (UW) in Canada.

Theoretical analysis

Interdisciplinary engineering education aligns with constructivist learning theories, particularly those emphasizing active, experiential learning and the social constructivist perspective.[11] By integrating problem-based learning (PBL), design thinking, and systems thinking into the curriculum, universities foster the development of engineers equipped to address complex global challenges. These methods emphasize not only technical competencies but also critical soft skills like collaboration, adaptability, and ethical reasoning.

This study reflects the transition from discipline-specific education to interdisciplinary models, necessitating structural and cultural shifts in academic institutions. These models resonate with the "Mode 2" knowledge production framework, which prioritizes context-driven, problem-focused learning.[12] Universities like Stanford and Aalborg exemplify this by integrating real-world projects into academic programs, bridging the gap between theoretical knowledge and practical application. While innovative, interdisciplinary education faces challenges, such as the balance between disciplinary depth and cross-disciplinary breadth. The successful implementation requires strong leadership, a collaborative culture, and an ecosystem that supports cross-functional learning, as seen in models like MIT's NEET and McMaster's Pivot.

The study conducted field research at most of the aforementioned institutions, engaging in in-depth interviews with deans of engineering schools and directors of programs (or centers). By analyzing and organizing the data collected from literature, surveys, and interviews, the study explores and interprets survey findings related to the objectives of interdisciplinary engineering education research. Based on this process, the research outcomes of this paper were developed. The following sections provide an analysis of interdisciplinary engineering education at the nine case study universities from Europe to North America.

ANALYSIS OF INTERDISCIPLINARY ENGINEERING EDUCATION MODEL

UCL's Integrated Engineering Programme (IEP)

Before 2010, the undergraduate programs at the Faculty of Engineering at UCL were characterized by a strong focus on engineering science, being very traditional with little emphasis on group work or practical experience. The seeds of engineering education reform were sown in early 2011, when the then Dean of the Faculty of Engineering increasingly recognized the need for a fundamentally different approach to undergraduate education.[13] Over the next three years, the faculty implemented a reform initiative for undergraduate engineering education, known as the IEP, which was officially launched in September 2014.

IEP introduction

The disciplines involved in the IEP include Mechanical Engineering, Electronic and Electrical Engineering, Civil Engineering, Chemical Engineering, Computer Science, Biochemical Engineering, Biomedical Engineering, Management Science, and Mechanical and Business Finance. The curriculum of the IEP consists of three modules, a project, and elective courses. Module 1: Engineering Challenges, where the topics are drawn from the globally impactful "Global Grand Challenges" program; Module 2: Design and Professional Skills; Module 3: Mathematical Modeling and Analysis.

The project, titled "How to Change the World," focuses on a real-world task closely related to the United Nations Sustainable Development Goals (SDGs). Student teams collaborate with industry partners to design engineering solutions. Recent industry partners involved in the "How to Change the World" project include the UK Department for Transport, Arup Engineering Consultants, Engineers Without Borders UK, Motorola Solutions, and Lloyds Banking Group.

In addition to gaining in-depth knowledge in specific subject areas within the three modules, students also take elective courses. Currently, more than 15 elective courses are available, including AI and Marine Engineering, Computer Programming, Environmental Engineering, Modern Foreign Languages, Entrepreneurship Education, Engineering Mathematics, and Modern Applications of Biomechanics.

The design of the IEP teaching framework is aimed at addressing the development of engineering and technology in the 21st century, as well as the industry's demand for graduates with innovative thinking. These graduates are not only technically proficient in their specific disciplines but also possess a broader knowledge base and are accustomed to collaborating with experts from other fields, effectively communicating their ideas (Figure 2).

IEP's features

Feature 1: Flexible and practical management approach.

The successful implementation of the IEP can be attributed to several factors, with the flexible leadership approach of the management playing a key role. This approach provides a balance between the project vision and mission, as well as the pragmatism required to make the initiative effective. This leadership style is viewed as empowering departments to drive reforms "from the

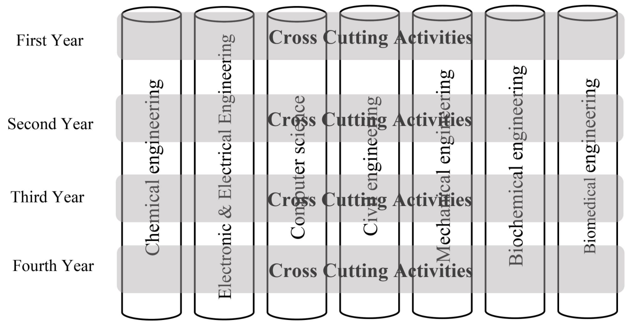

Figure 2. Integrated Engineering Programme teaching framework.

bottom up," ensuring that the unique needs, professional backgrounds, and cultures of each department are fully reflected.[14]

Feature 2: Universal curriculum structure.

All students in the Faculty of Engineering follow a common curriculum structure during their first two years of study. The core of this structure is real-world project scenarios, which require students to address genuine engineering problems. These projects typically stem from the university's collaborations with various industries, regions, and communities. Student teams from diverse disciplinary backgrounds are required not only to consider the technical aspects of the solutions but also to evaluate their social, environmental, and public policy impacts. This approach not only helps students "break down disciplinary barriers" and critically understand the role and position of engineering disciplines, but also equips them with the tools for "effectively collaborating with people from different fields".

Feature 3: A tangible platform for engineering education reform.

The IEP project team, along with the newly established UCL Centre for Engineering Education, ensures that UCL has a solid platform to sustainably advance interdisciplinary engineering education reform.[15] As the primary designers and promoters of the IEP, the Engineering Education Centre connects faculty and educational resources from both the Faculty of Engineering and the Faculty of Education. Through this initiative, the IEP project team was awarded the Collaborative Award for Teaching Excellence in 2017 by Advance HE, the UK's higher education advancement organization.[16]

Summary

The IEP has transformed the way engineering education is delivered at UCL. Through an innovative interdisciplinary approach, the IEP has revised the existing eight undergraduate programs in the Faculty of Engineering, addressing the industry's demand for enhancing students' employability. The teaching framework proposed by the IEP, based on "problem-based" and "active learning" principles, has not only encouraged greater creativity among faculty in their teaching but also allowed students to deeply experience how engineers influence industry and society at the early stages of their careers. By implementing the IEP, UCL has established a new mode of collaboration between educators, professional institutions, and industry. It has fostered strong links between higher education and the engineering sector, continuously meeting society's demand for engineering talent. More importantly, it has actively attracted and nurtured domestic engineering talent, driving engineers' active participation in the development of the UK economy.

