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A Transdisciplinary Knowledge Approach Using a Holistic Design Thinking Methodology for Engineering Education

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Introduction

Given the wealth of design practices, it is worth examining that engineering design educators often lack methodologies for students that provide sufficiently broad perspectives and robust approaches to anticipate the dynamic complexity of engineering design challenges of the 21st century. This deficiency is partly rooted in undefined or shifting boundaries around design practices and educational responsibilities between engineering educational curriculum and industry [1]. Many postsecondary engineering education programs do not offer four-year sequential design courses and face challenges in developing pedagogies to assist students in learning and establishing complex and meaningful design relationships [2], [3].

Research suggests that these relationships entail expanding knowledge bases and triggering fundamental paradigm shifts in current design methodologies [3], [4] - [9]. These findings advocate for increased flexibility in thinking and an enhanced ability to comprehend needs in relation to ecology, the environment, and providing agency and transparency in interactions with technology, particularly in an age of complex artificial intelligence (AI) systems. This necessitates a deeper understanding and application of empathy and knowledge of global complexities. It emphasizes flexible thinking to anticipate and access the ethical, economic, political, and health impacts of the proposed designs, technology, and solutions that students will engineer. These implications also encompass the broader health and addiction impacts of technology, as well as its effects on the social and the ecological fabric [10].

The challenges confronting engineering include concurrently stabilizing existing infrastructure while fostering the creation of new infrastructure and addressing global crises exacerbated by technology. Additionally, evaluating technological impacts on quality-of-all-life and non-life issues aims to enhance the diversity of human, organismal, environmental, and more-than-human voices in design methodologies [11] - [13]. Educating the next generation of engineers in design theories and methodologies that transcend common paradigms is essential to their understanding of the impacts of proposed innovative technologies and reducing unforeseen consequences. This will depend on broadening their knowledge base, which can significantly influence their comprehension of design in today's era of expanding system complexities, transcending traditional interdisciplinary boundaries in engineering.

A challenge facing engineering colleges is determining the significance they should assign to broad transdisciplinary knowledge and design within their curriculum. Engineering design educators grapple with integrating substantial knowledge content, transcending industry and user-centered design approaches, and addressing design as a practice in an age of complex systems of interaction. Additionally, they continue to seek ways to incorporate real-world problems and dynamics into the classroom setting. While human-centered design thinking approaches, alongside experiential learning practices found in Kolb's *Experiential Learning*, are beneficial, there is still more that engineering design education can accomplish [14] - [17].

Providing students with deeper knowledge and holistic design methodologies that foster emotional and cognitive development, challenge beliefs, and encourage different perspectives, and leverage their curiosity, creativity, and interpersonal and soft skills in the advancement of economic, social, and environmental justice remains a challenge. Although various teaching approaches to engineering design exist—such as specification-driven, sequential processes, industrial production, user-centered, or human-centered—their focus typically lacks the comprehensive transdisciplinary knowledge necessary to address these challenges. These abilities include understanding nature, flexibility in thinking modes, psychology, development of intellectual curiosity, effective communication, and leveraging knowledge from humanities, social sciences, neuroscience, and ecological sciences. This breadth is crucial in overcoming design thinking limitations and promoting more effective knowledge and synergism in teams.

Many engineering curricula limit student learning of transdisciplinary knowledge and understanding of diversity of needs in design practices, potentially due to an overemphasis on mathematical and analytical-based reasoning and problem-solving centered around fundamental scientific principles and concepts geared towards theoretical research [18], [19]. This limitation is also attributed to the emphasis on computational algorithms, software instruction, end-user focus, and lack of holistic design methodologies and interdisciplinary collaboration. Additional there is a deficiency in the incorporation of design history, theory, and related design courses.

What is missing is a way to make the design education more encompassing of the in-depth knowledge and skills needed to prepare students for a view of engineering design that goes beyond human-centered perspectives. The investigated pedagogical philosophy links the student's ability to see the practice of design, the tools, devices, and systems as impacting all life and the environment. It encourages students to consider humans and the environment as more than just economic commodities. Their capacity to envision these alternative possibilities is fostered by an approach that emphasizes expanding their knowledge beyond traditional engineering discipline and integrating love, compassion, empathy, ethics, and abstract thinking into their understanding. This enables them to pose and evaluate questions of future impacts in the consideration of a diversity of needs. Furthermore, this paper theorizes that understanding the interconnections among nature, empathy, ethics, reason, imagination, design, and technology in being human leads to the development of a holistic engineering approach and holistic design thinking practice. Such an approach should be flexible and mindful enough to adapt to many problems. The pivotal role of flexible thinking modes, particularly emphasizing visual, critical, causal, associative, and abstract thinking skills, further bolsters this methodology in engineering design. Moreover, ethics will play a crucial role in establishing contemporary design methodologies that prioritize transparency and agency between humans, nature, and complex artificial intelligence systems.

In 2023, qualitative results spanning an eight-year period were examined to evaluate the impact of teaching a Holistic Engineering (HE) pedagogy. This pedagogy encompasses a Holistic

Design Thinking (HDT) methodology enriched with extensive transdisciplinary knowledge [17]. The investigation included instruction at both the postsecondary and secondary levels. Specifically, feedback was obtained from undergraduate and graduate students who were enrolled in separate HE postsecondary design courses starting in 2015. The findings highlighted the limitations of postsecondary course content due to time constraints, prompting a focus on developing a yearlong college preparatory secondary HE education program for fourth-year students. Implementing this, observational data and feedback were collected from three cohorts of fourth-year secondary students before and after graduation. This data collection spanned a four-year period between 2019 and 2023 [17]. The aim was to discern which knowledge components and learning practices of their yearlong secondary HE program significantly contributed to their success at the postsecondary level. The findings revealed that students who receive comprehensive instruction and practice across a diverse spectrum of knowledge, including fostering flexible modes of thinking, qualitatively demonstrated enhanced creativity and collaboration within design teams. Additionally, they reported developing a deeper understanding of themselves and cultivating more profound purposes.

Building on this trajectory, this paper explores the implications of the HE pedagogy on engineering design education, examining its role in preparing students for engagement in design practices, and considering what may motivate their deeper understanding of design. It provides historical context underscoring the pivotal role of design in engineering education and advocates for a more holistic approach to design methodologies. The research also investigates whether expanding upfront transdisciplinary knowledge to engineering students supports the adoption of an HDT methodology and whether it is a viable approach in engineering design education. Additionally, it examines the impact of adopting holistic emotional, cognitive, and mentoring learning practices on students. It also assesses their perceptions of various skills and practices such as critical reading, flexibility in modes of thinking, communication, analog practices, empathy, ethics, time management, and team dynamics. Furthermore, it explores how these practices influence academic success in college and students' ability to recall knowledge when needed.

Moreover, it continues the longitudinal study into its fifth year, tracking four cohorts of secondary students who graduated from the HE program. It incorporates qualitative interview data collected into 2024 from thirty-nine of these former secondary students. These students were surveyed about the knowledge content and learning practices in their HE secondary program that contributed to their success at the postsecondary level. Notably, the first graduating cohorts are now in their final year of college. The research contends that students equipped with upfront transdisciplinary knowledge supporting design thinking and an understanding of both the intellectual and emotional concepts of self, love, and compassion are adept at employing both emotional and cognitive empathy skills to uncover diverse needs and collaborating effectively in design practices.

Additionally, this paper examines the pedagogical influences on an integrated transdisciplinary knowledge approach and an HDT methodology. It provides an overview of the relationship between design and engineering, advocating for its more dominant inclusion in engineering curriculums. Furthermore, it argues for the inclusion of more transdisciplinary knowledge and an expansion of design methodologies beyond human-centered approaches in engineering education.

Design Background

Design and engineering are integrally linked, with numerous definitions of “engineering” incorporating the word design [20]. Engineering establishes creative and causal relationships that imbue design with significance. There is a rich history of design within engineering education, acknowledging its vital importance as a strand woven throughout centuries of engineering thinking [21]. Exploring the background of design theory and development in engineering education could help elucidate its importance and leading role in engineering. This connects to the necessity for further research into broadening views on how engineering design education can adapt to benefit students.

Design is not only at the heart of engineering but also serves as a crucial determining factor in the life of every organism on the planet. Perhaps due to confusion about its value in engineering education, as evidenced by its lack of prominence in curricula, there are no fixed laws or agreed upon ubiquitous design methodologies to provide to students [22]. Design occupies a space of ambiguity, which engineering educators often find uncomfortable [23].

Is design academically important, a means to an end, implicitly understood, just a matter of choice? Is it practical, collaborative, focused on user-friendliness, human-centered, holistic, economically feasible, about creating profit, or ethical? Or is it existent only in speculation, something learned and done after graduation, leaving room for it to be executed poorly in engineering? This lack of clear definition, boundaries, educational practices, and agreed-upon properties is not surprising given its history [24]. One might even ask: does it have an overarching theory or practice? Is there recognition of the shift from individual designer to collaborative or team design, especially amidst the increasing development of complex technological systems and impacts on the environment over time? And what implications does this shift have on fundamental engineering education?

Acknowledging that engineering education struggles with this knowledge base is crucial because it relies not only on technical skills but interpersonal and soft skills, and importantly transdisciplinary knowledge across many disciplines that have, for years, resided outside the realm of engineering education. Alongside higher order reasoning, love and empathy, imagination, and the ability to design are basic attributes of what it means to be human. It is a ubiquitous aspect of human nature, remaining an untapped potential in engineering education.

While representations of design can be found in nature, such as the nests of the Bower birds or the complex structures created by wasps and bees, human design is transcendental. A moment spent looking around you as you read this will confirm it is at the center of human existence. Without it, humans would not be the most adaptable, fast, and dangerous creatures on the planet. From spears to gunpowder to nuclear weapons, the designs we create aim to maintain our dominance over nature and each other in a complex interaction for passing on of genes, comfort, pleasure, and moral subjectivity. This status has only become possible through our flexible adaptability and diverse design practices, which partly serve to overcome nature. However, nature itself remains the dominant force in the universe, and even on Earth we see that displayed in global warming responses and diseases caused by viruses.

Since design does not exclusively reside within engineering, the question in educational institutions is whose purgative is it: industry and the business world, the students, the professional engineers, the educators, or the professional 'designers'? What role does engineering education play in ensuring fortitude and practice in this crucial aspect of engineering and of being human.

The history of design is one of evolutionary dynamic knowledge transference and innovative unexpected connections [25]. Design is the unique human ability to change our environment and create objects with non-natural usage and meanings to reorder nature. This reordering of the world is consequential, driven by imperfect human ambitions and choices subject to subjective aesthetic, ethical, and moral scrutiny of their impacts. It is of infinite variability based on culture, discipline, resources, environment, reasoning, imagination, and reflection, but rooted in human niche for rapid adaptability. Human design began with a cognitive ability tied to visual neural pathways and ability to think visually—visual thinking and the hand to abstract and manipulate matter for practical applications [26]. This functionality came through the power of observation, curiosity, imagination, abstraction, and goal-directed deliberation. It also came with understanding form and aesthetics and development of judgment of beauty. While form has been influenced by various disciplines including art, architecture, and cultural practices, today's design function is created by engineering, incorporating applied sciences and social trends to enhance cultural and psychological impacts. Given the inherent importance of design within engineering, it is logical for it to be integrated into engineering education. A brief overview of its historical relationship with engineering can provide context for its prominent inclusion.

When considering design as a human process, its roots can be traced back to human's connection with stone tool making and technology 1.4 million years ago, as well as the earliest human art 30,000 years ago [27], [28]. The history presented here is incomplete and changes with each new archaeological find [29]. Early human tool design was centered on human needs and evolutionarily tied to the development of empathy, tied to extensions of the hand and mind, and based in part on felt responses and bodily thinking. There is compelling evidence of trial and error in design processes before the development of formalized analytical thinking and scientific principles [30]. The design of the headstay and backstay ropes shown in the Egyptian sailing ship frieze from the Tomb of Vines (1,400 BCE) appears to resemble a truss from a 21st-century perspective, but it is unclear how much was based on prior reasoning versus trial and error [31]. Early human artifacts, such as cave paintings and sculptures, also provide insight into early human design practices and the role of form and aesthetics in design. However, the written historical record of evidence of early humanoids' cognitive awareness of design as a formal process is weak, or nonexistent. Even the way we think about design, whether as a linear process, cyclical, or continuous can impact how we embody it in the world of objects, plans, devices, technology, human, or more-than-human concerns [32]. These more-than-human concepts include ecological agency and systems, biocentrism, Anthropocene, non-life entities, and AI and robotic systems.

