Work in Progress: What is Design in the Context of a Mechanical Engineering Ph.D. Program?

Grace Burleson, Janet Tsai, and Daria Kotys-Schwartz
Mechanical Engineering, University of Colorado Boulder

Abstract

Design has long been considered a fundamental focus area within the mechanical engineering discipline. At the undergraduate level, students are given the tools and resources to gain knowledge and skills in critical design competencies, such as ability to scope problems, develop analytical models, and test and validate solutions. However, there is limited scholarship regarding the conceptualization and definition of design at the doctoral level within the mechanical engineering discipline. This manuscript presents ongoing work at our university to add a design focus area in the mechanical engineering PhD program. First, we conducted a preliminary review of mechanical engineering PhD programs within the U.S. to first confirm our hypothesis that design is considered a fundamental research area in the mechanical engineering discipline and, second, to gather inspiration for the development of our own design focus area. Next, we conducted focus groups with over one-third of our department's faculty to uncover perceived benefits and concerns of adding a design focus area. Overall, our preliminary findings indicate the design is a well-established area of research within mechanical engineering doctoral programs in the U.S. We also gathered strong support from our faculty that is encouraging our department to move forward with implementing a focus area in design. Our focus groups also uncovered important concerns and questions that we will address moving forward. Ultimately, we aim to define how our department can contribute to graduate research and education in design. Future work will investigate the different ways design is conceptualized, researched, and applied at the graduate level in mechanical engineering programs across the U.S.

Keywords

Mechanical engineering, Design, Engineering design, Graduate engineering education, Design education

1 Introduction

Design can refer to both the processes and outcomes of the creation of artifacts, such as systems, objects, and technologies (Simon, 1969). Design is itself a distinct discipline, with its own methods of inquiry and body of literature, sometimes referred to as design science (Papalambros, 2015) or design studies (Cross, 1982). The practice and study of design is associated with many fields, including engineering, architecture, information science, business, art, and more. In mechanical engineering, design is typically described as a methodological approach that includes many different stages, tasks, and analytical decision-making processes that assist design teams with the creation of functional products (Breiing, Engelman, & Gutowski, 2009). As such, preparing mechanical engineers with the necessary design knowledge skills remains a central component of engineering education, particularly at the undergraduate level (Lee, 2009; Turns et al., 2004) – but what about at the doctoral level?

Across the U.S., mechanical engineering PhD programs prepare students for conducting independent, innovative research in a variety of fundamental areas. PhDs are granted for the creation of new knowledge within specific disciplines. Research within mechanical engineering can include mechanics, materials, thermal-fluid sciences, dynamics, design, and more. Scholars agree that scholarship in these areas is critical for the advancement of engineering practice and pedagogy (Hubka & Eder, 2012).

However, the mechanical engineering department at the University of Colorado Boulder (CU Boulder) currently does not have a focus area dedicated to design. The department currently categorizes its focus areas across seven applications: (1) air quality, (2) biomedical, (3) material science, (4) mechanics of materials, (5) micro/nanoscale, (6) robotics and systems design, and (7) thermal-fluid sciences. While all areas are underpinned by the application of design methods, there is not a specific area of design as it is conceptualized in fields such as design studies and design science. In an effort to consider if the mechanical engineering department at our university should pursue the inclusion of an additional focus area in design (with a broader definition than what the department currently uses), this paper investigated the ways in which mechanical engineering PhD programs in the U.S. define design within the context of their programs and gathered feedback from a subset of faculty members within our department to identify perceived benefits and concerns.

2 Background

2.1 Design in engineering education

Historically, engineering schools have placed the focus of design on preparing students for careers as practitioners, rather than on research and the production of knowledge (i.e., conducting design research and writing academic papers). However, a growing body of research has emerged focused on design theory, methodology, pedagogy, and practice; design has become an accepted object of study and academic discipline (Voûte et al., 2020; Meyer & Norman, 2020; Papalambros, 2015). As a result, engineering and design education has developed and diversified considerably, applying advancements from design scholarship, while adapting to changes in demand from society and global competition for better products and systems (Redström, 2020).