Technische Universiteit Delft's ICI

Technische Universiteit Delft (TU Delft), established in 184, is one of the leading institutions for technological education and research in Europe. Known for its strong focus on innovation and multidisciplinary collaboration, TU Delft consistently ranks among the world's top engineering schools. The university emphasizes sustainability, technological innovation, and global collaboration, preparing students to tackle pressing societal challenges. TU Delft's educational philosophy is grounded in the belief that modern engineers must possess interdisciplinary skills, a mindset for lifelong learning, and the ability to apply knowledge to real-world problems.

ICI Introduction

TU Delft's model of interdisciplinary engineering education is structured around its ICI framework. The ICI leverages PBL, collaborative projects, and a networked ecosystem of academia, industry, and research. The model focuses on equipping students with skills for addressing complex engineering challenges that require interdisciplinary expertise, working with external partners on four thematic basis: robotics, health & tech, AI, energy (Figure 3).

Central to the ICI model is the integration of technical depth with broad interdisciplinary collaboration. Students engage in cross-departmental projects, industry partnerships, and experiential learning, all supported by state-of-the-art facilities and expert mentorship. The ICI model highlights the interaction between interdisciplinary teams, industry collaboration, research integration, and flexible curricula to address real-world challenges.

Meanwhile, TU Delft provides an innovative learning spaces. The Innovation & Impact Centre of TU Delft assists in setting up collaborations between industry, government and knowledge institutions to co-work on

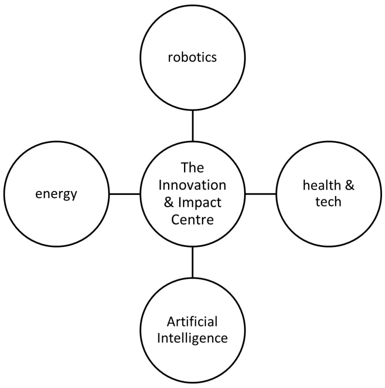

Figure 3. Integrated Collaborative Innovation themes.

global challenges and bringing innovations and stimulate the technology transfer to society. TU Delft's campus includes advanced maker spaces, simulation labs, and collaborative hubs designed to facilitate teamwork and creativity. These environments support hands-on learning and interdisciplinary collaboration.

ICI's features

Feature 1: Interdisciplinary challenge-based learning (CBL) .

The model places students in real-world, open-ended challenges that demand interdisciplinary approaches. Students work in diverse teams, combining expertise from various engineering domains to co-develop innovative solutions for complex problems, such as climate resilience or smart cities.

Feature 2: Flexible curriculum with specialization tracks.

TU Delft's engineering programs offer students a modular curriculum that balances technical depth with interdisciplinary breadth. Specialization tracks are paired with cross-disciplinary electives, enabling students to tailor their education to their career goals while fostering interdisciplinary fluency.

Feature 3: Strong industry and research integration.

Partnerships with global companies and research institutions are embedded in the curriculum. Industry professionals co-develop course content, provide mentorship, and offer internships. Research integration allows students to contribute to cutting-edge projects, often resulting in tangible innovations.

Summary

TU Delft's model of interdisciplinary engineering education exemplifies a forward-thinking approach that blends technical expertise with collaborative innovation. The ICI framework effectively prepares students for the complexities of modern engineering by emphasizing CBL, curriculum flexibility, and robust industry integration. This model not only equips graduates with the skills to navigate interdisciplinary challenges but also serves as a benchmark for global engineering education reform.

Aalborg University's Megaprojects

Since its establishment, Aalborg University has adopted "PBL" as its teaching method throughout the learning process, with all courses based on problem-solving and focusing on interdisciplinarity. As humanity faces global challenges related to climate change and environmental issues, Aalborg University believes that education must transcend disciplinary boundaries and address major challenges through "megaproject" collaborations. To enhance interdisciplinarity between various disciplines, particularly in engineering, Aalborg University began implementing PBL-based interdisciplinary education in the early 2000s. In recent years, this approach has been further expanded with a focus on addressing sustainability issues in human society. In the fall of 2019, Aalborg University officially launched its "Megaprojects" interdisciplinary education program.

Megaprojects introduction

The "Megaprojects" initiative is a typical interdisciplinary project launched by Aalborg University in collaboration with the Aalborg City Government. It spans all departments of the university, and project selection is based on global issues aligned with the United Nations' 17 SDGs (UN SDGs). The global challenges faced by the international community are complex and interconnected. To find viable solutions to these complex problems, experts from different fields must work together, which is the underlying philosophy behind Aalborg University's interdisciplinary education in megaprojects, conducted across five of its faculties.

The Megaprojects initiative is an overarching framework (Figure 4), with each "megaproject" focusing on three key areas (Focus). These key areas are subdivisions of themes related to the megaproject, oriented around specific problems and focusing on the UN SDGs. Each key area may contain up to two challenges (Challenge), with each challenge further subdivided into several projects (Project). The duration of each megaproject is 2-3 years.

The first two megaprojects in collaboration with the Aalborg City Government have been identified: "Simplifying Sustainable Living" and "The Circular Region." The "Simplifying Sustainable Living" project divides the challenges into three key areas: waste, green consumption, and transportation. The Aalborg City Government aims to maximize citizen engagement in reducing waste generation, improving waste sorting

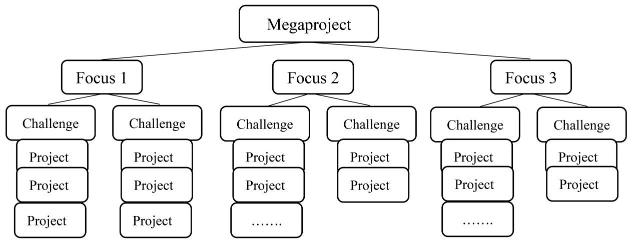

Figure 4. Megaprojects structure.

capabilities, and making sustainable transportation a more attractive option. In the "Circular Region" project, the Aalborg City Government has set the goal of making the North Denmark region the first circular region in the world. The "Circular Region" project divides the challenges into three main key areas: institutional reform, knowledge sharing, and circular economy practices.