The English word ‘design’ has its origin in the 1540s, meaning “to plan or outline or a scheme or plan in mind” derived from the French ‘desseign’ which was itself derived for the Latin ‘designare’ [33]. From the renaissance into the eighteenth century, artisans and craftsmen saw the emergence of a new discipline—engineering designers—who went beyond planning and building bridges, roads, and fortifications [21]. They were actively involved in constructing and studying machines, mechanical systems, and manufacturing processes. By the mid-1800s the term ‘design’ had broadened to encompass concepts of original ideas, planning, drawing, and the arts. In Western culture, design education also experienced growth throughout the 1800s, with institutions such as the National College of Art and Design in Norway (1818) and the Rhode Island School of Design in the United States (1877) [34]. Concurrently, the first three colleges offering engineering education opened in the United States between 1817 and 1824 and included design as part of their curriculum [35]. During the period from the 1800s through the 1930s, engineering educational incorporated robust hands-on engineering ‘design’ practices, focused on learning about machinery, mechanical inventions, applied science and industrial methods [21],[36], [37].

In the early 20th century, the initial theories on the cognitive process of design and designing primarily focused on creativity [38], [39]. As interest in and formal teaching of design grew, it remained outside the realm of any single discipline, existing as neither a separate branch of knowledge nor a discipline of its own. By the 1930s, these design processes expanded to encompass engineering and architecture [40]. As an industrial designer, Henry Dreyfuss worked on human factors and ergonomics, publishing two works in 1955 and 1960 that included specific anthropometric charts for industrial designers to use [41]. However, this approach was devoid of consideration of human-centered needs. During this period, and extending through the 1960s, there was ongoing debate around what disciplines (arts, engineering, industry, architecture, etc.) could be deemed to encompass design. Engineering, adopting a textbook-based approach that emphasized scientific analysis and mathematical modeling, saw a decline in hands-on design, build, and test engineering education [42]. This post World War II standard pedagogical model of engineering education resulted in an increase in lectures and a passive role for students in courses. This emphasis on narration led to students who felt alienated from the learning process [43].

Starting in 1954, Bruce Archer conducted research on design, examining the distinctions between artists and engineers. He developed a rigorous and systematic approach to the practice of industrial and engineering design [44] - [47]. His contributions to design methodologies and practices aimed to establish a science of design, considering design as linear and algorithmic process, and emphasizing the cognitive aspects in design thinking. Additionally, he played a pivotal role in establishing design research to investigate methods of design as a discipline. His work extended across various fields, including ergonomics, system analysis, and cybernetics. He positioned design as a third triad of knowledge, alongside the humanities and the sciences, contributing significantly to the development of current design theory and practices.

By the late 1950s, there was a recognition that engineering graduates were facing challenges in executing design projects [21]. In 1959, mechanical engineering professor John Arnold developed seminar engineering courses at Massachusetts Institute of Technology and Stanford

University titled ‘Creative Engineering’ [48]. These engineering courses focused on the philosophy of engineering design, emphasizing the creative potential in design engineers [49], [50]. They present a perspective on how emotion and feeling can influence creativity and consequently the design process. Arnold’s work advocated for the awareness of designers’ emotional and thinking process, along with the reformulation of design processes to better comprehend the broader concepts of human thought and behavior, considering both implied and expressed needs. Differing from Archer, he did not view the design process as merely a series of programable steps in a linear progression. Arnold’s pivotal design methodology encompasses many of the attributes currently associated with design thinking and human-centered design.

In his 1959 lecture at Stanford University in Arnold’s engineering seminar, the mechanical engineering professor Robert McKim discussed human centered design and the role of designers responding to the needs of the whole person, considering both reasoned and felt responses [51]. He emphasized the importance for designers to comprehend the physical, emotional, intellectual, and visual needs of the organism for which they are designing. McKim’s contribution to design thinking, particularly utilizing visual thinking, is captured in his 1973 work *Experiences in Visual Thinking* [52]. His perspective on ‘designerly’ thinking argues that process is not everything in design; there is an element akin to psychology, the mind’s eye, and creativity, intuition, or gestalt involvement. This work serves as a crucial link in developing the visual, creative, ideation, and psychological abilities of engineering designers, contributing to the methodologies of design as a human centered continual learning process.

From a broader historical engineering perspective, design had moved away from being at the center of engineering education, being replaced by more formal, analytical and research engineering-based practices by 1952 [21]. With the onset of the Cold War, engineering education practices in the United States underwent further shifts towards a theoretical research-based approach, emphasizing scientific analysis and mathematical modeling [53], [54]. Starting with Arnold in the late 1950s and continuing into the 1960s, several engineering educators and colleges attempted to reintroduce design back into the engineering curriculum, although this revival did not gain widespread traction [55], [56]. A four-year engineering design education curriculum is still not widely adopted in engineering colleges in the United States and is often limited to an introductory first-year engineering class and a fourth-year capstone project [57].

In 1969, Simon published the work *Science of the Artificial* extending the cognitive and psychological aspect of creative design thinking, central to the work of Arnold, and the systematic design thinking of Archer, to AI [58]. Simon’s work further developed the science of design in cybernetics and AI, positing it as distinct from the natural sciences and as a design theory for engineering. His contributions are pivotal in the development of design theory research, fostering understanding of the human-machine interface and integration, which is central to the ethical issues faced in engineering design today, especially with trends observed by transhumanists philosophies.

These trends in technology design are not merely esoteric; rather, they are central to the evolving landscape of engineering education. They shed light on how engineering colleges currently offer learning opportunities and will continue to do so in the future, whether through online platforms driven by AI or other means. Additionally, they prompt questions about the extent to which hands-on learning and mentorship, crucial for engineering design, will be integrated into educational programs. This thematic exploration delves into the overarching objectives of universities, encompassing education, research, and preparation of graduates for the workforce, a subject that has long been topic of debate and evolution [59].

Building on the shifts that occurred in engineering education through the 1970s, the focus at engineering colleges remained primarily theoretical and predominantly mathematical and analytical during the 1980s. Despite this focus, industry continued to heavily rely on engineering graduates engaged in design, build, and test cycles [60]. Considerable collaboration occurred between industry and engineering departments at colleges to develop computational algorithms for computer simulation tools aimed at reducing cost and developmental design cycles [61]. With an emphasis on theoretical and computational simulation, both engineering colleges and industry began to see benefits in the 1990s in predicting the performance of complex systems to potentially decrease the cost of prototype design and test cycles [62], [63]. This period marked a paradigm shift from reliance on prototyping and testing to an overreliance on computational simulation [64]. In 2014, Povinelli argued as to the correct balancing between prototyping and testing, and simulation, in the mapping to and accurate assessment of reality, as illustrated in Figure 1 [65].

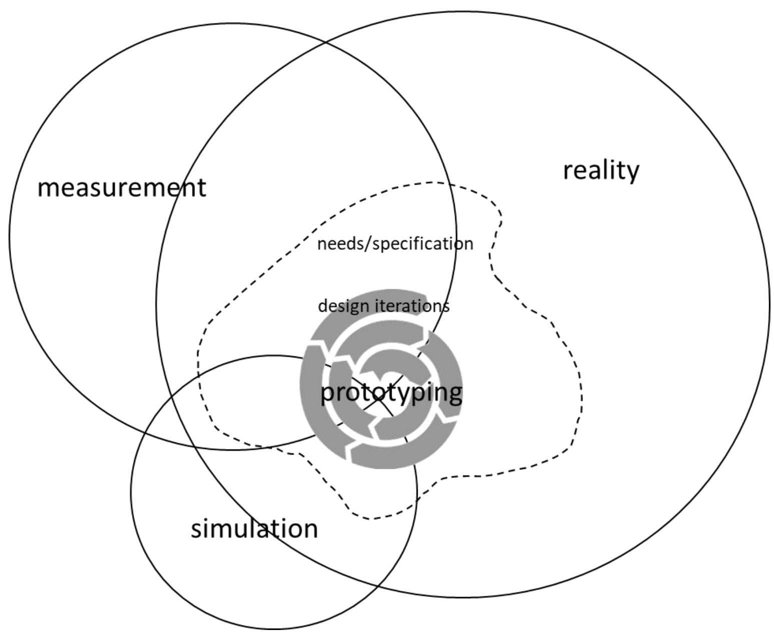

Figure 1. Shifting Balances Between Desing, Build, and Test, and Algorithmic Simulation

With the advent of available computer simulation software for numerous aspects of electrical, mechanical, chemical, civil, and other engineering disciplines' performance calculations and predications through the 2000s, another shift occurred within engineering industry. This shift placed value on the heuristic capabilities of engineering graduates rather than solely theoretical and algorithmic ones and emphasized their abilities to work in collaborative design teams that prioritized design, interpersonal, and soft skills alongside technical expertise [66] - [68].

In the 2000s, David and Tom Kelly at design firm IDEO popularized design thinking and human-centered design, drawing from the work of McKim and Arnold [69]. Jonathan Cagan and Craig Vogel, in 2001, introduced a more systematic approach to consumers product designs using a cycle of social, technological, and economic factors [70]. The diverse currents of work on design theory and processes across different disciplines have led us to a moment where phrase like ‘design thinking’ and ‘human-centered design’ have taken on diverse meanings and practices, evolving into distinct design methodological frameworks in engineering education. However, engineering design methodologies need to evolve further into more transdisciplinary knowledge bases, incorporating philosophies that can establish holistic and more-than-human design practices. These perspectives encompass transparency not just in machine human interface but in algorithms and agency between humans, complex AI systems, and ecology.

While these design theories have begun to acknowledge the transdisciplinary nature of design, they have yet to fully embrace the concept and philosophy that a design that exists outside of any one discipline must encompass them all. Traditionally, there has been a lag time between the needs of industry, or society as a whole, and the balance struck by engineering education, whose role should include fundamental research into these design practice concerns.

However, in the field of engineering education, multiple challenges persist, including the level of design taught and the integration of evolving design theories, methodologies, and beliefs into courses [71]. This is particularly challenging within the mandatory curriculum of each engineering discipline, necessitating tradeoffs in course offerings to accommodate a rigorous sequence of design courses across all years. This paper argues that these courses must also incorporate the teaching of rigorous transdisciplinary knowledge integrated to support holistic design methodologies, placing them on par with the technical, theoretical, and analytical courses taught within engineering curricula.

Curriculum Argument

In general, undergraduate engineering curriculum approaches typically place a strong emphasis on core theoretical subjects such as Calculus, Chemistry, Physics, among others, alongside applied analytical and computational science-based technical courses [72]. These foundational courses play a pivotal role in shaping the technical knowledge and cognitive development of engineering students. However, an increasing disparity has emerged between the necessity to maintain the quantity and rigor of these technical courses and the evolving demands of industries and business propelled by technological advancements that emphasize heuristic abilities and interpersonal and soft (IS) skills [73]. The growing reliance on computer simulation algorithms and AI in society and industry has diminished the demand for a deep understanding of analytical theory formulation and increased the demand for IS skills and a broader range of competencies. Notably this includes multiple thinking skills, along with communication skills, creativity, understanding of design team dynamics, and project experience [74].

Over time, another notable shift has occurred, marked by the rising complexity and precision of technological systems, coupled with the concentration of diverse knowledge specialization [75]. This evolution emphasizes a transition from individual design to a more prominent focus on collaborative or team design. Consequently, there is a growing need for engineering colleges to impart knowledge, instruction, and practical experiences in interpersonal and team skills. This goes beyond the traditional capstone fourth-year design project, where instructors group students into teams with the expectation of navigating complex team dynamics without rigorous knowledge or guidance [76].

Access to design knowledge and practice within the undergraduate curriculum is often confined to a segment of introductory courses and a fourth-year capstone project, occasionally touched upon in fragments within other engineering courses [22]. Regrettably, engineering colleges do not all structure design as a comprehensive technical sequence of knowledge and competencies, and design is usually presented with a limited understanding of historical context, theoretical foundation, best practices, and practical experience [23]. Essential transdisciplinary knowledge crucial for success in practical design and collaborative work within design teams is generally considered extraneous to the traditional engineering curriculum.