Many scholars have worked to identify the critical design skills and competencies that engineers should possess after completing an engineering undergraduate degree. Angeles et al. (2004) suggested that students should have (1) the ability to apply math and science fundamentals to design processes and analysis, (2) hands-on competency in the use of tools relevant to their domain, (3) knowledge of formal design methodologies, such as ideation and modeling techniques, (4) ability to adapt and work professionally, (5) project management and business skills, (6) communication skills, and (7) teamwork skills. Others have classified design competencies based on critical stages of design processes: information gathering, problem definition, idea generation, evaluation and decision making, implementation, communication, teamwork, and process improvement (Davis et al., 1997).

While much effort has gone into studying and improving undergraduate engineering design education, especially within the mechanical engineering discipline, much less work has been cited at the graduate level, particularly the PhD. Most commonly, a PhD degree in engineering focuses on advancing theory and applying findings to a practical problem (Barbieri, Vaidyanathan, & Peterson, 2012). Scholars also suggest that design at the PhD level must be broader than traditional engineering disciplines, incorporating more history, philosophy, ethics, cultural studies, and politics (Meyer & Norman, 2020).

Research is a fundamental component of any PhD. With a growing and maturing design research discipline, scholars have suggested that the focus of a design PhD can include: research on design methods and processes, improved understanding of engineering practice, ways to increase product development performance, and investigations of design education (Atman et al., 2014, Turns et al., 2004). Others have pointed out that research should result in outcomes that advance our knowledge and practice of design, such as constructs, models, and methods (Winter 2008).

2.2 Mechanical Engineering PhD Program at CU Boulder

The mechanical engineering department at CU Boulder has over 1,300 students and nearly 70 faculty. Specifically, the PhD program has 122 students as of March 2024. Students within the PhD program choose from seven focus areas (Table 1) that guide their selection of courses, preliminary examinations, and research. Each focus area is defined on the department's website and includes a list of strength areas that represent the work faculty conduct within that focus area.

Table 1. The focus areas of the mechanical engineering PhD program at CU Boulder, as of Spring 2024.

PhD focus areas	Definition of focus area	Strength areas of each focus
Air quality	Air quality research encompasses a broad range of topics impacting human health and the environment, including fundamental studies, technology development and policy implications.	Air quality monitoring and characterization; Air quality health and climate impacts; Air pollution control
Biomedical	Biomedical engineering employs quantitative methods in physics, chemistry and biology to develop innovative medical technologies.	Biomechanics; Biomaterials; Fluidics; Mechanobiology; Imaging; Medical devices
Material science	Faculty in material science carry out research in many areas including polymers, thin films, soft actuators, battery materials, laser ultrasonics, flash sintering, nanomaterials for energy, heat transfer, and metamaterials.	Acoustic, phononics, and thermal metamaterials; Energy storage; Separation membranes and porous materials; Polymeric materials; Topological materials
Mechanics of materials	Mechanics of materials focuses on quantitative description of the motion and deformation of solid materials subjected to forces, temperature changes, electrical voltage or other external stimuli.	Computational mechanics; Multiscale modeling of growth in engineered tissues; Stretchable electronics; Wrinkling; Facture; Stretch; Smart materials; Additive manufacturing