Megaprojects' Features

Feature 1: Adhering to Aalborg University's deoxyribonucleic acid (DNA)—PBL.

Aalborg University is one of the best universities in the world that PBL as its teaching method. Through PBL-based megaprojects interdisciplinary education, students are able to identify and analyze problems from real, problem-based large projects and propose solutions. The solutions provided by students, in collaboration with external partners in natural, real-world challenges, always have one central element—solving practical, real-world problems.

Feature 2: A well-established management and service syste.

To ensure the comprehensive and orderly implementation of the megaprojects interdisciplinary education, each megaproject has clearly defined the responsibilities of various departments involved, including project managers, host departments, coordinators, working groups, and advisory boards. The project manager plays a key role, responsible for the overall coordination, process management, and project planning of the megaproject. Each megaproject must also be assigned to a host department, which is responsible for appointing a coordinator. The advisory board handles the overall decision-making for the megaprojects and holds at least two meetings per year as needed.

Feature 3: A sustainable physical center.

To cultivate engineers with a vision for sustainable development and innovative thinking, Aalborg University officially established the United Nations Educational, Scientific, and Cultural Organization (UNESCO) Category II Center—"Aalborg Center for Engineering Science and Sustainable Development Studies" in 2014. The Aalborg Center aims to integrate Problem-Based and PBL, engineering education research, and sustainable development into a cohesive framework, innovatively embedding PBL teaching into the interdisciplinary educational process.

Summary

Aalborg University believes that global issues are best addressed through megaprojects, which elevates the PBL teaching method to a new level. By facilitating interdisciplinary, cross-course, and cross-semester collaboration in megaprojects, the university brings together students, faculty, and industry experts with diverse knowledge and skills to learn from each other. The PBL-based megaprojects interdisciplinary education implemented by Aalborg University provides comprehensive solutions to Denmark's and the world's current sustainability and social issues, addressing global challenges through collaboration across campuses, universities, and borders. In terms of interdisciplinary education, input from other disciplines enhances students' holistic skills and fosters their ability to collaborate across disciplines with a focus on sustainability. More importantly, as Jakob Stoustrup, Vice Dean of the Faculty of Information Technology and Design at Aalborg University, states, while innovative technological solutions are essential, it is equally important to always keep in mind human behavior and needs.

Stanford University's Human-Centered Engineering for Global Solutions (HCEGS)

Stanford University, located in California's Silicon Valley, is a global leader in education, research, and innovation. Known for its entrepreneurial culture and proximity to some of the world's leading technology companies, Stanford excels in fostering creativity and collaboration across disciplines. Within the School of Engineering, Stanford has embraced interdisciplinary approaches to address complex global challenges, combining engineering expertise with insights from humanities, business, medicine, and environmental sciences. This commitment is embodied in its interdisciplinary engineering education model, which equips students with skills to solve real-world problems through collaboration, innovation, and critical thinking.

HCEGS introduction

Stanford's HCEGS model focuses on interdisciplinary collaboration, with a strong emphasis on addressing societal challenges such as climate change, sustainable energy, healthcare, and equity. This model integrates engineering, design thinking, and systems thinking with insights from fields like psychology, economics, and sociology. The model is centered around three pillars: (1) Human-centered design (HCD). Encourages empathydriven problem-solving and user-focused innovation. (2) Interdisciplinary collaboration. Fosters partnerships among multiple academic domains. (3) Systems thinking. Focuses on understanding interconnected systems and their broader societal impacts.

Through this approach, Stanford ensures that its graduates are prepared to lead transformative efforts in diverse industries and sectors (Figure 5).

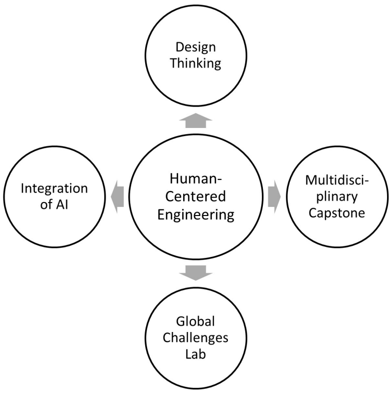

Figure 5. Human-Centered Engineering for Global Solutions (HCEGS) model.

HCEGS's features

Feature 1: Design thinking and experiential learning.

Stanford pioneered the Design Thinking methodology, which is a cornerstone of the HCEGS model. Courses are project-based, encouraging students to empathize with users, define problems, ideate solutions, prototype, and test in iterative cycles. The d. school (Hasso Plattner Institute of Design) provides students with hands-on opportunities to solve real-world problems, such as designing affordable healthcare devices for underserved populations.

Feature 2: Multidisciplinary capstone projects.

Under the HCEGS model, students participate in multidisciplinary capstone projects that involve collaboration with peers from other disciplines (*e.g.*, computer science, business, environmental sciences). These projects tackle real-world challenges like renewable energy systems, AI-driven healthcare solutions, and urban sustainability. Students are mentored by faculty and industry professionals, bridging the gap between academia and practical application.

Feature 3: Global challenges laboratory.

Stanford's Global Challenges Laboratory provides a dedicated space for students to work on global issues in diverse teams. This facility emphasizes interdisciplinary research and equips students with advanced tools for simulation, data analysis, and rapid prototyping. Example projects include designing low-cost solar panels for off-grid areas and exploring carbon-neutral construction materials.

Feature 4: Integration of AI and Emerging Technologies.

The HCEGS model incorporates emerging technologies like AI, robotics, and data analytics into engineering education. Students learn how these technologies intersect with societal needs, enabling them to design ethical and impactful solutions.

Summary

Stanford University's HCEGS model is an interdisciplinary approach that empowers students to tackle real-world challenges with innovative, collaborative solutions. By combining design thinking, systems thinking, and experiential learning, Stanford equips students with the skills necessary to lead transformative efforts across industries. The integration of emerging technologies and a focus on societal impact make the HCEGS model a benchmark for interdisciplinary engineering education. Stanford's commitment to fostering global solutions through collaboration and innovation ensures its graduates are equipped to address the pressing issues of the 21st century, from climate change to healthcare equity. This model stands as an inspiration for engineering education worldwide.