These ongoing questions pertain to the fundamental role of engineering colleges in adequately providing knowledge access and preparing students for the workforce [77], [78]. Notably, in the last decade there has been a discernable trend within ABET curriculum requirements, emphasizing IS skills and broader knowledge acquisition driven by societal, economic, and environmental imperatives [79].

The fundamental structure of an undergraduate engineering curriculum should integrate a comprehensive sequence of four-year design courses infused with transdisciplinary knowledge [17]. These courses should serve as the cornerstone and framework, fostering a holistic understanding that transcends disciplinary boundaries and provides access to knowledge that includes theory of design as well as experiential collaborative practices across diverse fields.

Design, at the core of human existence and the heart of engineering, presents a paradox due to its underrepresentation in engineering education [22]. Understanding this anomaly requires exploring the history of human design, the evolution of engineering disciplines, and their teaching methodologies. Despite its fundamental role, design comfortably resides outside of traditional engineering education, necessitating the courage to take ownership of it. Being at the existential core of engineering necessitates educators to embrace it at the center of their curriculum [80]. This ownership comes with significant ethical, economic, social, political, and environmental considerations and risks. However, design is driven by function, a domain where engineering, through the applied sciences, plays a dominant and pivotal role.

The planet we inhabit is rapidly becoming a byproduct and outcome of human design. This evolution prompts an examination of why design, despite its centrality, is not the backbone of engineering education today. This understanding must be coupled with a recognition that our increasing reliance on technology often leads to a loss of interpersonal, empathy, ethics, and communication skills. Thus, engineering design education must also involve understanding the significant impact of technology on human behavior. The fate of our planet hinges on engineering design, underscoring the critical need to comprehend its significance. The absence of a robust design curriculum in traditional engineering education necessitates a paradigm shift. Recognizing that the entirety of the technical engineering curriculum supports real-world design upon graduation, it becomes imperative to impart comprehensive design knowledge within the educational system. Engineering students stand to benefit from learning and practicing design thinking skills in a classroom setting that extends into experiential learning.

The profound influence of design on engineering problem-solving and its role in promoting social equity, economic prosperity, and ecological resilience are pivotal aspects. Engineering has had a significant role in fostering economic growth and creating opportunities for others. Engineers are uniquely positioned to address these existential design challenges and must possess transdisciplinary knowledge and design skills to ensure success. Ultimately, engineering colleges bear the responsibility of imparting design education [3]. Design not only forms the ethical core of engineering but also its framework and dictates its implications and beneficiaries. To safeguard existence, it is imperative to integrate design thinking into the core fabric of engineering education.

At the same time, advocating for increased design education at the postsecondary level necessitates a profound rethinking of design methodologies. In a world undergoing rapid transformation under the Anthropocene, we witness the emergence of AI and overall system complexities that deeply influence design in pivotal shifts across societal connections, governance, in the rapid integration of humans with technology [81], [82]. Pushing for expanded design education in engineering necessitates a paradigmatic overhaul of curriculum. This shift demands not just a methodological change but a comprehensive reorientation, embracing the integration of transdisciplinary knowledge involving human behavior, environmental, and a more-than-human philosophical outlook, as well as a holistic approach to student learning. Such knowledge, inherently non-linear, defies traditional sequential programming, urging a radical shift in engineering and design education principles.

Pedagogical Influences

The paper elaborates on a transdisciplinary knowledge pedagogical approach, rooted in constructionist teaching principles and inductive practices that emphasize student-centered, active, and cooperative learning strategies [83], [84]. This approach has evolved over three decades of experience as a research and design engineer, teaching engineering design at secondary and postsecondary levels, and within industry [16], [17], [85]. Refined based on observations and student feedback indicating a desire for more fundamental knowledge, this holistic emotional and cognitive approach begins with addressing individual challenges and growth. It incorporates social-emotional and active learning through individual and experiential team-based design projects, grounded in analog practices.

The HE pedagogy emphasizes the use of transdisciplinary knowledge integration, leveraging emotions and metacognition to enhance students' agency and abilities. Initially, the focus is on establishing proficiency in flexibility in modes of thinking, the scientific method, critical reading, sketching, communication practices, and reflective and analytical writing. It underscores the interplay between reasoning, imagination, creativity, abstraction, ideas, and design as essential thinking skills in problem-solving, alongside ethical thinking and deliberation in anticipating design consequences.

Drawing upon the foundational theories and experience-based learning models of Piaget, which focus on action, reflection, and construction, as well as Dewey's exploration of the vital connection between education and experience through observation, knowledge, judgement, and purpose [86], [87], this pedagogy extends into Kolb's work on experiential learning. Kolb's cyclical model of learning, which incorporates the integration of abstract cognitive frameworks with experience, provides relevance to design practices through experience, reflection, abstraction, and testing [88], [89]. Their collective work emphasizes experiential learning beyond the classroom and into everyday life settings, serving as a useful framework for this approach. Additionally, the HE pedagogy, utilizes Zull's work on whole-brain transformational learning rooted in a neurobiology, highlighting the importance of emotions, sensory experiences, and spatial relationships in connection to previous knowledge and the learning process [90], [91]. This research, along with studies from Mind, Brain, and Education researchers, establishes a link between emotions, cognition, reflection, and creativity as principal factors that facilitate learning [92].

HE emphasizes the integration of mind, body, and spirit in the learning process, advocating for small learning communities with educators holding engineering degrees and design work experience, known to positively impact on teacher-student engagement, student learning and motivation, and future academic outcomes [93] - [95]. Experienced educators are crucial in employing episodic memories to create personalized examples aiding students in recognizing and integrating details, leading to connections with previous knowledge, deeper understanding, and formation of new and actionable concepts [91], [96], [97]. The HE pedagogy aims to connect the students' emotional, cognitive, and bodily abilities in learning from a cognitive science perspective, introducing various learning mechanisms from an evolutionary and behavioral perspective [98], [99].

The approach explores the impacts of emotions and brain chemical responses (dopamine, serotonin, noradrenaline, etc.) on habit changes, fostering agency in goal-directed deliberative and cognitive learning practices crucial for higher education. It incorporates deliberative practice methods for knowledge acquisition and transference, emphasizing the formation of episodic memories through mindfulness of experiences and reason coupled with imagination, essential for creativity in engineering design, problem solving, and executive awareness [100]. Ambiguity and ill-defined problems are used to provide motivating doubt to spur students' discovery. This approach underscores the importance of integrating psychology, neuroscience, and experiential learning findings into engineering educational practices.

The HE pedagogical approach outlined in this section integrates a transdisciplinary framework with constructivist teaching principles and inductive practices to promote student-centered, active, and cooperative learning strategies. Figure 2 illustrates the transdisciplinary knowledge and holistic pedagogical influences on HDT.

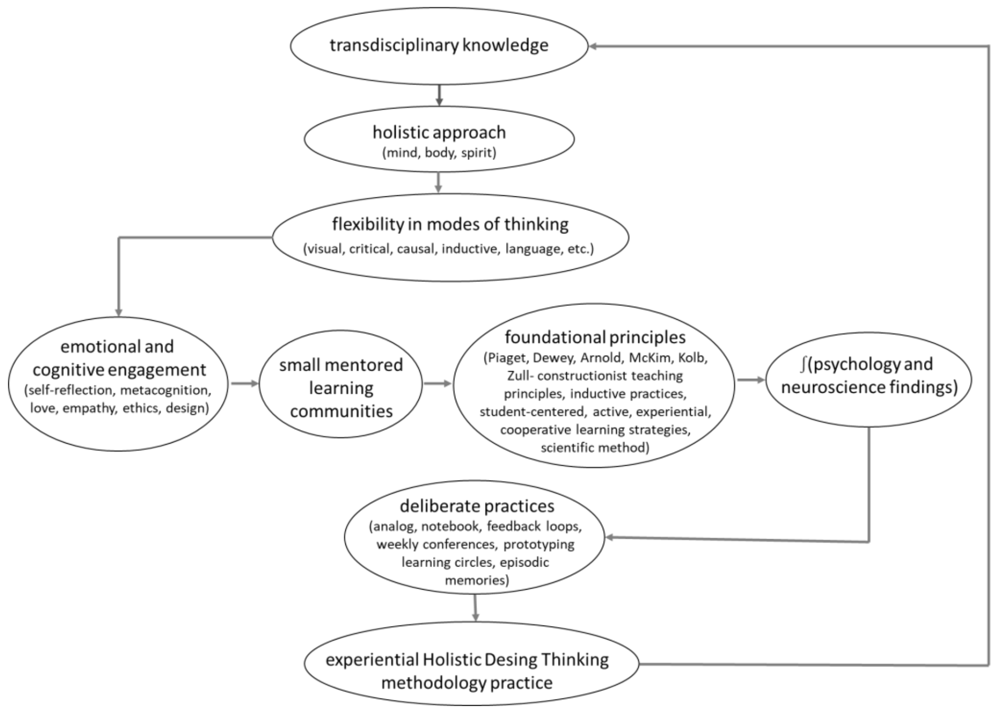

Figure 2. Pedagogical Influences

Rooted in foundational theories of Piaget, Dewey, Kolb, and Zull, the pedagogy emphasizes experiential learning and whole-brain transformational learning, drawing on insights from physiology, neurobiology, cognitive science, and psychology. By integrating emotions, metacognition, and small learning communities led by experienced educators, it aims to holistically address individual and community cognitive, emotional, and bodily aspects of learning. Deliberate practice methods, along with the incorporation of psychology and neuroscience findings, enhance student agency, creativity, and flexibility in thinking, particularly in the context of engineering design education. The HE pedagogy endeavors to establish a more universal design curriculum integrating these pedagogies and practices with the work of Arnold and McKim. This integration involves adopting transdisciplinary knowledge without boundaries, as a fundamental component of a holistic approach to education and the creation of new knowledge and design. Overall, this approach offers a comprehensive framework for fostering broader and deep learning and student engagement in ethical engineering design and practices.

Transdisciplinary Knowledge and Application to Design

The integration of transdisciplinary knowledge lies at the core of the HE pedagogy and approach to engineering design education. Before embarking on advanced collaborative design projects, students are expected to gain proficiency in this knowledge. The pedagogy emphasizes the intrinsic human capacity for design and fosters students' awareness of their daily design engagement from the onset. As they progress from structured individual tactile and social learning community design projects to those with broader, interwoven transdisciplinary knowledge, they acquire a deeper understanding of the aspects of design. Paramount attributes cultivated through this pedagogy include curiosity, imagination, introspection, self-awareness, reflection, analog practices, design acumen, and collaboration skills. This approach addresses the comprehensive knowledge necessary to achieve synergy within the evolving demands of engineering design roles, encompassing concepts relevant to the world, life, and non-life. In today's era marked by system complexity and the Anthropocene, it is imperative that engineering education embrace a diverse knowledge base.

Expanding upon this comprehensive approach, it is important to note that transdisciplinary knowledge extends beyond mathematics, science (physics, chemistry, biology, and environmental science), and engineering. It also encompasses classical branches such as the humanities (philosophy, history, art, cultural studies, etc.) and social sciences (psychology, sociology, anthropology, economics, political science, etc.), as well as neuroscience and ecological sciences. Specific areas covered include modes of thinking (critical, causal, visual, inductive, design, system, categorical, imaginative, abstract, associative, emotional, tactile, bodily, etc.); communication theory; psychology; love; empathy; ethics; character; history of design, science, engineering, and technology; neuroscience; political science; economics; art; and beauty. Moreover, it entails a detailed examination and reflection on the origins, history, and practice of design, design thinking, and design theory.

Design thinking, a pivotal aspect, is defined as encompassing a mode of thought intrinsic to human beings, enabling them to adapt to their surroundings. It engages in various processes, including reasoning, imagination, curiosity, and play, leading to the creation of novel solutions. There is a particular emphasis on individual thinking modes and fluid transitioning between them, particularly highlighting critical, causal, associative, and visual thinking. Visual thinking, closely intertwined with various attributes of engineering design capabilities, plays a pivotal role. It fosters creativity through iterative cycles of observing, sketching, and envisioning, facilitating the development and utilization of the mind's eye, which is crucial in design thinking.