Micro/ nanoscale	Research involves micro- and nano-electromechanical systems (MEMS and NEMS) for transducers, sensors and actuators with a new interdisciplinary initiative in engineering for quantum technology applications.	Quantum technology; Thermal nanotechnology; Bio and environmental nanotechnology; Nanotechnology in systems and devices; Nanomaterials
Robotics and systems design	Robotics and systems design research focuses on identifying fundamental principles and methodologies that enable engineered systems to exhibit intelligent, goal-oriented behavior, and developing innovative instruments to monitor, control and manipulate systems.	Endoscopy automation; Surgical robotics; Tration, adhesion, and dynamic modeling; Bio-inspired robotics; Computational dynamics; Self-healing actuators
Thermal-fluid sciences	Thermal-fluids research is focused on a wide range of both fundamental and applied problems related to energy conversion, heat and mass transfer, combustion, and fluid mechanics.	Mico/nano heat transfer; Chemical kinetics and combustion; Cardiac fluid dynamics; Laser diagnostics; Computational fluid dynamics; Multiscale modeling and simulation; Renewable energy generation; Biomass utilization

3 Scoping Review

3.1 Method of scoping review

In an effort to begin developing a new PhD focus area in design at the mechanical engineering department at CU Boulder, we first conducted a preliminary review of mechanical engineering PhD programs. We aimed (1) to confirm our hypothesis that design is considered a fundamental area in the mechanical engineering discipline and (2) to gather inspiration for the development of our own design focus area. First, we looked at the top 12 mechanical engineering graduate programs in the U.S., as ranked by U.S. News in 2023.[1] Second, we looked at additional mechanical engineering graduate programs that we knew had strong design emphasis, either through our personal connections or its faculty presence at large engineering design conferences (e.g., International Conference on Engineering Design, International Design and Engineering Technical Conferences). For each program, we reviewed the department's website for their list of research areas, which were sometimes referred to as "fundamental areas" or "research groups" (i.e., clusters of faculty who conduct research in designated areas). Department websites were reviewed in September and October of 2023.

3.2 Findings from scoping review

Of the top 12 mechanical engineering graduate programs in the U.S., eight include a specified focus area in design or equivalent (e.g., "product innovation" at Carnegie Mellon University), as of Fall 2023 (Table 2). Across these eight programs, design is described both as the pursuit of specific solutions as well as the development of tools and models to improve

[1] Accessed October 2023: https://www.usnews.com/best-graduate-schools/top-engineering-schools/mechanical-engineering-rankings

design processes (e.g., optimization, design strategies). In four programs, manufacturing is highlighted as an important emphasis in design. Two programs describe the inclusion of "social constraints" and "social needs" as part of their focus on design.

Table 2: Prevalence of design as a focus area within the top 12 mechanical engineering graduate programs in the U.S., including its definition within each program.

Universities	**How design is defined within the Mechanical Engineering Ph.D.**
1. MIT	"Design: In the Design research area, everything from a steam turbine to a gaming console is conceived, designed, fabricated, assembled, and delivered by an engineer who understands design, manufacturing, sustainability, and the supply chain."
2. Stanford University	"Design: Some actively design and manufacture devices or products; others study the design process including team design and team learning, a traditional strength in our design curriculum. In addition, we develop tools to facilitate the creation of engineering products at a variety of scales and complexity. We interpret the word 'design' widely, reflecting the broad value systems we cultivate in the Department. We also believe that a better understanding of societal needs, aided by association with social sciences, will further assure the relevance of the fields we choose to work in."
3. Cal-Tech	No specific design focus area described on the department's website.
4. University of California - Berkeley	"Design: Faculty in the Design field of Mechanical Engineering work on problems affecting the analysis, synthesis, design, automation, fabrication, testing, evaluation, and optimization of mechanical systems."
5. Georgia Tech	"CAE & Design: The goal of the CAE-Design Research Group is to develop computer-based, systems-oriented methods and the supporting infrastructure that facilitate the effective design and realization of engineering products and systems for the global marketplace."
6. University of Illinois - Urbana Champaign	No specific design focus area described on the department's website.
7. University of Michigan	"Design: Design is an act of creating products and systems to fulfill specific needs under physical and social constraints. In the global marketplace, where products are imported from the countries with the lowest production cost, design innovation is a key to helping industrialized nations stay competitive."
8. Purdue University	"Design & Manufacturing: If you want to build it, first you've got to design it. That's why Design & Manufacturing is such a vital aspect of engineering research at Purdue, discovering the ideals for mechanical systems, computational models, and human ergonomics."
9. Cornell University	No specific design focus area described on the department's website.
10. Princeton University	No specific design focus area described on the department's website.
11. Carnegie Mellon University	"Product Innovation: Pushing the frontiers of design theory, methods, and automation in areas ranging from consumer-based innovation to new design tools and materials."