Princeton University's "Engineering + Humanities" model

The Keller Center for Innovation in Engineering Education, affiliated with the School of Engineering and Applied Science, was established in 2005 as the physical platform for implementing interdisciplinary engineering education at Princeton University. As the hub for interdisciplinary engineering education at Princeton, the Keller Center connects students from engineering, the humanities, arts, social sciences, and natural sciences, and also links them to the broader campus community and other networks. The Keller Center bridges the gap between engineering and the humanities, offering educational opportunities that help learners shape valuable career paths.

The Keller Center's motto is "Create. Educate. Serve," and it offers courses and programs across four key dimensions: (1) Entrepreneurship; (2) Design and Design Thinking; (3) Innovative Education; (4) Social Impact, thereby implementing interdisciplinary engineering education (Figure 6).

Introduction

The Keller Center for Innovation in Engineering Education offers two main series of courses: (1) Entrepreneurship, Innovation, and Design Courses: This

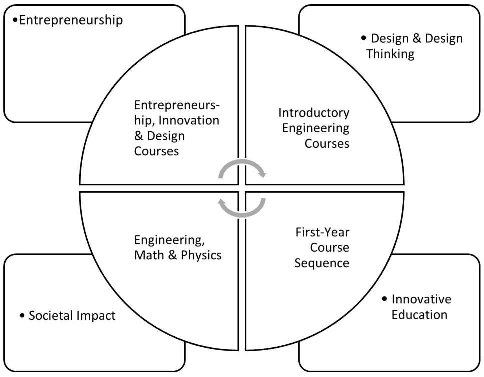

Figure 6. The Keller Center's "Engineering + Humanities" model.

series aims to cultivate students' critical thinking skills, while positioning innovation and entrepreneurship as activities for economic growth, social transformation, and potential future employment opportunities. (2) Introduction to Engineering Courses: These introductory courses are designed for first-year students, focusing on the challenges society faces within the context of modern engineering. They also cover foundational knowledge in mathematics and physics, including two course sequences: the first-year course sequence and the Engineering, Mathematics, and Physics (EMP) sequence.

The Keller Center also promotes sustainability entrepreneurship education through five key initiatives: (1) e-Lab Incubator; (2) Innovation Forum; (3) Entrepreneurship Immersion Projects, which offer students internships at emerging startups in New York, Shanghai, and Tel Aviv, providing valuable real-world experience; (4) Student Project Funding, focusing on science, technology, engineering, and mathematics (STEM) research activities, particularly encouraging projects related to entrepreneurship and design thinking; (5) Tiger Challenge.

Features

Feature 1: The "Four Dimensions" framework.

Through the development of unique courses and projects focused on four key areas—entrepreneurship, design and design thinking, innovative education, and social impact—the Keller Center has created a targeted educational approach that enables students to gain a systematic and coherent understanding and practice of engineering.

Feature 2: The "Two Sequences" curriculum system.

The two course sequences developed by the Keller Center are a critical component of Princeton University's approach to 21st-century engineering education. Traditional first-year courses typically provide learners with basic knowledge for future work. However, Princeton University believes that the first year is a crucial period for students considering engineering. The first-year courses in EMP not only lay the foundation for their future studies but also help students make decisions about their professional focus in the following three years.

Feature 3: The "Engineering + Humanities" Interdisciplinary Engineering Education Platform.

Technology is a vital part of solving societal challenges, and engineering transforms scientific discoveries into solutions. However, to address today's immense societal challenges, interdisciplinary thinking and an entrepreneurial mindset are essential. As Princeton University's interdisciplinary engineering education platform, the Keller Center integrates disciplines such as the humanities, entrepreneurship, arts, and public policy with engineering research, enabling all students to realize their aspirations to solve societal problems. The center aims to nurture students into leaders who will drive society with technology, innovative thinking, and entrepreneurial spirit.

Summary

The diversity of expertise is the key to generating innovative ideas. Therefore, Princeton University believes that innovation lies in interdisciplinarity, and views interdisciplinary research and education as the norm. Cross-departmental and cross-disciplinary teaching and research are prevalent at Princeton, where scientists and humanists, engineers and social scientists collaborate in various ways to conduct extensive interdisciplinary research and teaching. Currently, Princeton University has 14 interdisciplinary research centers. As the primary school responsible for engineering education, the School of Engineering and Applied Science combines the advantages of world-class research institutions with the excellence of the liberal arts, making Princeton's distinctive "Engineering + Humanities" interdisciplinary engineering education unique in the world.

MIT's NEET

Entering the 21st century, MIT has also been rethinking undergraduate engineering education, specifically "what students learn and how they learn." In September 2016, it officially launched the NEET program.

NEET Introduction

The NEET program is a student-centered, project-based, and interdisciplinary collaborative certificate program designed for all second-year students, with a focus on integrated, project-based learning. The implementation of the NEET program is based on four principles: (1) New Machines and New Systems: The

NEET program argues that most engineering education today revolves around "isolated disciplines," with curricula that are prescriptive and repetitive, ultimately producing fixed "types" of engineers. The new engineering education focuses on the new machines and systems that will be established in the 21st century, offering students holistic training in an entirely different way. (2) Creators and Discoverers: Students should use foundational knowledge as a basis for research and practice, acting as creators and discoverers. NEET provides students with the foundation to manage new technologies, theories, models, and methods. (3) Best Learning Methods: NEET believes that education should focus on the best ways for students to learn, finding the ideal balance between classroom learning and project-based work. The NEET program is built around this idea, encouraging students to become active collaborators in their learning process. (4) New Ways of Thinking: MIT believes that teaching students how to learn independently is foundational. Therefore, they propose twelve new ways of thinking: (1) Learning how to learn; (2) Creativity; (3) Discovery; (4) Interpersonal skills; (5) Personal skills and attitudes; (6) Creative thinking; (7) Systems thinking; (8) Critical and metacognitive thinking; (9) Analytical thinking; (10) Computational thinking; (11) Experimentation; (12) Humanization.

The core component of the NEET program is its "project-centered curriculum structure" (Figure 7). As a three-year project-based certificate program, students begin the NEET program in their second year and continue until graduation. NEET has introduced five thematic courses, referred to as "Threads", which are: (1) Advanced Materials Machines; (2) Automated Machines; (3) Digital Cities; (4) Life Machines; (5) Renewable Energy Machines. Students can choose one of these five "Threads" to participate in interdisciplinary projects. Regardless of the chosen theme, learners will gain a wide range of transferable skills and interpersonal skills through various hands-on projects, research, courses, seminars, activities, and social and career development opportunities. Upon completion of the program by the fourth year, students who successfully complete the courses will receive a project certificate.