Building upon the broader knowledge base and the foundational aspects of design thinking, the curriculum also explores psychology and neuroscience to comprehend human and machine behavior, memory, emotional regulation, and emotional intelligence and how these factors influence design outcomes. Additionally, students explore the role of love in fostering compassion and empathy, aiming to mitigate indifference across the spectrum of design engagement. They learn about the evolutionary connection between empathy and design in human beings and the importance of preserving this bond, guarding it against the influences of ego and power. Through exercises focused on empathic listening and dialogue skills, students cultivate both emotional and cognitive empathy [101], [102]. These attributes along with ethical thinking serve as the bedrock of designerly thinking in HDT, underscoring the significance of understanding oneself and cultivating purpose through emotional and intrinsic motivation.

Creativity is a vital component in transdisciplinary learning, involving imagination, experiencing, play, observation, curiosity, open-mindedness, information exposure, questioning, and exploration. Activities like imagination, role-playing, reading, reflection, writing, and sketching are instrumental in nurturing creativity [103]. The integration and application of imagination and play not only enhances creativity but also fosters empathy, ethics, design, and problem-solving within the transdisciplinary pedagogy. This holistic approach creates connections among various transdisciplinary knowledge areas, strengthening knowledge scaffolding. Figure 3 illustrates the outwardly spiraling integration of transdisciplinary knowledge in the holistic pedagogical approach.

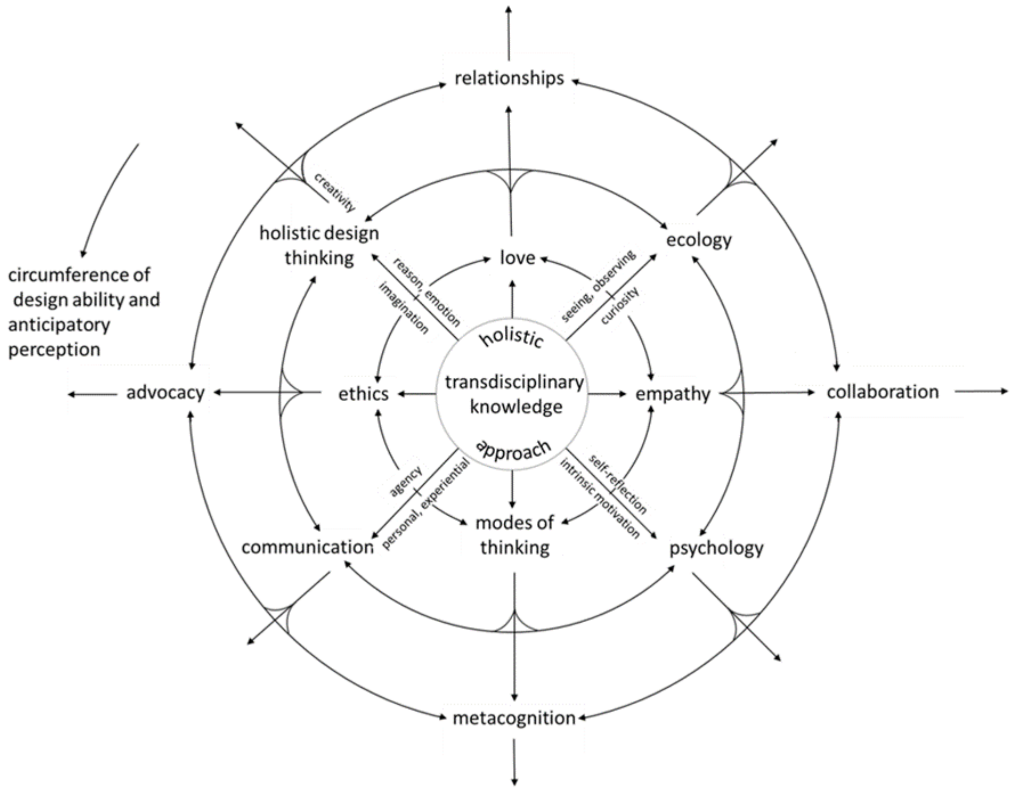

Figure 3. Transdisciplinary Knowledge in the Holistic Pedagogical Approach

The approach aligns with the requirements of engineering design education outlined by ABET and the expectations set by industry for engineering graduates [73]. These include addressing the requirements and expectations that encompass heuristic abilities and ethical considerations, fostering inclusive environments, promoting experiential learning, the capacity to make informed judgments, and acquiring and applying new knowledge through diverse learning strategies. Moreover, the approach not only addresses societal and ecological needs, but also is tailored to handle enrollment pressures and adapt to evolving the societal-technological landscape, which includes the imperative for engineering colleges to meet students' remedial education needs. Research underscores the importance of initially focusing on developing critical reading, effective communication, analytical and reflective writing, flexibility in modes of thinking, and time-management skills, as they lay the groundwork for students' future agency in learning [17]. These skills have been identified as underdeveloped in secondary and postsecondary students.

Addressing this foundational knowledge and any underdeveloped skills in students sets the stage for their more advanced learning strategies. They engage in a dynamic process of practicing and creating knowledge through iterative cycles of observation, curiosity, imagination, and creativity. Furthermore, the approach is aligned with transdisciplinary education and determination theory, promoting a dialogical and student-centered learning environment where students play an active role in shaping their knowledge, beliefs, and behaviors. The introduction of transdisciplinary knowledge before engagement in design teams enriches students' capacity for empathy, ethical decision-making, understanding of diverse needs, management of team dynamics, and application of knowledge [16], [17]. Establishing connections between transdisciplinary knowledge and scientific and engineering concepts is paramount, serving as a bridge between IS and technical skills and closing gaps between transdisciplinary and interdisciplinary domains. As students' progress, they concurrently enhance their individual, social, and team design capabilities, supported by the introduction, practice, and agency of broader knowledge and skills. With the integration of more entwined transdisciplinary content, students actively engage in self-directed and collaborative practices with peers to construct their understanding.

This integration is facilitated through the continuous exchange of observational feedback and constructive learning experiences, aimed at nurturing students' holistic comprehension of the world and the interconnectedness of knowledge. Consequently, students develop the capacity to construct and apply new knowledge both within and beyond the confines of the classroom, equipping them to actively participate in intricate, dynamic, collaborative team environments and experiential hands -on projects. The overarching learning objective is to provide students with many opportunities to practice, model, receive feedback, reflect upon, and enhance all facets of the HDT methodology before undertaking significant team design projects. This includes the practice and application of design thinking tailored to each student's individual abilities. As students refine their knowledge and individual design competencies, they gain a heightened awareness of the complex, interrelated, and ethical challenges confronting the world. Additionally, they recognize the collaborative dynamics necessary to navigate within design teams to address these challenges effectively. Upon achieving mastery, engineering students engage in real-world collaborative design endeavors, collaborating with peers, the environment, professionals from diverse disciplines, end-users, potential users, investors, stakeholders, and companies, fostering a multidimensional approach to problem-solving and innovation.

As the educational approach emphasizes the integration of transdisciplinary knowledge, empirical studies provide valuable insights into its practical outcome. Findings from a study involving an HE pilot course consisting of first-year engineering undergraduate honors students, engaging in an experiential team project focusing on a city's failing infrastructure and exposed to transdisciplinary knowledge encompassing empathy, ethics, communication, design thinking, collaboration, and reflective writing, reveal formative outcomes [16]. The fifty-one students appreciated the collaborative teamwork, hands-on nature of the course, and the opportunity to contribute to real-world challenges with environmental implications. They particularly valued learning a design thinking process, which included empathizing with end users, ethics, ideation, prototyping, testing, and iteration.

The course effectively instilled limited IS skills, such as effective communication and empathy, as well as an understanding of ethical obligations, such as preventing property damage and saving lives. Students reported benefits in data collection, analysis, and effective communication. The research suggests that early exposure to real-world problem-solving is crucial for engineering students, providing a foundation for applying theoretical education.

Overall, the study demonstrated the effectiveness of integrating transdisciplinary knowledge with experiential learning into the first-year college engineering curriculum. This integration equipped students with some valuable skills and enhanced their understanding of the engineer's role in addressing contemporary infrastructure problems. However, it also highlighted some challenges; students expressed the need for adequate time to explore issues in depth, feeling that one course was insufficient and left them feeling overtaxed. Additionally, they felt there was a need for exposure to more knowledge and autonomy in project selection. Observations and surveys indicated that first-year students may not be ready to undertake such a large project and may lack a universal understanding of the design and other skill sets they were learning.

Building on these findings, another study was initiated to investigate the impact of increased time dedicated to transdisciplinary knowledge and a holistic design methodology on fourth-year secondary students, and how this affects their future abilities in college. These students spent their last year of secondary education immersed in the HE pedagogy. This secondary college preparatory program provided multiple cohorts of students with approximately eight times more exposure to the HE pedagogy compared to a typical postsecondary three-credit-hour course. This study aimed to understand the pedagogy's impact and effects as students graduated from the secondary program and progressed through engineering college, faced challenges, and participated in team design projects [17]. The study highlights the significance of dedicated time and exposure to various categories of transdisciplinary knowledge including visual, critical, and design thinking; leadership; HDT; team dynamics and teamwork; reflective and analytical writing; empathy; ethics; communication; ideation; and experiential learning.

Students articulate the enduring relevance of acquired transdisciplinary knowledge and emphasize the program's role in self-discovery and shaping their worldview and broader life purpose within the field of engineering. The findings indicate that students in the program, influenced by transdisciplinary knowledge, develop a more comprehensive understanding of the interconnectedness of the world around them when approaching design problems.

The holistic approach, blending emotional engagement with transdisciplinary knowledge, emerges as a pivotal factor contributing to students' success and sense of purpose. The research underscores that the HE pedagogy, with its focus on transdisciplinary skills embedded in HDT, equips students with the necessary competencies to collaborate effectively and creatively teams and tackle complex design challenges in real-world scenarios.

The goal is to foster a holistic understanding of the world, promoting the integration of knowledge and facilitating the creation and application of new insights both within and beyond the confines of traditional classrooms. The emphasis on transdisciplinary knowledge, ingrained into their cognitive processes and memory, confers lasting benefits as students express their intention to apply this knowledge in academia, professional contexts, and future pursuits.

Holistic Design Thinking Methodology

The design thinking methodology employed in this study builds upon previous research that introduced broad transdisciplinary knowledge and its application to shape the practice within the HDT methodology [17]. The pedagogy of knowledge acquisition and practice in the classroom, including cycles of experience, reflection, abstraction, and evaluation, mirrors the cycles the observed in the design relationship of love, empathy and ethics; curiosity, research, and need finding; ideation and prototyping: and iterative evaluation.

At the core of the HDT pedagogy is the goal to improve students' overall actionable knowledge in design practices and ability in creating and collaborating in effective design teams both inside and outside the classroom. By fostering experiential design practice that engages with human behavioral and environmental needs, students learn to collaborate and co-design in a learning environment where failures are more valuable. They engage in empathizing, innovating, and developing ethical solutions that consider the broader interconnectedness of technology, humanity, and the environment. They also cultivate the ability to weigh ethical decisions and understand the growing conflict between empathy, the environment, ecology, and technology, driven by the rapid pace of technological innovation.

Proficiency in various transdisciplinary knowledge domains is essential before engaging in HDT and participating in design teams. This is because knowledge topics are integrated, with each aspect interconnected, leading to a deeper and broader synergistic understanding and relationship, viewed from a design perspective. The term 'relationship' is utilized in HDT as there is not a universal 'design process' but rather a design relationship between modes of thinking, behaviors, humans, and the world. It is the relationship between these things that generates design. Figure 4 illustrates the HDT methodology.