12. University of Texas-Austin	"Advanced Manufacturing and Design: …We innovate and advance the state of the art in engineering new processes, machines, predictive modeling capabilities, and design strategies. We complement these innovations with core expertise in robotics, quality control, design engineering, computational engineering, and materials processing, and motivate our work with applications as varied as medical devices, honeycomb materials, and biomaterials."

Acknowledging that the 12 most highly-ranked programs are not a representative sample of how design may be defined within mechanical engineering doctoral programs, we also looked into six additional universities that are well-known in the engineering design community due to their regular involvement at engineering design conferences. Table 3 presents the definitions of design focus areas within four of these mechanical engineering PhD programs. Two other mechanical engineering PhD programs with design focus areas are not included in the table because we could not find specific definitions on their websites, these included: "Manufacturing and Design Innovation" at University of Texas-Dallas and "Design, Optimization, and Entrepreneurship" at George Mason University. Future work aims to systematically review how mechanical engineering departments in the U.S. conceptualize design.

Table 3: Definitions of design focus areas at universities with strong reputations for conducting design research in their mechanical engineering departments.

University	**How design is defined within the Mechanical Engineering Ph.D.**
Brigham Young University	"Design: Engineering design affects everyday life - everything around us has been designed. Design involves the systematic interplay between creation and validation with the intent to bring useful parts, products, or systems, to the marketplace. Researchers in engineering design develop theories, methodologies, and tools that improve the design process and bring new capabilities to the hands of the mechanical designer. This includes computer aided engineering, systems design, product development, numerical and optimization methods, and the integration of engineering with other disciplines."
Clemson University	"Design: Research in the area of design spans a wide variety of activities ranging from early-stage customer needs assessment and ideation to design embodiment, detail design and optimization, to Design for X topics (Design for Manufacturing, Design for Sustainability, Design for Environment, etc.)."
Oregon State University	"Design Engineering Research: Design is the area of engineering which most distinguishes it from the sciences. Our research focuses on understanding and improving the process of design in order to facilitate the creation of new products and technologies."
Pennsylvania State University	"Product Design & Manufacturing: The product design and manufacturing (PDM) research supergroup focuses on fundamental research and advancements of design methodologies and manufacturing processes of smart-enabled devices. Areas of interest include but are not limited to: Additive Manufacturing, Hybrid Manufacturing, Engineering Design Methods, IoT-enabled, Smart Devices, Design for X (DfX), Human-machine Systems, Interdisciplinary Design."

4 Preliminary department focus groups

After conducting this preliminary review of mechanical engineering PhD programs in the U.S., leadership within our mechanical engineering department agreed that it would be

worthwhile to investigate the possibility of adding a design focus area to the PhD program. We then organized a series of rapid focus groups with faculty to identify beliefs and conceptions about design in mechanical engineering, and gather feedback regarding the possibility of adding a PhD focus area.

4.1 Method for focus groups

Focus groups were conducted at the department's annual retreat held in-person in January 2024. During the retreat, faculty and staff were organized into groups of 3-6 and rotated through a series of five 30-minute breakout sessions. One breakout session, organized by us (the authors), was titled "Hands-on learning and design education across M.E." The session focused on broadening industry interaction, enhancing hands-on activities, and identifying beliefs regarding design at the PhD level. To gather feedback regarding the possibility of a design PhD focus area, we asked participants: *What are the perceived benefits and concerns for adding a design PhD research focus area?*

We held the breakout sessions in a conference room with whiteboards. Participants were given sticky notes and pens to write down their thoughts and reactions to the three discussion topics. During the sessions, we facilitated and moderated discussions to ensure that all three topics were covered during the allotted time and that all comments were captured onto sticky notes and clustered on the corresponding whiteboard (pertaining to discussion question 1, 2, or 3). Across the five breakout sessions, we engaged with one staff member and 22 faculty members (representing roughly one-third of faculty in the department), including teaching faculty, research faculty, and tenure-track faculty across all existing focus areas as defined by the department (Table 1).