NEET's Features

Feature 1: Project-based interdisciplinary engineering education.

The NEET program argues that traditional, class-centered course designs typically focus on a series of well-defined courses that are often closed-ended. In contrast, the NEET program is an open-ended, project-based education. NEET believes that the project-centered learning approach differs from the PBL method advocated by Aalborg University in Denmark.

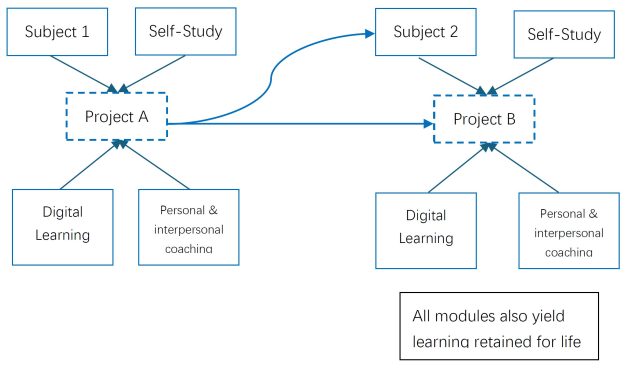

Figure 7. The New Engineering Education Transformation project-centric Curricular construct.

PBL is a teaching method where students mainly acquire knowledge and skills in the classroom.[17] In NEET's project-centered "scaffolding" teaching model, the focus of the course shifts to the projects themselves.

Feature 2: Interdisciplinary engineering education based on emerging technologies.

NEET believes that new machines and systems are what future engineers will need to build in their careers. These future engineers must be capable of working on complex, highly networked machines and systems that are part of larger systems. These machines and systems, built on emerging technologies, will have greater autonomy and support sustainable environments. Preparing young people to design these "new machines" requires a fundamentally different approach to comprehensive, interdisciplinary training.

Feature 3: Platform-based interdisciplinary engineering education.

Under the leadership of Edward Crawley (a founder of the conceiving—designing—implementing—operating [CDIO] engineering education model, a member of the US National Academy of Engineering, and a foreign member of the Chinese Academy of Engineering), the NEET program at MIT is managed by a dedicated project team. This project platform ensures the smooth implementation of the NEET program, enabling interdisciplinary, interdepartmental, and cross-research field collaboration across MIT's engineering school.

Summary

MIT believes that higher education is currently undergoing a period of transformation, with digital tools and experiential learning accelerating innovations in engineering education. The NEET program boldly reimagines MIT's engineering education to meet current societal needs and future development trends. The NEET project is built around "new machines and new systems," and actively fosters new ways of thinking and cognitive methods in students, such as critical thinking, creative thinking, and engineering ethics. In MIT's 2018 Global Benchmarking Study on Undergraduate Education, best practices, benchmarks, and evidence from global stakeholders and institutions were documented. Based on these findings, the NEET program is preparing to train the engineers of tomorrow.[18]

University of Toronto's Institute for Interdisciplinary Engineering Education and Practice (ISTEP)

The University of Toronto has long been a leader in engineering education in Canada. To further promote innovation in engineering education, the Myhal Centre for Engineering Innovation & Entrepreneurship was established in 2018. The center aims to foster extensive collaboration among researchers, students, industry partners, and alumni. At the same time, the Myhal Centre building was officially opened. The space design of the Myhal Centre fully considers interdisciplinary collaboration, experiential learning, engineering leadership, and innovation entrepreneurship courses. It includes flexible active learning spaces, prototype facilities supporting courses and extracurricular design projects, as well as dedicated spaces for student clubs and entrepreneurial teams. In the same year, the Faculty of Engineering officially established the ISTEP. ISTEP brings together the engineering faculty's existing academic plans, course offerings, scholarship programs, and faculty, creating a vibrant engineering education ecosystem through both academic research and teaching practice.

ISTEP introduction

As Canada's first interdisciplinary engineering education program, ISTEP offers targeted courses and training across eight dimensions for students: (1) Engineering Leadership: the Troost Engineering Leadership Education Institute provides transformative courses and extracurricular learning opportunities, teaching learners how to think analytically and systematically to maximize their impact as innovators and leaders in their future careers. (2) Global Perspective: Based on interdisciplinary projects from the Global Engineering Centers, ISTEP collaborates with on-campus and external partners to integrate global environmental considerations into engineering curricula and student experiences. (3) Communication: The Engineering Communication course aims to help undergraduate engineering students develop professional-level communication skills. (4) Ethics and Social Impact: ISTEP actively promotes courses in social technology theory and engineering ethics, providing students with opportunities to understand the impact of engineering on society and the environment, and the role of engineering ethics in fair and just decision-making. (5) Engineering Business: The Faculty of Engineering offers a set of courses co-designed with the School of Management, providing learners with an opportunity to explore the engineering field from a business perspective. (6) Entrepreneurship: Engineering business and entrepreneurship are closely integrated. ISTEP provides a rich entrepreneurial ecosystem, fostering a vibrant entrepreneurial culture across the faculty and university. (7) Engineering Education: The "Collaborative Specialization in Engineering Education" is an interdisciplinary program specifically designed for students from the Faculty of Engineering and the School of Education who are interested in engineering education and research. (8) Career Development: ISTEP supports the career development of engineering graduates through various career planning initiatives.

ISTEP believes that academic research drives teaching practice, and teaching practice, in turn, fosters academic development. Through academic research, ISTEP aims to reconstruct the engineering field of the 21st century and the identity of the modern engineer. The core academic research of ISTEP focuses on three interconnected major areas, forming three key themes of synergy: (1) Engineering Education. ISTEP is evaluating the benefits of teaching innovation strategies and the use of spaces that allow students to engage in richer and deeper learning experiences. (2)Professional Competency. ISTEP is exploring how engineering students can develop into leaders, work effectively in teams, and enhance their professional and communication skills. (3) Engineering Practice. ISTEP is examining the methods and tools that modern engineers use to address workplace challenges. Additionally, it is developing a set of integrated technical and professional skills to promote lifelong learning for future engineers (Figure 8).