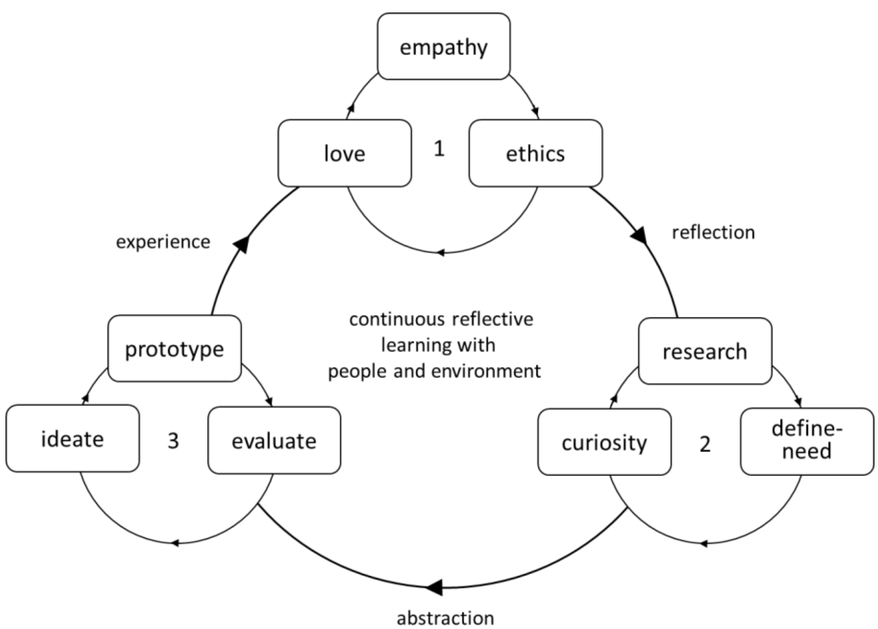

Figure 4. Holistic Design Thinking Relationship

The methodology is distinguished by its cyclical and iterative relationship, comprising three main cycles that progress through understanding, observing, and resolving needs. The term 'resolving needs' is used here to convey that not all perceived human or machine needs must be met, and furthermore, not all needs necessitate the introduction of new technology. The ability to anticipate short- and long-term unintentional and detrimental consequences of possible new technological designs and discontinue their development is foundational to this methodology.

The initial cycle involves love, empathy, and ethics in need finding. This is followed by the second cycle of curiosity, research, and defining needs. The progression continues into the third cycle of ideation, prototyping, and evaluation. Throughout the iterative relationship, designers navigate between analysis and synthesis to arrive at solutions or resolutions that promote love, empathy, and ethics in their engagement with people, concepts, the environment, and things.

This continuous and iterative process involves the first cycle, where experience and observation overlap, flowing into the second cycle of reflection and hypothesis. Finally, it evolves into the third cycle of abstraction and evaluation.

Within each cycle, there are several micro cycles. Figure 5 illustrates the micro cycle of love, which involves understanding, and is expanded out of the first cycle depicted in Figure 4.

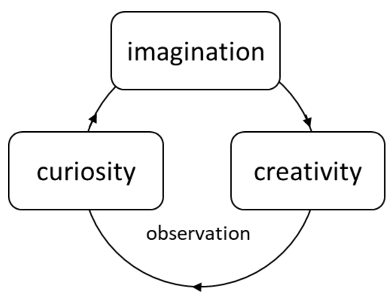

Figure 5. Micro Cycle within Love

This expanded view of love constitutes a cyclical understanding through love, compassion, and the discovery of needs. Central to HDT is the endeavor to identify needs through collaboration among designers, people, nature, and the environment. Love for oneself and others arises from understanding and absence of indifference, while compassion is acknowledged as a natural state of the mind closely tied to empathy.

The roles of imagination and curiosity are fundamental aspects of human cognition. Our perceptions enter the free play of cognition in a cycle that involves reasoning and imagination, further promoting empathy and ethical development [104], [105]. Imagination and curiosity are interconnected. Imagination can be fueled by curiosity, and curiosity can lead us to imagine different perspectives and possibilities of what could be. Figure 6 illustrates the micro view of curiosity from the second cycle of Figure 4. It represents a continuous cycle of curiosity, imagination, and creativity, intertwined with observation.

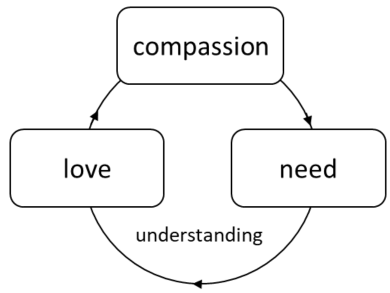

Figure 6. Micro Cycle within Curiosity

Similarly, creativity holds a leading role in design, and curiosity emerges from observation fueled by feelings and emotions of interest. Imagination is an important bridge between curiosity, reason, and creativity. Although represented as cycles, the attributes of feelings, emotions, and cognitions are not confined within a linear cycle but are continually accessed in HDT.

For example, during the ideation phase in the third cycle, after ideas are generated and before prototyping, they are re-valuated for ethical impacts, beginning with considerations of love and empathy. In HDT, the transition from each proceeding cycle to the next allows for flexibility, enabling movement back again as the designer advances in the syntheses process. Figure 7 illustrates this synthesis across cycles with dashed lines.

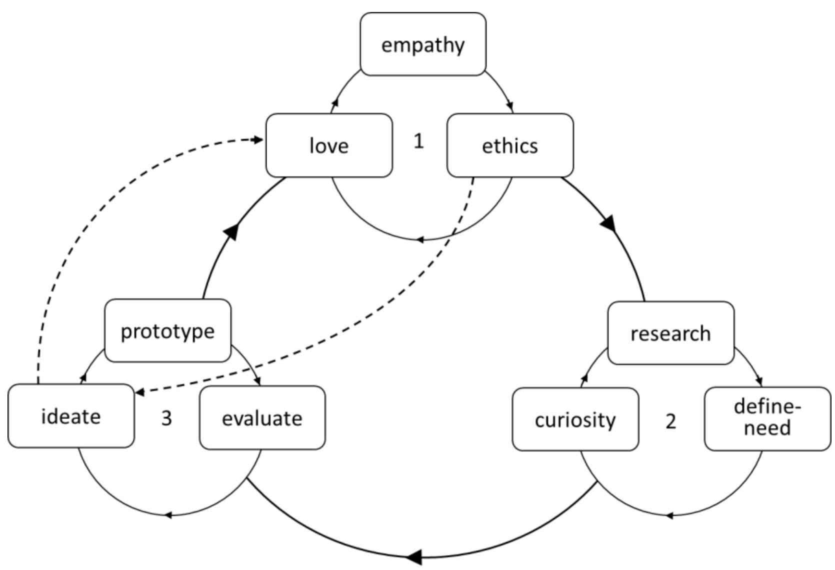

Figure 7. Continual Access to Cycles of Assessment within the Nonlinear Process

In this relationship, the cycles of feelings, emotions, cognitions, and actions can be engaged non-linearly over the sphere of understanding, observation, and resolution. They exist within the context of leadership, collaboration, team dynamics, work, time management, organization, and assessment. Figure 8 illustrates how the attributes of the methodology relationships can be engaged at any point or time and do not need to follow a specific order or process.

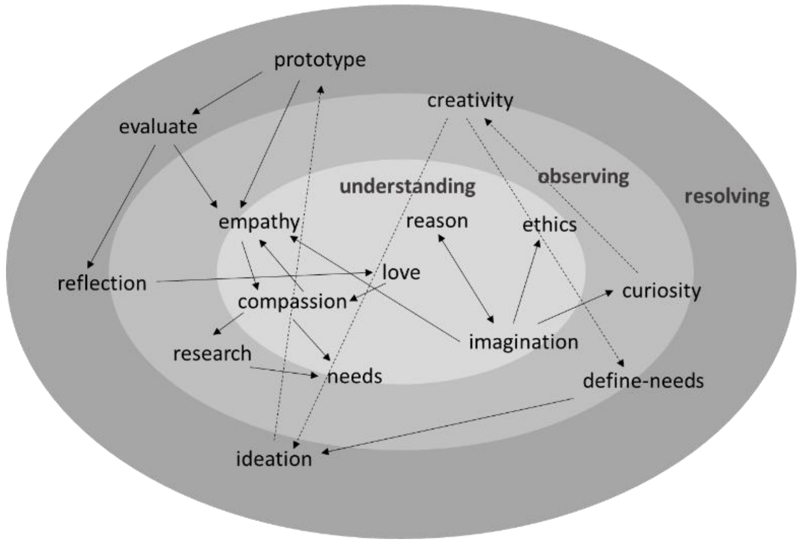

Figure 8. Nonlinear Attributes of the Holistic Design Thinking Relationship

Research Methodology

This research investigated the impact of a holistic transdisciplinary knowledge pedagogy and HDT methodology approach to engineering education, examining outcomes at both the secondary and postsecondary levels. The secondary longitudinal study focused on several key areas: 1) the introduction of integrated transdisciplinary knowledge and its influences on students as they advanced through college, 2) evidence linking student learning at the secondary level to success in engineering college, 3) student responses to love, empathy, and ethics as core knowledge subjects in an engineering design course, 4) the attributes of transdisciplinary knowledge valued as secondary students progressed through college, and 5) factors contributing to life's purpose, success, and college retention rates.

Specific outcomes to be assessed include student development in personal, social, and academic preparedness, as well as design thinking and IS skills. Specific transdisciplinary learning outcomes include self-reflection, intrinsic motivation, time management, communication practices, modes of thinking, love, empathy, ethics, team dynamics/teamwork, and homework practices. The study also examined the effectiveness of analog practice in critical reading; annotation and marginalia; reflective and analytical writing, as well as notebook methods. Furthermore, it investigates the promotion of holistic thinking and the ability to navigate complex real-world problems, alongside demonstration of retention and the utilization of diverse knowledge throughout college. Embedded within this framework are environmental factors such as time in course, teacher experience, small class size, and mentoring.

The specific goals of this research include answering eight questions: 1. Is expanding upfront transdisciplinary knowledge to engineering students in support of the adoption of an HDT methodology a viable approach for engineering design education? 2. What are students' perceptions of valued transdisciplinary knowledge, and were there shifts from the secondary program upon entering college? If so, did these shifts change over the course of their college years, and why? 3. Were students able to retrieve transdisciplinary knowledge flexibly over the college years? 4. What knowledge components and learning practices of the secondary program did students perceive as contributing most significantly to their success at the postsecondary level? 5. Do students develop a deeper understanding of their personal identities and cultivate more profound purposes through the HE pedagogy? 6. What connections to historical and evolving design methodologies can tell us about engineering design pedagogies? 7) What is the impact of holistic emotional and cognitive learning practices in engineering design courses? and 8) How does spending more time in a design course with a smaller class size impact students?

To address these inquiries, twenty-one courses were conducted utilizing this pedagogy and the HDT methodology. Eight courses were taught at the upper secondary level, and one at the lower level. Additionally, twelve courses were taught at the postsecondary undergraduate and graduate levels. The data presented here includes outcomes from four separate school years of a half-day year-long fourth-year high school (secondary) HE program, followed by the students' subsequent years in college, covering the period from 2019 through early 2024. Each year, two separate class cohorts of secondary fourth-year students participated, with an average of eight students per class. Students were selected through an application process across fifteen school districts. The program involved a total of sixty-four students, with fifty-eight successfully completing it. Further details about the experiential nature of this program can be found in a prior publication [17]. Course surveys were administered, and follow-up interviews with secondary students occurred after graduation and during their college years. Additionally, the data discussed here includes examples from two undergraduate postsecondary engineering courses in 2017.

The postsecondary data collection of former secondary students involved conducting telephone interviews in December of each year. These interviews used a standardized set of seven questions, with recorded responses. These questions included: 1) What university or college are you attending, and what is your major? 2) How many credit hours are you taking per semester, and what is your GPA? 3) What was your most difficult and easiest class, and why? 4) What were the most challenging aspects of the transition to college in terms of social, emotional, and academic factors? 5) What high school course content from the HE program do you find valuable in college, and why? 6) What changes do you think could be made to the high school portion of the HE program to increase its benefit to first-year college students, and why? and 7) What are your next plans for college? Additional data were collected through phone calls, text messages, and in-person meetings, often initiated by the students.

This qualitative data was utilized to gather a nuanced understanding of learning outcomes, offering insight into student perceptions and motivation [106]. Postsecondary survey interview responses underwent content, thematic, qualitative coding, narrative, and word frequency analyses to generate tabular data. These responses were analyzed based on key categories of transdisciplinary knowledge and practices stated in the interviews, which were associated with the pedagogical outcomes, focus areas, and research questions. Subsequently, the data were scrutinized by examining the student-provided responses, identifying trends, patterns, and retention rates. Comparative, contextual, and theory-building approaches were employed to facilitate perception, interpretation, and explore relationships within the data, aiming to either support or challenge pedagogical strategies.

This information is then used to address broader questions, such as whether expanding upfront transdisciplinary knowledge to engineering students, as illustrated in Figure 3, in support of the adoption of an HDT methodology, is a viable approach for engineering design education.