4.2 Findings from focus groups

In the focus groups, we asked the question: "What are the perceived benefits and concerns for adding a design PhD research focus area?" Overall, we received strong support from faculty members across the department to develop a specific design focus area, with only one faculty member indicating an objection to the idea. A variety of benefits and concerns were highlighted, as described in Table 4. Many of the concerns were presented as questions for further consideration if the department moves forward with adding a design focus area.

Table 4: Findings from focus groups with faculty members from CU Boulder's mechanical engineering department: Perceived benefits and concerns with adding a focus area in design for the PhD program

Perceived benefits	**Perceived concerns**
● There is already a design track in the MS program, this would create a stronger link across the graduate students ● Highlighted as "invaluable" for the department, better systemic design knowledge within the department (potentially more collaborations within the department)	● What is the job market for after they graduate? We need to clarify the specific outcomes and skills for graduates of this track ● Are the current PhD requirements (e.g., course work, preliminary exams) flexible enough?

● More diversity of backgrounds in the department, might lead to more interdisciplinary research experiences for students ● Could help the department have an "eye for the future" since design is a rapidly evolving and maturing field ● Students want this research area ● Could lead to collaborations across other departments ● Design for Manufacturing (DFM) is increasing, would be helpful to include this as part of the focus area ● American engineering industry has PhD design needs	● Would students struggle in more "traditional" ME courses? There are potentially more diverse backgrounds to accommodate for. ● We would need to differentiate from other programs on campus that offer design focuses (e.g., information sciences) ● We might not have enough tenure track faculty focused on design, do we need more to make the focus area successful? ● How do we define what is design and what is not? ● One individual: "you can't do a PhD in design, it's too broad"

5 Discussion & Next Steps

Overall, findings from the preliminary review and focus groups have led the department of mechanical engineering at our university to pursue the development of a focus area in design for the PhD program. Preliminary evidence indicates that design, including theories and methodologies for creating artifacts, is a fundamental area within the mechanical engineering discipline. Next steps include gathering targetted feedback from faculty in the department who conduct design research to develop and finalize the required materials for focus areas in our department; these include: (1) one-paragraph description of the focus area and (2) list of "strength areas" within the focus area. To ground the interviews and gather feedback, we have developed a first draft of these materials:

Initial draft of the design focus area description:

> "Research in design involves the scientific study of the creation of artifacts and their embedding in physical, social, psychological, economic, political, and virtual environments. This area of research within Mechanical Engineering aims to advance the practice and pedagogy of design engineering, including understanding the people who design solutions and those who use them, the processes and methods of designing, and its effect on engineered solutions and outcomes within society."

Draft of area strengths within the design focus area:

- **Design Theory and Methodology:** Underlying science of processes that designers use to develop engineering solutions
- **Computational Design and Optimization:** Development and use of technology to visualize, analyze, and make decisions during design processes
- **Systems Engineering:** Multi-disciplinary approaches for the design and operation of complex systems within their broader socio-technical environments.
- **Engineering for Sustainable development:** Development of design methods and processes to meet the needs of the present without compromising the ability of future generations to meet their own needs.

- **Design for Manufacturing:** Methodologies and processes for designing parts, components, and products for ease of manufacturing and product realization.
- **Inclusive & Human-Centered Design:** Methodologies and processes that place stakeholders at the heart of the design process in an effort to create solutions that understand and enable people of all backgrounds.
- **Design Education:** The teaching and learning of design knowledge and skills.