ISTEP's features

Feature 1: The physical center and building.

As the physical platform for interdisciplinary engineering education, the establishment of the Engineering Innovation and Entrepreneurship Center marks the beginning of a new era for engineering education at the University of Toronto. It also signifies the transformation of the university's engineering education and research. The Engineering Innovation and Entrepreneurship Center building is home to leading multidisciplinary research centers and project teams. Its interactive classroom technology, open-concept frontier laboratories, and collaborative spaces for students, faculty, and alumni are becoming ideal spaces for cultivating today's engineering students and future engineering leaders at the University of Toronto.

Feature 2: The interdisciplinary innovation ecosystem.
An interdisciplinary engineering education innovation ecosystem based on three major themes and around eight dimensions. The University of Toronto's interdisciplinary collaborative research is based on three major themes, creating a synergistic effect that promotes interdisciplinary engineering education. At the same time, ISTEP integrates and expands the curricula of various engineering disciplines and offers interdisciplinary courses and training around eight dimensions, creating a dynamic and innovative interdisciplinary engineering education ecosystem.

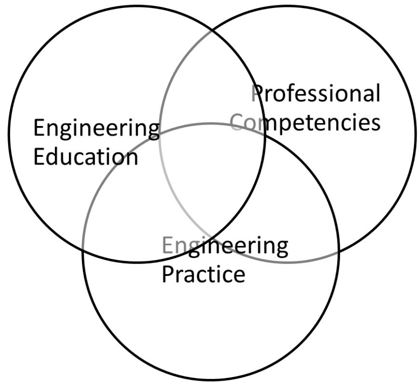

Figure 8. Interdisciplinary Engineering Education and Practice (ISTEP)'s three key themes of synergy.

Summary
The University of Toronto's "entity center + building + curriculum three-in-one" model of interdisciplinary engineering education provides a solid foundation for cultivating the interdisciplinary skills necessary for future engineers. As Greg Evans, Director of the ISTEP, explains, whether within the university or with external partners, we collaborate widely to explore the nature of interdisciplinary competencies in the engineering field, understand modern engineering practices, and better equip engineering students to adapt quickly to the changing demands of the workforce.

McMaster University's "Pivot"
With the arrival of the second decade of the 21st century, McMaster University's Faculty of Engineering recognized the need to change the current approach to engineering education. The Faculty believed that a large-scale transformation was essential to break through traditional methods. In 2019, McMaster restructured its undergraduate curriculum, redesigning classrooms and emphasizing experiential learning—all aimed at preparing future engineers to face the rapidly changing challenges of the world. This $15 million engineering education transformation initiative was named the "Pivot" project.

Introduction
The "Pivot" project integrates teaching, research, and extracurricular experiences through three interconnected pillars: curriculum reform, restructured classrooms, and enhanced experiential learning.

Pillar 1: Curriculum reform
The "Pivot" project redesigned a course called "Engineering 1", which combines four separate courses—Engineering Design and Drafting, Engineering Calculations, Professional Engineering Practice, and Materials Structure and Performance—into a unified "Engineer's Course". The project also adjusted the first-year general education curriculum, reducing the nine courses in the first year to five. The redesigned curriculum moves away from isolated thinking and creates a seamless, project-based learning experience. It provides students with more self-directed and project-based learning opportunities, forming a central thread that runs throughout the entire program.

Pillar 2: Restructuring the classroom
Restructuring education means changing where and how we deliver learning. By creating an innovative, studio-style, entrepreneurship-inspired space to redesign classrooms, students are encouraged to become agile thinkers. A large startup-like space will replace the traditional engineering fundamentals classroom. This space, known as the "Design Center," will be connected to the Engineering Experience Learning Incubator, serving as a focal point for collaboration with industry partners.

Pillar 3: Enhanced experiential learning
The project expands experiential learning by offering students more extracurricular opportunities. Examples include: (1) Enhanced experiential education: Establishing living-learning communities and participating in the Grand Challenges Scholars Program. (2) Increased support for clubs and teams. (3) Boosting undergraduate research experience. (4) Increasing participation in co-op programs, among other initiatives.

The "Pivot" project will launch its first experimental phase of the integrated capstone course in September 2020. The design of the integrated capstone course is divided into three levels, from bottom to top: (1) Level one: Provides foundational courses + challenge-based experiences. (2) Level two: Identifies relevant projects based on emerging industry trends. (3) Level three: Cultivates students' core technical skills + enduring competitiveness (Figure 9).

The goal of the integrated capstone course is to pilot

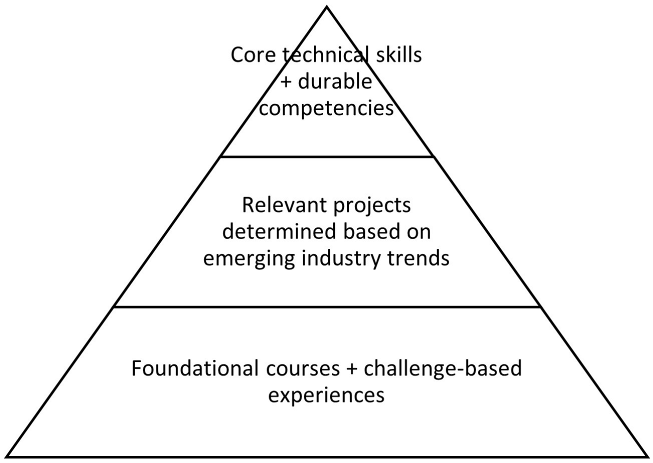

Figure 9. Pivot's Schematic diagram of integrated capstone.

with 100 students, and then expand this interdisciplinary pilot project to 11 engineering programs accredited by engineering education standards, involving approximately 1000 students.

Through the training provided by the "Pivot" project, students will acquire five core competencies: (1) Discover + Create; (2) Integrate + Solve; (3) Business + Innovate; (4) Global + Diversity; (5) Citizen + Community.

Features

Feature 1: Curriculum reform.

McMaster University's innovative interdisciplinary engineering education has made significant adjustments to its curriculum, focusing more on the students themselves rather than on specific projects they engage in. Design thinking, innovative thinking, and entrepreneurship are integrated into all courses.

Feature 2: Reconstructing the classroom.