The research also incorporated observational data, weekly individual student conferences during the secondary program, and pre- and post-surveys. The outcomes of the first three years of secondary graduates have been previously discussed in another publication [17]. This paper extends the analysis into its ninth year to include outcomes of surveys conducted from December 2023 to January 2024, covering four graduating cohort years of the program and five years of the longitudinal study. Thirty-nine former secondary students participated in these interviews. Out of the fifty-eight students who completed the secondary course as of June 2023, thirty-eight were still enrolled in engineering colleges, pursuing various engineering disciplines. Ten students had chosen fields other than engineering. Additionally, four students had discontinued their college attendance, and the status of the remaining six students was unknown.

Application

The application of providing broad transdisciplinary knowledge to inform an HDT methodology in engineering education has been implemented in secondary and postsecondary courses. It has been applied across various engineering courses, including seven undergraduate, five graduate, and eight secondary courses. Additionally, it has been utilized in capstone projects, independent studies, and junior high school engineering design courses. Undergraduate and graduate courses were typically conducted within a single semester, with some design projects extending over two semesters. Upper secondary courses, on the other hand, spanned the full fourth year of high school. Attributes of this pedagogy were imparted in several other courses as the design methodology underwent continuous research and refinement. The application of the HDT methodology to real-world projects occurs after students have mastered the specific knowledge contained within each cycle.

For example, in developing prototyping skills needed in HDT, students participate in a series of smaller object prototype projects. Through these projects, students acquire proficiency in utilizing the mind's eye, conceptualization, hand eye coordination, sketching, drawing, building, evaluation, feedback, and iteration, as well as working with materials and tools.

Among these projects is a 'pierced holes' exercise, where students work individually and iteratively, transitioning from verbal, visual, imaginative, inductive, associative, sketch, tactile, emotional, and bodily thinking to create a tactile object solution. It entails moving back and forth between using the mind's eye; sketching; scissors, tape, and paper; scissors, tape, and cardboard; and culminating in the use of a template and clay. Moving between these methods allows most students to solve the problem in the allotted time, reinforcing the link between reason, imagination, curiosity, empathy, design, and technology. Some students become frustrated when unable to find a cognitive solution with their mind's eye or sketching, fostering motivating doubt. However, when they work with clay, they unconsciously utilize embodied and bodily thinking to shape it. They channel their emotional energy through the material, squeezing it through the holes, multiple times until the right shape emerges. This exercise enables students to cultivate flexibility in their modes of thought, allowing them to transition between different thinking modes thereby becoming more creative and adaptable problem solvers.

Additional prototyping projects incorporate aspects of HDT to develop both individual conceptual understanding and team dynamics knowledge. These projects include designing, building, and testing an individual kinetic/potential energy device to perform work, as well as designing, building, and evaluating a team pendulum clock and a team prototype Mars landing vehicle, in addition to exploring student-generated design project ideas. These projects also connect scientific and engineering concepts of physics, chemistry, and biology to transdisciplinary knowledge. The key to success lies in fostering patient learning communities of belonging as transdisciplinary knowledge and practice are introduced. This process allows students to fail and then succeed, taking agency and fostering self-motivation and enthusiasm in eventually cultivating their own design project ideas. The gradual introduction of design complexity enables them to practice team dynamics on smaller projects while being monitored by the teacher and receive assessment and feedback. Upon completion and application of transdisciplinary learning, students organize into optimal three-person experiential project design teams.

As they progress through this pedagogy, students first engage with design teams in role-playing as end-users, stakeholders, and environmental entities. This allows students to learn when the stakes are lower, honing and practicing their design thinking, IS, communication, management, presentation, and other team skills. Subsequently, they advance to real-world team design projects, addressing actual users, stakeholders, and environmental concerns.

Over a nine-year period, diverse student design projects involving actual end-users, stakeholders, and environmental issues included an adaptive mobility vehicle, climate-adapted recycling bins, text-to-Braille decoder, a portable ramp for people with disabilities, a high-tech bus stop, a city park redesign, an economic impact analysis of how engineering innovation can reduce systemic poverty, suitcase reimaging, a touch-free airplane receptacle lid, horizontal motion adaptation of wheelchairs, adaptive design for people with disabilities, recycling trash receptacles, a no-lift wheel barrow, and lighting design and implementation in a public park.

An example of an undergraduate design team project, spanning two courses, which utilized the transdisciplinary knowledge pedagogy and HDT methodology involved an idea generated by the professor's observation of trash receptacles in airplane bathrooms during international flights. Through usage and observations, it was noted that the trash receptacle lids had to be touched to dispose of waste products, potentially leading to waste touching the lid or getting stuck between the lid and the receptacle. Given the class was comprised of students who had flown internationally, several of them had observed this same phenomenon. Ethical issues raised included concerns about health and safety regarding the potential transmission of disease through viruses and bacteria. Anticipatory ethical issues included these and overall mechanism safety requirements on airlines. The design problem assigned to the team was well-framed: to create an anticipatory, ethical touch-free lid for a bathroom trash receptacle on a Boeing 737 airplane. This team implemented the cyclical and iterative HDT methodology approach.

This project commenced with the cycle of love, empathy, and ethics by investigating the needs of international flight travelers who used the bathroom. The team also engaged two engineering stakeholders from Boeing, and Eastern China Airlines. Balancing the passenger health, ease, and comfort with airplane weight, power consumption, and safety concerns was a crucial trade-off. The team researched the design and specifications of the airplane, considering the environmental, safety, and space constraints.

Using the HDT methodology, the teams iterated through several prototypes of a hand touch-free system. Throughout the cycles of the HDT, students met with users and stakeholders impacted by the design to gain an understanding of expressed needs through a perspective of love, empathy, ethics, and design constraints. Feedback was collected from these perspectives as part of an iterative HDT relationship. Figure 9 shows the touch-free airplane trash receptacle lid prototype system.

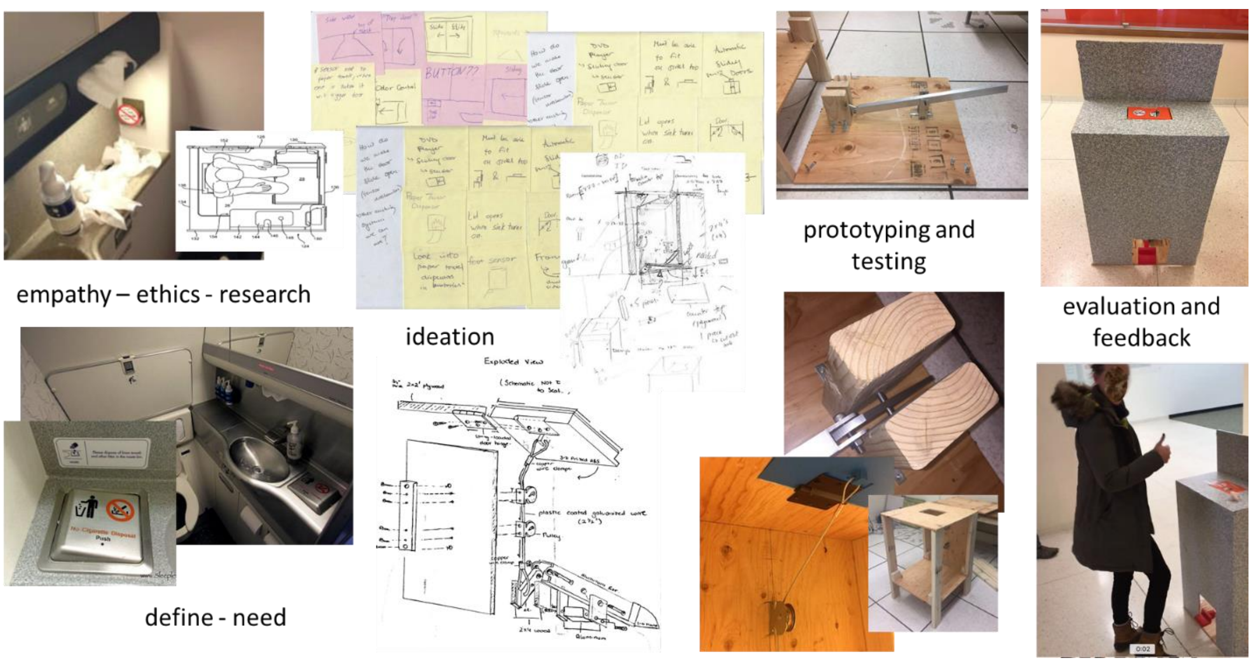

Figure 9. Touch-Free Airplane Receptacle Lid

The students expressed a sense of joy at engaging the public by having potential users evaluate the device in a public space frequented by international travelers. They heard direct feedback on how their design made international travelers feel a sense of comfort and safety. The feedback from stakeholders aided in their understanding of parameters of allowable design. They spoke of the deeper connection to their ideas and the value of feedback as a motivator for improvement.

Through the practice of transdisciplinary knowledge and HDT, students feel the importance of their skills in tackling practical world challenges. They recognize how ethical engagement and prototyping iteration can enhance intuition and create valuable episodic memories in problem-solving, and they see the necessity of embracing failure as a part of the learning process. This, in turn, fosters self-confidence, self-learning, and personal growth.

By emphasizing love, empathy, and ethics as intersections with design, students internalize how what they are learning connects to their ability to achieve design outcomes. The moment when students see their engineering design work in the world with people, they can experience a transformation of learning as the higher purpose of transdisciplinary knowledge and the HDT methodology. In practice, helping teams become intrinsically motivated and reach a transformative learning experience is central to HDT experiential learning projects.

According to one postsecondary student, “we delved into our identities as individuals and human beings in order to unearth the deeper meaning behind why we decided to become engineers, who we were, and how to shape our futures” and “how to relate to others better, how to understand them, and [it] completely changed my preconceptions of what it means to be human.” Additionally, these undergraduate course projects illustrate the need to expand the number of design courses to fully engage in the HDT methodology, as students expressed their concerns about covering the amount of transdisciplinary material and completing an experiential project in one course.

Feedback was gathered from students in the courses, including on the HE pedagogy, HDT methodologies, classroom learning methodologies, and knowledge content using direct oral feedback, surveys, and end-of-course reflection writings. Previously reported data spanning eight years included specific examples of individual and team projects using this pedagogy, such as city water infrastructure, transitional vehicle for students with neurodevelopmental delays, recycling-adapted trash receptacles, wearable blankets, and car trash receptacles [16], [17]. Over this period, the amount of course time and the breadth and depth of transdisciplinary knowledge and student practice has increased. Based on the results of this research more upfront knowledge and practice on critical, causal, and visual thinking have been added, as well as focus on demonstrating critical reading, effective communication, analytical and reflective writing, habit formation, and time-management.

Results and Discussion

The results of surveys conducted from December 2023 to January 2024 with thirty-nine former secondary students who graduated from the HE program were analyzed and compared to transdisciplinary knowledge associated with the pedagogical outcomes and focus areas. The first two graduating classes of secondary students were in their fourth year of college.

These survey results, along with previous reported data, were analyzed in the context of specific questions tied to the goals of the research. A set of seven standardized questions, as described in the Research Methodology section, were used in the interview surveys. In particular, the analysis of survey results aimed to understand and assess students’ perceptions of valued transdisciplinary knowledge and HDT relationships, while also determining whether there were any shifts over the course of their college years and the reasons behind any changes.

The qualitative responses of the postsecondary students provide valuable insight into the subtilities of their perceptions and motivations, offering a clearer individual picture than quantitative information. Several respondents have continued to mention that the course helped them “figure out what to do in life,” emphasizing the importance of mentoring in the program. Another fourth-year student described the course as teaching the “principles of life,” noting that the small “learning community helped—and was not worried that everything wasn’t a straight path but one that encourage exploring thoughts and imagination,” fostering a sense of belonging.

They mentioned looking back grateful for the morning circle, where they shared thoughts and feelings, along with various genres of short readings that helped introduce new knowledge. Two fourth-year college students, majoring in fields other than engineering, stated that the program provided a unique and valuable experience, significantly contributing to their overall college success.

Numerous students reported that they continue to gather with their cohort learning communities during college breaks or maintain ongoing communication through digital platforms. They also emphasized the value of written self-assessment reflections completed for the weekly individual conferences and mentoring sessions with the teacher, describing it as powerful for fostering self-agency in learning.

Another aspect mentioned almost universally was how the course facilitated a smooth transition to college. In terms of the social adjustment, students reported that being in the course, where a learning community was fostered through broad knowledge, diverse small class size, and active and experiential learning helped them quickly adapt and make new friends in college. A fourth-year student recalled how eye opening the course was and noted that the material covered remained useful in college.