5.1 Limitations and areas for further research

This manuscript describes our ongoing work to develop a focus area in design within a mechanical engineering PhD program. The findings presented are limited in a variety of ways. First, our preliminary review of mechanical engineering PhD programs was limited to programs based in the U.S. Future research should investigate how design is defined in other global regions, such as in Europe, which has a strong history of design graduate education. We also only reviewed mechanical engineering programs; we would likely uncover insights from the ways other disciplines describe and define design. Importantly, we have not yet investigated how industry defines and conducts design research; future work should investigate the career pathways and opportunities for design PhDs post-graduation outside of academia. Moreover, our review was not systematic; for the sake of time, we focused on the top 12 highly-ranked mechanical engineering graduate programs, as well as the universities that we knew were strong in design.

It is important to note that the term design holds many meanings and interpretations. It can be a verb (“to design”), noun (“the final design”), or adjective (“a designed object”). In this work, we did not investigate alternative terms or phrases that might mean design, and we did not investigate the boundaries of what design *is* or *is not*. Future research should look into the breadth of definitions and interpretations of design within the mechanical engineering discipline.

References

Angeles, J., Britton, R., Chang, L., Charron, F., Gregson, P., Gu, P., Lawrence, P., Stiver, W., Strong, D., Stuart, P., & Thompson, B. (2004). The engineering design competency. *Proceedings of the Canadian Engineering Education Association (CEEA)*.

Atman, C., Borgford-Parnell, J., McDonnell, J., Eris, O., & Cardella, M. (2014). Engineering design education: Research, practice, and examples that link the two. In *Cambridge Handbook of Engineering Education Research.* Cambridge University Press, Cambridge, UK, pp. 201-228.

Barbieri, E., Vaidyanathan, V., & Petersen, O. G. (2012). On engineering technology education: BS to PhD. *Journal of Engineering Technology*, 29(2), 20.

Breiing, A., Engelmann, F., Gutowski, T. (2009). Engineering Design. In: Grote, KH., Antonsson, E. (eds) *Springer Handbook of Mechanical Engineering*. Springer Handbooks. Springer, Berlin, Heidelberg.

Cross, N. (1982). Designerly ways of knowing. *Design Studies*, 3(4), 221-227.

Davis, D. C., Crain, R. W., Trevisan, M. S., Calkins, D. E., & Gentili, K. L. (1997). Categories and levels for defining engineering design program outcomes. *American Society of Engineering Education Annual Conference*.

Hubka, V., & Eder, W. E. (2012). *Design science: introduction to the needs, scope and organization of engineering design knowledge*. Springer Science & Business Media.

Lee, N. (2009). Project methods as the vehicle for learning in undergraduate design education: a typology. *Design Studies*, 30(5), 541-560.

Meyer, M. W., & Norman, D. (2020). Changing design education for the 21st century. *She Ji: The Journal of Design, Economics, and Innovation*, 6(1), 13-49.

Papalambros, P. Y. (2015). Design science: why, what and how. *Design Science*, 1, e1.

Redström, J. (2020). Certain uncertainties and the design of design education. *She Ji: The Journal of Design, Economics, and Innovation*, 6(1), 83-100.

Simon, H., 1969, *The Sciences of the Artificial*. MIT Press.

Turns, J., Adams, R., Linse, A., Martin, J., & Atman, C. J. (2004). Bridging from research to teaching in undergraduate engineering design education. *International Journal of Engineering Education*, 20(3), 379-390.

Voûte, E., Stappers, P. J., Giaccardi, E., Mooij, S., & van Boeijen, A. (2020). Innovating a large design education program at a University of Technology. *She Ji: The Journal of Design, Economics, and Innovation*, 6(1), 50-66.

Winter, R. (2008). Design science research in Europe. *European Journal of Information Systems*, 17(5), 470–475.