The traditional "chalk and talk" teaching method is replaced by experiential learning activities such as self-guided learning and group work. Group learning activities strengthen students' problem-solving skills and provide comprehensive experience in applying knowledge to real-world issues, encouraging both depth and breadth of knowledge and experience.

Feature 3: Experiential learning.

McMaster University's innovative interdisciplinary engineering education combines the development of students' abilities to solve complex problems, critical thinking, adaptability, and creativity. It integrates learning experiences both inside and outside the classroom with industry-relevant contexts. With innovative teaching methods and comprehensive experiential learning, students will learn in the context of grand challenges and be encouraged to approach complex problems from a multidisciplinary perspective.

Summary

McMaster University's innovative interdisciplinary engineering education is project-based and team-oriented, encouraging students to engage in research collaborations, participate in clubs, and enhance their sense of community. All of these activities prepare students to become socially aware citizens, ready to face global challenges in the fast-paced, dynamic real world. According to Dean Ishwar Puri of the Faculty of Engineering, the implementation of the "Pivot" project represents the most significant transformation in student experience at McMaster Engineering in the past 60 years. It will radically change the undergraduate learning experience and position McMaster Engineering as a leader in engineering education reform, setting an example for programs across Canada, the United States, and the world.

University of Waterloo's Co-op education + PBL

The UW is a leader in innovation and interdisciplinary education, particularly in engineering. The institution's engineering programs are designed to equip students with the technical expertise and interdisciplinary knowledge necessary to tackle complex, global challenges. Waterloo's Interdisciplinary Engineering Education model emphasizes experiential learning, collaboration across disciplines, and the integration of industry experience into academic studies. This model prepares students to not only be proficient engineers but also to innovate, collaborate, and solve real-world problems (Figure 10).

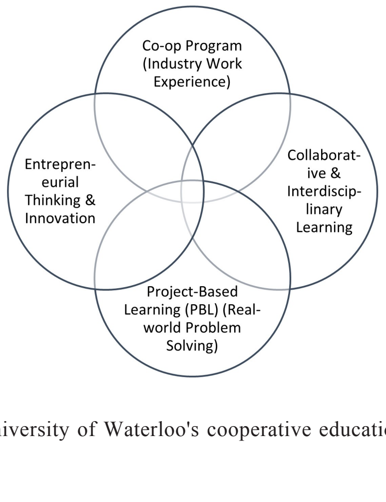

Figure 10. University of Waterloo's cooperative education + problem-based learning.

Introduction

Waterloo's engineering education approach integrates several key elements: cooperative education (co-op), PBL, entrepreneurial thinking, and flexibility in curriculum design. By fostering a multidisciplinary approach and encouraging students to explore various fields of engineering and beyond, the university ensures that graduates are well-equipped to meet the evolving demands of the engineering profession.

Features

Feature 1: Cooperative Education program.

The UW's co-op program is a cornerstone of its engineering education model. This feature allows students to gain real-world work experience by alternating between academic terms and paid work placements with industry partners. The program facilitates exposure to a wide range of sectors, such as technology, healthcare, manufacturing, and environmental industries. Through co-op placements, students develop practical skills, enhance their problem-solving abilities, and build professional networks, all of which are invaluable when entering the workforce.

Feature 2: Collaborative and interdisciplinary learning.

Waterloo emphasizes collaboration both within the engineering faculty and across different disciplines. Students often work in teams composed of peers from various engineering programs as well as other faculties such as business, computer science, and environmental studies. This interdisciplinary collaboration promotes a broader understanding of complex problems, encouraging students to develop holistic solutions. Students also gain essential teamwork and communication skills, preparing them for leadership roles in diverse professional environments.

Feature 3: PBL.

Project-based learning plays a central role in Waterloo's engineering curriculum. Students engage in hands-on projects throughout their academic career, often working on real-world problems in collaboration with industry partners, faculty, and researchers. These projects are typically multidisciplinary, encouraging students to apply their engineering knowledge in innovative ways while learning to address the complexities of real-world engineering challenges. By working on tangible problems, students develop critical thinking, problem-solving, and project management skills.

Feature 4: Entrepreneurial thinking and innovation.

Waterloo fosters a strong entrepreneurial culture within its engineering programs. Students are encouraged to develop innovative solutions to engineering problems and explore ways to commercialize their ideas. The university's close ties with innovation hubs, business incubators, and start-up accelerators provide students with resources and mentorship to turn their ideas into viable businesses or technologies. Entrepreneurship is integrated into the curriculum, with courses and projects designed to encourage creative thinking, product development, and market application.

Feature 5: Global exposure and research opportunities.

The UW offers students opportunities to gain international experience through exchange programs and global internships. Additionally, the university is known for its strong research initiatives, many of which are interdisciplinary in nature. Students are encouraged to participate in research projects that address global challenges, such as sustainability, healthcare technology, and energy efficiency. These experiences help students gain a global perspective on engineering problems and solutions, further enhancing their skills in tackling complex, worldwide issues.

Summary

The UW's interdisciplinary engineering education model is designed to produce engineers who are not only technically proficient but also innovative, collaborative, and adaptable to the dynamic needs of the modern world. By integrating key features such as co-op, collaborative learning, project-based problem-solving, entrepreneurial thinking, and global exposure, Waterloo ensures that its students are well-prepared to address complex, interdisciplinary challenges.

This model allows students to develop both the hard technical skills and the soft skills required for success in the engineering profession. The integration of hands-on experiences, real-world projects, and industry engagement throughout the curriculum allows students to gain practical knowledge and build strong professional networks. Graduates are equipped to thrive in diverse and evolving fields, whether in industry, research, or entrepreneurship, and are positioned to become leaders who drive innovation and sustainable solutions to global engineering challenges.

CONCLUSIONS AND POLICY RECOMMENDATIONS

Conclusions

The transformation of engineering education through interdisciplinary collaboration has become an inevitable trend

Whether they are the IEP, the ICI framework, or problem-based large-scale projects (Megaprojects) in interdisciplinary education in European universities; or the HCEGS model, the interdisciplinary engineering education model combining engineering and the humanities, the NEET initiative in U. S. universities; even the ISTEP, the Pivot project, and Co-op + PBL program in Canada universities, examining the timelines of these various institutional projects reveals that the transformation of higher engineering education has already become a future development trend, and interdisciplinary engineering education has become a necessity.