A second-year student mentioned the practice of inviting former students, in college and recent college graduates, to share their experiences and perspectives, as being extremely helpful in thinking about their life’s path and goals. Another fourth-year student remarked on how the course’s structure resembled that of college, providing valuable preparation for the real world. Additionally, two first-year students and several third-year students described how the rigorous homework practices in the course helped them manage the workload in their college programs.

As previously reported, some secondary students continue to have intense negative responses to homework, although many recognize its future benefits [17]. Overall, throughout the four years of the secondary program, there has been a growing societal and institutionalized negativity towards rigorous homework practices, with the impact in the 2022-2023 school year being particularly significant.

A third-year student described how the general method of approaching a problem to solve using critical, causal, and visual thinking has been extremely useful in college, even applied to math problems. Students continued to speak of the knowledge gained and power of self-reflection in being able to monitor themselves and adjust. There were also numerous comments regarding the benefits of fixing attention span, ability to focus, and study habits prior to college. It was also interesting to note that one second-year student described that when they were in a slump at college, they were able to recognize what was going on—being unable to critically read—because they remembered the way it felt like when they could from the course.

Students continue to emphasize the importance of learning how to critically read, noting its usefulness from a transdisciplinary perspective due to the nightly analog homework practice and wide variety of genres covered in the course. This practice and exposure expanded their abilities and perspectives, aiding in managing the diversity of readings in college. A third-year student described using these critical reading methodologies to understand a textbook when they had trouble following the professor's lectures.

Teaching critical reading is foundational to the HE pedagogy, with the analog pedagogical approach previously highlighted in a paper [17]. Students are provided with paper copies of all readings and expected to demonstrate critical reading through annotation, marginalia, and writing. Annotation and marginalia aid in developing critical reading skills by connecting comprehension to active notation, facilitating identification of author's thesis and main point, and linking reading to previous knowledge and experiences. Reading begins with identification of genre, relevance, and evaluation of the author's credibility. Analytical, critical, and reflective writing analysis consists of four handwritten paragraphs in the notebook, cycling between comprehension at the macro to the micro level. The first analytical writing paragraph is used to show comprehension of the authors' thesis and main points.

Responses during these recent interviews, also linked to the course pedagogy but not previously categorized, included mentions of causal thinking, abstract thinking, and the ability to accept failure as a valued attribute. Although not listed in the previous study, these attributes are important aspects of the HE pedagogy and learning outcomes and are now included in Table 1. A second-year student in a past interview reflecting on the previous high school course said it "taught me so many valuable skills about empathy, love, ethics, and creativity that I would have not obtained anywhere else." A third-year student, in this current survey, reported continuing to grow in their understanding of how empathy is tied to character. Several students described how the exposure to ethics in the program helped them in college including being more knowledgeable and aware of ethical philosophies, constructs, cases, and applicability to real life and engineering problems.

Another commonly mentioned attribute on the transdisciplinary table is communication practice. Students mentioned the ability to recognize what type of speech act (conversation, discussion, dialogue, debate, diatribe, etc.) was being engaged in with peers and professors and respond accordingly. A sophomore described using this knowledge, empathy, and understanding others when working in teams at college and being able to "see differences as a strength within our group" and "diffusing likely hostile discussions when the group disagreed." They spoke of the power of the course, which gave them more opportunities to practice speaking and presenting than any other secondary course they had, which was extremely beneficial in college.

Table 1 presents the total response data for the four secondary graduating cohorts, comprising individuals transitioning from high school, current college students, and cumulative totals.

Table 1. Totals of Student Self-Identified Valued Knowledge High School and College

transdisciplinary knowledge topic	total student- identified values exiting high school	total student-identified values during college through 2023	total student-identified values during college through 2024	total of values student-identified in high school and college
critical reading (across genres)	7	21	40	47
reflective and analytical writing	0	12	16	16
self-reflection	11	7	12	23
intrinsic motivation	2	8	13	15
time management	6	20	34	40
organizational skills	0	2	2	2
modes of thought	5	4	7	12
critical thinking	6	10	21	27
causal thinking			6	6
visual thinking	14	5	13	27
creative thinking	2	0	2	4
abstract thinking			1	1
love	3	1	3	6
empathy	17	12	17	34
ethics	12	12	22	34
communication practices	10	11	27	37
ideation	2	6	9	11
team dynamics/teamwork	7	19	32	39
psychology/IS skills	0	7	13	13
leadership skills	0	1	3	3
diversity	0	2	3	3
voluntary focus	0	1	5	5
patience	1	1	1	2
candor/trust	0	1	2	2
Holistic Design Thinking	17	20	36	53
emotions	1	1	1	2
episodic memories	2	0	0	2
rigorous homework practices	0	23	31	31
lectures	0	3	5	5
notetaking	0	8	11	11
overcoming adversity/fear of failure	0	1	3	3
notebook method	0	6	18	18
engineering principals	1	0	0	1
engineering careers	1	0	1	2
internships	0	1	5	5

It is important to note that the transdisciplinary category of "communication practices," listed in Table 1, encompasses student responses related to concepts of communication theory and practice, Theory of Mind, conflict resolution, and empathetical listening. This category also overlaps with the "psychology/interpersonal skills" category. Previous work's category "psychology/interpersonal skills" has been revised to 'psychology/interpersonal and soft skills' or "psychology/IS skills" to better reflect the grouping of knowledge and interview responses.

Regarding the quantitative results presented in Table 1, several categories have been added, and two additional labels have been slightly adjusted to better reflect the actual transdisciplinary knowledge and student-reported benefits. Two new categories—causal thinking and abstract thinking—have been introduced. Slight changes were made to two existing category names to better reflect the pedagogy. 'Critical reading' was changed to "critical reading (across genres)" to better reflect actual course practices, which included the use of analog annotation and marginalia. Similarly, the sketchbook method, which implicitly implied that the pages were blank and not lined and that analog practices were used to capture all information and for writing, was changed to “notebook method,” where the practices remained unchanged. In the most recent interviews, a second-year student and two third-year students mention how important it was to have been introduced to and utilize the notebook method in the course, specifically using a blank-page notebook that encouraged nonlinear, abstract, and visual thinking in the capturing ideas, diagrams, notes, and sketches. They stated it was a powerful tool for their thinking practice.

While not specifically referenced in the table, numerous students reported aspects of the program that helped them in determining life’s purpose. Students expressed that they felt “The lessons I learned from the class, I feel that I will be capable of making a positive impact on the world through engineering.” Another student stated, “I plan to take the new knowledge from the class and apply it to my future [and] implement it into my life, college, and the workplace. Finally, a student summed up the experience by saying, “This class has made me think about how I can use my career path as not just a fulfillment for me, but for the world around me.”

Qualitative data indicate that secondary students may not initially respond positively to transdisciplinary knowledge in an engineering class. There is eagerness to dive into the “fun part” of team building and testing, suggesting a preference for hands-on activities. Moreover, feedback collected suggests a common experience where previous teachers assigned projects with little guidance on team dynamics, design thinking, or communication skills. In feedback from college students, the data suggests that they are more welcoming of transdisciplinary knowledge and found it useful in design teams.

Many students spoke of the importance of HDT methodology to their college experience and having a much greater understanding of design, team dynamics and teamwork, and the overall design process than their peers. Two second-year students and third-year student spoke about being able to lead the ideation practices for their teams based on what they had learned in the course as part of the HDT methodology. Another student spoke of using it in their summer internship, where they led all the other interns in an ideation session and producing a solution for management that ended up remarkably close to what was ultimately used. A fourth-year student spoke of the concepts learned in the class, including the use of HDT in an experiential design team project, highlighting their benefits in both the business world and real-world applications. Several other postsecondary students also spoke of the experiential team design project of continuing foundational impact in how they approach design projects in college and internships.

Numerous students expressed being ahead of the curve from their peers in design thinking and in understanding the psychology of working with others based on the wide variety of knowledge they received in the course. One student said of the transdisciplinary knowledge they learned, “it just comes up all the time in dealings with my classmates, and working on teams, and even with the people I live with.” Students have expressed that learning through the transdisciplinary knowledge pedagogy and using the HDT provided them with “skill sets that I didn’t know I struggled with as well as ways to improve those skills.” In working with the HDT methodology, students said it “reshaped my understanding of the missing intricacies of my concepts about being an engineer" and "the better you can interact and connect with others the more of a positive impact you can have on each other's lives." Students also stated the value of this knowledge when working in internships and the importance of internships during the program.

An important aspect of the HDT methodology, as illustrated in Figure 7, is its grouping of relational competencies in human behavioral interactions. This arrangement creates a useful flow based on its cyclical nature and flexibility in transitioning among competencies. Observational data and feedback collected through interviews suggest that this model provides students with a valuable collaborative system for both contemplating and practicing aspects of love, empathy, ethics, and design.

Secondary students have shared, "The first super surprising thing I learned from the class is just how involved love is in engineering. To be able to help others and fulfill their needs you need a base of love that then leads into empathy." They emphasized "the importance of learning to love yourself. Once you trust yourself and can properly self-reflect on mistakes you can learn how to love yourself and then empathize with others." Another student remarked, "We learned just how connected we are to each other and how connected love is to everything we do, even engineering. For us to fully understand how empathy can be used in the design process." A secondary student expressed, "I think that being able to think about ethics and empathy while designing will get me closer to my goal of positively impacting people as it will decrease the chances of me creating things that will hurt people." Another student noted understanding "the importance of ethics and morals, and how they play a part in engineering."

It is important to note that although the HE and HDT pedagogies include transdisciplinary knowledge instruction on self-reflection, leadership, time management, organization, psychological safety, team dynamics, management, and assessment that has not been detailed in this paper. They are inherent components of the transdisciplinary knowledge that students acquire prior to working in experiential design teams. Evaluation and resolution are specifically part of the HDT design methodology cycle.

The cumulative results of the knowledge areas valued by all college students in Table 1 demonstrated a distinct clustering in order of importance of knowledge. Specifically, students self-identified critical reading, HDT, time management, team dynamics/teamwork, rigorous homework practices, and communication practices in the top responses. There is a shift in order of valued knowledge in this top grouping from the previous year; critical reading, HDT, time management, and team dynamics/teamwork were valued slightly above rigorous homework practices. There is a substantial increase in the valued responses of communication practices in this latest survey, which moved from a mid-response to a top grouping response.

Ethics, critical thinking, notebook methods, empathy, and reflective and analytical writing were clustered in mid-responses. Again, a slight shift in valued knowledge occurred in this mid-tier; critical thinking and notebook methods were valued slightly above reflective and analytical writing.

The next clustering included visual thinking, intrinsic motivation, psychology/IS skills, self-reflection, and notetaking. Again, slight shifts occurred, with most categories changing by less than two, except for ideation, which moved to the next lower clustering from previous years. Ideation, modes of thought, causal thinking, voluntary focus, internships, and lecture practices were clustered next, followed by love, leadership, diversity, and overcoming adversity/fear of failure. The largest increase from the previous years was in the value placed on critical reading, followed by HDT, communication practices, time management, team dynamics/teamwork, notebook method, critical thinking, ethics, visual thinking, and rigorous homework practices.

It is interesting to note that; reflective and analytical writing, rigorous homework practice, notetaking, psychology/IS skills, notebook methods, lecture practice, diversity, organizational skills, voluntary attention, leadership, internship, and overcoming adversity did not show up in any of the previous high school student exiting polls even though they were important aspects of the program and included in the transdisciplinary knowledge they received. The findings support the benefit in secondary education in critical reading, engagement in the HDT methodology, time management skills, rigorous homework practice, and knowledge of team dynamics/teamwork in subsequent college success. It also demonstrates the advantages of transdisciplinary knowledge in communication practices, critical thinking, ethics, notebook methods, reflective and analytical writing, empathy, visual thinking, intrinsic motivation, self-reflection, and psychology/IS skills.

The shift identified in the data over the cohort's college year responses is of importance. Students reported changes in the transdisciplinary knowledge they valued and found useful from when they exited the secondary program to when they were in engineering college. Significant shifts occurred in the increased value they placed on rigorous homework practices, time management, critical reading, reflective and analytical writing, and the analog notebook method. The two highest-ranked values reported by college students were critical reading, HDT, time management, and rigorous homework practice.

Even more significant is the combination of categories including modes of thinking, critical thinking, visual thinking, causal thinking, and abstract thinking, which emerge as the most valued skillset. Students consistently emphasize and importance of accessing these modes and moving flexibly between them in navigating relationships and problem-solving, crucial for their college success. The interviews also reveal an overlap in categories, such as team dynamics/teamwork, psychology, interpersonal skills, and soft skills, making them challenging to distinguish. However, the combination of these categories is highly valued by college students. This trend suggests that college students increasingly value the transdisciplinary knowledge and practice acquired during their secondary program, even though it was not as highly valued in the secondary school exit polls. Importantly, it shows that students retained this knowledge―particularly in IS skills, empathy, ethics, design thinking, and team dynamics—and continue to draw upon it throughout their advanced college years. Their adeptness at accessing transdisciplinary knowledge further underscores the effectiveness of the pedagogy. Although not conclusive, the actionable access to this broad knowledge base has anecdotal evidence in the form of student responses regarding its perceived relevance to their abilities in college.

Furthermore, this research contends that the fundamental structure of an undergraduate engineering curriculum should be enriched with transdisciplinary knowledge and integrated in a cohesive sequence of design courses spanning four years. This should be structured to coincide with the student's emotional and cognitive development. Similar to the approach taken in the secondary program described here, these courses should be seen as the developmental cornerstone, fostering comprehensive understanding beyond individual disciplines, with the aim of nurturing exceptional skilled design practices of engineers. A notable distinction between the secondary program discussed here and engineering college practices lies in the dedicated time within a course specifically focused on transdisciplinary knowledge and design. This broad transdisciplinary knowledge is typically not part of traditional engineering curriculums. While typical engineering colleges provide an introductory class in the first semester and capstone classes for fourth-year students partially focus on some of these transdisciplinary knowledge topics and design, the secondary program emphasizes the consistent and sustainable development of transdisciplinary knowledge and understanding essential for engaging in design practices throughout its half-day, year-long curriculum. The secondary high school fourth-year program extended over a full year, comprising approximately 180 days or 540 hours. During this period, students spent 162 of those hours working directly with engineers and 100 hours in college English courses, resulting in about 278 hours of transdisciplinary knowledge and engineering design course time. In contrast, a typical college course of three credits hours totals approximately thirty-seven classroom hours.

The argument put forth is that engineering colleges should offer a design course every semester, totaling 296 hours. The course sequence should begin with a broad transdisciplinary knowledge base and continually expand it into design thinking practices. These courses should build upon previous knowledge in a holistically sequential manner. This would match the amount of class time from the secondary program courses, indicating that a similar amount of material could be covered. This approach supports the implementation of the same transdisciplinary and HDT pedagogical approach used in the secondary program coupled with an experiential design team project. The study suggests that through adopting a more comprehensive knowledge approach, a more universal design methodology could emerge, balancing the integration of broad, analytical, and practical knowledge.

An important limitation of this research is that it does not establish full causation; rather, it relies in part on evidence based on human behavioral observations and qualitative data. While the research included quantitative data and analysis to support many aspects of the secondary program outcomes, such as comprehension and practices of critical reading, writing, engagement in various modes of thought, analog practices (writing, sketching, notetaking, etc.) , design practices, problem solving, leadership skills, time management, habit formation, communication abilities, empathetic practices, ethical reasoning and evaluation skills, establishing more causal relationships of knowledge comprehension and integration beyond the secondary program is elusive due to lack of detailed quantitative data and observations.

Regarding the specific goal questions of whether the HE pedagogy leads to a deeper understanding of oneself and the cultivation of more profound purposes, the data remains inconclusive beyond the secondary program and postsecondary interviews. Among the fifty-eight former secondary program students examined, thirty-eight were still attending engineering colleges, pursuing degrees in various disciplines such as Electrical, Mechanical, Aerospace, Chemical, Civil, Bio, Industrial Systems, Material Science, and Computer engineering.

Additionally, ten students pursued fields other than engineering, including Computer Information Technology, Architecture, Fine Arts, Biology, Business, Industrial Design, Construction Management, and Advertising and Public Relations. Four students had stopped attending college, and the status of six students was unknown.

Regarding the inquiry into the impact of holistic emotional and cognitive learning practices in engineering design courses, the qualitative data lacks causal relationships. While correlation exists among the qualitative responses of former students of their perception of various aspects of emotional and cognitive learning connections fostered through the classroom environment and practices, it is not universal. Instances where students did not perceive immediate benefits, especially among those lacking intrinsic motivation in the program, are notable. It is common for students to recognize the benefit of knowledge retrospectively, as was reported by several students in this study. Pedagogical practices such as individual weekly student conferences provide opportunities to observe and monitor the impact of reflective practices, feedback, knowledge integration, and prototyping and testing behavioral strategies in habit formation linked to improvement. These practices occur on a student-by-student mentoring basis, requiring emotionally and cognitively attuned to adjustments in what works for each specific student. The building of trust in a kind, caring, and mentoring environment was noted by students as a contributing factor to their successful implementation of learning strategies. Therefore, the individual stories of how students apply this knowledge vary, introducing complexities that defy objective measures of success. Therefore, the results or impact of this research should be interpreted with caution. While they hold significance on an individual student basis and have some general applicability, they may not offer provable conclusions in all cases.

Most students involved in this secondary study were selected through an application process during their third year of high school, suggesting an above-normal interest in engineering. While it is not assumed that additional years immersed in the pedagogy would not be beneficial, the established framework of the program only allowed fourth-year students to participate. Furthermore, it is worth noting that not all the same graduating secondary students responded to surveys each year of their college education. Limitations also arise in the codification of interview response and overlaps in transdisciplinary knowledge. Additionally, the analysis provided here lacks consideration of such factors as GPA's, internships, and employer feedback, which could further elucidate any discriminating factors of pedagogy.

Several limitations are apparent in the research's applicability, including the need for a sufficient number of dedicated design college courses and challenges related to class size. While small class sizes are significant in the secondary program, their universal implementation at the college level presents hurdles. Another critical limitation stems from the nontraditional aspects of this engineering pedagogy and curriculum, which necessitates a reliance on specific political, economic, and social contexts, as well as particular institutional settings. For secondary education, it requires the support of parents, administrators, and other collaborative partners. In postsecondary education, it relies on the support of faculty, administrations, engineering departments, and the college as a whole.

Questions persist about the economic practicality of implementing this pedagogy and holistic philosophy, particularly concerning class size. While there are broader benefits, even in larger class sizes, for engineering education to adopt a more holistic philosophy and transdisciplinary knowledge approach to curriculum and design, widespread implementation has not yet been attempted. The postsecondary courses reported here were pilot design courses and not integrated into the larger engineering college curriculum. This poses a significant problem for postsecondary education, as economics and other factors, including online courses and AI algorithms, exert pressures on mentored experiential learning and traditional lecture-based learning, both aiming to disseminate knowledge and achieve learning objectives. It is crucial to note that this work, grounded in analog classroom practices, intentionally diverges from techno-optimist or transhumanist solutions, such as replacing professors with individual learning stations that track students' eye movements and engagement with the material. Instead, it emphasizes a different direction—a return to smaller learning communities that foster individualized attention, creativity, and mentoring relationships between students and multifaceted experienced instructors.

Conclusions

The primary objective of this research is to describe and analyze a distinctive pedagogy of engineering design education. This pedagogy is characterized by extensive integrated transdisciplinary knowledge and a holistic design methodology rooted in principles of love, empathy, and ethics. Pedagogically, the cycles of design are attuned with the cycles of experiential learning. Structurally, the secondary Holistic Engineering program comprises course hours equivalent to eight three-credit-hour college courses, along with an experiential design project component, and class sizes of around eight students. Foundationally, this structure appears to address deficiencies in knowledge and abilities, enabling students to explore life's purposes, preparing them for engineering college, and initiating the acquisition of in-depth knowledge of design thinking. The pedagogy emphasizes student self-assessment and agency, as well as reflective, active, and experiential learning. This research reports that implementing this approach has been shown to benefit students academically, professionally, and personally, fostering continuous learning relationships with people and ecosystems.

A secondary objective is to assess how students, exposed to this pedagogy during secondary education, perceive its utility as they advance through college. The study also explores questions related to students' finding unique abilities and motivations, including one's sense of purpose and direction in life. It emphasizes the impacts of a secondary education program rooted in a learning community that embraces emotional expression, sharing, analog practices, flexibility in modes of thought, curiosity, and cognition, fostering free play between reason and imagination from which creativity, empathy, and ethics can emerge.

Results from applying the HE pedagogy in postsecondary courses of up to three-credit hours suggest that the allocated time is insufficient for adequately covering and transferring transdisciplinary knowledge including design thinking, as well as conducting an experiential team design project. This underscores the need for more comprehensive time allocation to accommodate a more universal design methodology. Conversely, results from the secondary program, where course time was increased by approximately eight times, led to deeper comprehension of knowledge and agency in design practices. Therefore, the research advocates for a dedicated core curriculum of design courses to support students' development throughout each year of postsecondary engineering education.

The findings indicate a benefit in the number of hours students are immersed in learning and practicing transdisciplinary knowledge and a Holistic Design Thinking methodology. The results suggest that more universal knowledge coupled with an HDT methodology provided students with competencies in human behavioral interactions and flexibility in transitioning among relational competencies.

The findings also indicate that students can access transdisciplinary knowledge acquired in the secondary program as they progress through college, utilizing it effectively in various contexts. Additionally, the research reveals the value of developing skills in critical, visual, and design thinking, critical reading, time management, communication, and teamwork, as well as fostering self-awareness and agency in learning. Practical benefits reported by students also include understanding and practicing of empathy, taking initiative, increasing focus, managing time effectively, improving homework practices, and engaging in more deliberate self-reflection.

The implications of these findings suggest that engineering educators and administrators should consider a significant shift in design pedagogies, leading to enhanced designerly thinking through design as a core curriculum. This shift emphasizes the integration of emotional learning, psychology, and neuroscience findings into engineering educational practices. However, successful integration may face challenges related to class size, traditional pedagogical approaches, and economic pressures.

Future work should focus on delving into interview data with finer granularity to further explore the connections between transdisciplinary knowledge and postsecondary success. More data and information should be collected as the remainder of the four cohorts complete engineering college to improve conclusions and refinement of the pedagogy. There is also a need to explore practical implementation of this pedagogy in engineering college structures, which may require reformatting of curricula and design courses.

As awareness of the harms and risks associated with social media and AI technology increases, it prompts a critical examination of their correlation with limitations of current design paradigms and practices. Concurrently, the integration of the study of the complexities of love and ethics into the curriculum of engineering education offers a unique opportunity to deepen our understanding of human existence and the holistic nature of the world. Furthermore, incorporating love as a formal part of an engineering design methodology is unique and empowers its attributes of compassion and empathy, allowing for a comprehensive consideration of diverse human and non-human needs. Similarly, the formal inclusion of ethics in engineering design methodology positions this transdisciplinary knowledge approach and Holistic Desing Thinking practice at the forefront of design philosophy and thinking.

As society evolves and machine intelligence approaches or moves beyond human intelligence and accelerates the merger of humans with machines and robotics with AI, the incorporation of love and ethics into our design practices becomes paramount. Navigating the complexity of emerging technologies like gene prime editing, cybernetics, brain-computer interfaces, and AI robotics, requires an understanding, integration, and use of love and ethics in our engineering design methodologies. This is crucial for anticipating unintended consequences, ensuring agency, and promoting transparency in ecology, the environment, and more-than-human interactions. A fundamental question remains: What level of comprehensive knowledge is most suitable for design education, especially in a rapidly advancing and increasingly technologically deterministic society? Exploring potential universalities in engineering design education methodologies may offer insights into alternative possibilities and directions.

To be human is, in part, to create ever-increasing technology, while also encompassing our ability to empathize, love, create poetry and art, and social structures of caring. As we venture forth as a species to explore the stars, it is a hope that we develop a symbiotic design relationship with technology and nature, enabling us to progress while preserving our intrinsic humanity and profound connection with nature. This relationship should value nature as distinct, invaluable entity separate from technology, yet intertwined in a manner that practices ethical consideration for everything.

Overall, this research advances a holistic and transdisciplinary pedagogy that cultivates a broader more universal understanding of knowledge and engineering design and its practices. It advocates for a sustained sequence of holistic design courses enriched with transdisciplinary knowledge as a fundamental component of undergraduate engineering education. It does this by first focusing on the relational aspects of love, empathy, and ethics in being human designers.

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