Disciplines are indispensable as the foundation of interdisciplinary collaboration

Interdisciplinary collaboration does not occur in a social vacuum but within an institutional environment formed by the relationships between researchers, disciplines, theories, and methods. As Harvey J. Graff, author of Disciplinary Knowledge: Interdisciplinarity in the 20th Century, pointed out, the interdisciplinary roots of disciplines are evident in the formation of fields that span natural sciences, social sciences, and humanities. As the foundation of interdisciplinary collaboration, disciplines are indispensable. Any concept of an interdisciplinary system relies on the existence of disciplines. An interdisciplinary field is likely more akin to an academic ecological niche rather than a mere overlay of different knowledge domains.[19]

The models for cultivating engineering talent through interdisciplinary collaboration are diverse

The model for cultivating engineering talent through interdisciplinary collaboration is diverse. There is no single path, model, or standard for interdisciplinary engineering education, and the cultivation process varies based on the institutional discipline structures. From the engineering education reforms implemented at various case institutions, whether it is a curriculum structure common to an entire department, large projects based on PBL, the "Engineering + Humanities" model, new thinking in engineering education, physical centers + buildings + courses, or the combination of curriculum + classroom + experiential learning, the models for cultivating engineering talent through interdisciplinary collaboration are varied. Case institutions combine their development strategies, fully leverage the advantages of traditional discipline structures, and develop and implement interdisciplinary engineering education programs that reflect their unique characteristics.

University interdisciplinary research and interdisciplinary education complement each other

University interdisciplinary education provides valuable human resources and intellectual support to address global societal challenges. The problems arising from global societal challenges also serve as project resources for interdisciplinary research in universities, and teaching and research in interdisciplinary collaboration complement each other. At the same time, interdisciplinary collaborative projects are closely tied to societal needs, with professional directions following cutting-edge technological trends. Interdisciplinary engineering education is centered around real-world projects, closely integrating certificate programs with degree programs, and embedding foundational and professional knowledge within real-world project-based learning throughout the four years of university education. This not only deepens and integrates students' understanding of disciplines but also improves and enhances universities' development plans, discipline construction, and curriculum design through interdisciplinary collaboration.

Policy recommendations

At the same time, the implementation of interdisciplinary engineering education also faces several challenges.

Challenge 1: For universities, on the one hand, there is a need to establish a coherent, grand, and evidence-based interdisciplinary education model. On the other hand, they must ensure that each department retains ownership of its discipline while being able to define its priorities according to its development strategy. Maintaining an effective balance between these two aspects is a major challenge.

Challenge 2: For departments, there are inherent challenges in interdisciplinary projects. For example, there may be conflicts in course scheduling, conflicts in the use of laboratory and project space, and inconsistencies between the requirements and accreditation of interdisciplinary courses and degree programs. Coordinating the relationships between interdisciplinary departments is a significant challenge.

Challenge 3: For faculties, the implementation of interdisciplinary engineering education has led to divergent roles for academic staff. The shift from a "course-based teaching" model to a "project-based teaching" paradigm has, on one hand, reduced the already limited teaching load for research-focused faculty, while on the other hand, has increased the workload for teaching-focused faculty. Adjusting to and reshaping the diverse roles of academic staff is a major challenge.

Challenge 4: For students, at the undergraduate level, most students plan their four-year study programs from the perspective of their own disciplines. They come to university to specialize in their chosen degree, and anything beyond the degree program may reduce their motivation to learn. Their primary goal is to master the methods of solving problems within their own field. Encouraging students to actively participate in interdisciplinary projects is a significant challenge.

So, how can the above challenges be addressed? This paper offers the following five policy recommendations for universities implementing interdisciplinary engineering education, based on the analysis of interdisciplinary engineering education reforms in nine case institutions.

Implementing interdisciplinary engineering education requires a strong leadership core

A strong leadership core is crucial for supporting interdisciplinary collaboration. For example, the successful implementation of the Integrated Engineering Program at UCL can largely be attributed to its core leadership and flexible, practical management approach. The engineering education reforms in the nine case institutions also reflect the importance of leadership, particularly in coordinating organizational structures, participating departments, teaching activities, and related resources. A strong leadership core and a forward-thinking interdisciplinary development strategy provide institutional support for the implementation of interdisciplinary engineering education.

Implementing interdisciplinary engineering education requires a culture of interdisciplinary collaboration

Only by forming a culture of interdisciplinary cooperation and cultivating interdisciplinary thinking can collaborative behavior emerge. Management guru Peter Drucker once said, "Culture eats strategy for breakfast." Fundamentally, any transformation, including changes in curriculum and educational methods, requires a cultural shift based on the values of the institution.[20] This is particularly true when implementing interdisciplinary engineering education based on the university's strengths in specific disciplines.

Implementing interdisciplinary engineering education requires a solid disciplinary structural foundation

Interdisciplinarity is composed of elements from different disciplines, which come together to form different methods, understandings, or contexts. In the process of interdisciplinarity, disciplinary elements interact with each other rather than simply adding up. Interdisciplinary engineering education should be based on the university's existing strong disciplines and supported by a reasonable disciplinary structure. Reforms aimed at promoting interdisciplinarity should build upon these strengths, bridging gaps between disciplines rather than attempting to overturn the existing disciplinary system.[21]

Implementing interdisciplinary engineering education requires real interdisciplinary collaborative projects

Engineering education, in collaboration with external partners, always centers around providing solutions to real challenges in natural partnerships. Projects with real-world scenarios help students apply their knowledge and skills to actual engineering problems, "solving real engineering problems." Interdisciplinary collaborative projects should be aligned with societal major needs, allowing students to identify and analyze problems from real, problem-based large-scale projects and propose solutions.

Implementing interdisciplinary engineering education requires a broadly participatory physical platform

Whether through the establishment of physical institutions or the construction of physical buildings, a project team with dedicated personnel is essential as a necessary element for implementing interdisciplinary engineering education. The training of engineering talent through interdisciplinary collaboration requires the creation, development, and maintenance of connections between faculty, students, and industry. This is the cornerstone of broader participation and sustainability.

DECLARATION

Author contributions

Xu LH developed the concept for the manuscript, reviewed the literature, formulated research questions, collected the data, conducted analyses and interpreted the data. The author read and approved the final manuscript.

Ethics approval

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Conflict of interest

The author has no conflicts of interest to declare.

Data availability statement

Not applicable.

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