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Distilling Sustainable Design Concepts for Engineering Design Educators*

JORDAN NICKEL, P. ROBERT DUIMERING and ADA HURST
Department of Management Sciences, University of Waterloo, 200 University Ave W, Waterloo, Ontario, N2L 3G1, Canada.
E-mail: jnickel@uwaterloo.ca

Sustainability and sustainable design have been a part of design discourse for over three decades, yet most designs today remain unsustainable. The size, complexity and at times redundancy of the literature on both sustainability and sustainable design have become barriers to the integration and acceptance of sustainable design within industry and education. This paper attempts to uncover an underlying structure to the literature and distill key concepts for engineering design educators interested in teaching sustainable design. The paper also synthesizes key attributes and skills common within sustainable design approaches to provide guidance for educators.

Keywords: sustainability; sustainable design; design education; engineering education

1. Introduction

Design is a tool and approach that humanity has used to shape nearly every aspect of its existence, whether consciously or not [1]. Design has been used in some form to develop most of the products, services, systems, and infrastructure people utilize today. This has the unfortunate effect of intrinsically linking design with the negative impacts of its outputs, which today include climate change, resource scarcity, waste accumulation, and the degradation of social infrastructure [2–4]. Despite decades of calls from researchers and experts to chart a more sustainable path forward, too little has been done to reduce negative impacts of society on environmental and social systems [3, 4]. However, the intrinsic link between design and the impacts of its outputs can also be harnessed to mitigate, eliminate, and potentially even reverse the effects of overconsumption. The volume of literature in the fields of sustainability, sustainable development and sustainable design can be daunting and has been an impediment to design educators desiring to implement sustainability concepts within their curriculum. This paper attempts to distill some fundamental concepts and definitions of sustainability and their operationalization within design to facilitate the incorporation of sustainable design into engineering design education.

The rest of this paper is organized to include the following sections: a review of the background literature on defining sustainability; an assessment of how design for sustainability approaches operationalize sustainability in the context of design; a discussion of the importance and relevance of sustainable design to engineering education, followed by a synthesis of common learner attributes and skills identified within the design for sustainability approaches reviewed; and finally a brief review of teaching techniques and pedagogical approaches recommended by the literature.

2. Background

2.1 *Defining Sustainability*

2.1.1 *Roots of Sustainability*

Sustainability refers to the ability of some attribute, process, or output to be maintained at a certain rate or level [5]. The term was initially used in the environmental context to describe the maximum rates of renewable resource extraction that could occur without threatening the integrity of the ecological cycles renewing those resources [6–8]. It is intrinsically tied to the concept of resource scarcity, and like the study of economics, seeks to reconcile the desire for increased quality of life with this scarcity. Reflecting this connection with scarcity, the term sustainability is typically combined with the term development to capture the sustainability of continually improving quality of life for people around the world. In the aftermath of WWII the concept of development, specifically economic development, was used to refer to improving material well-being indicated by increased flows of goods and services, and growth in per capita income [9]. However, the goal for increased economic development to Western standards around the world came with the predicted increase of resource usage beyond the carrying capacity of planet Earth [10].

2.1.2 *The Brundtland Report Definition*

In response to this perceived unsustainability and its conflict with the desire for increased economic development in many areas of the world, the UN

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World Commission on Environment and Development, commonly referred to as the Brundtland commission after its chairperson, defined sustainable development in 1987 as *"development which meets the needs of the present without compromising the ability of future generations to meet their own needs"* [11, p. 41]. The Brundtland report's concept of sustainability has been clarified into four primary dimensions: safeguarding long-term ecological sustainability, satisfying basic human needs, and promoting intragenerational and intergenerational equity [12, 13].

The first dimension – safeguarding long-term ecological sustainability – has two justifications within the Brundtland definition: the anthropocentric justification that for humans to continue to meet their basic needs indefinitely, Earth's natural systems must be conserved; and the moralistic justification that there is an obligation to other living beings and future generations [13]. It is these two justifications that form the basis for the other three primary dimensions.

Satisfying basic human needs is the basis for the development within sustainable development. Basic needs can be described using various frameworks such as Maslow's and Max-Neef's hierarchies [14, 15], or the Brundtland report's own list, which includes employment, food, energy, housing, water supply, sanitation and health care [11]. While the focus on basic needs does not preclude living standards that provide for more than basic needs from being sustainable, they are only considered sustainable if these living standards meet the first principle of assuring long-term ecological sustainability [13].

The last two primary dimensions – intragenerational and intergenerational equity – stem from interpersonal justice. *Inter*generational equity is an extension of the current protections granted to vulnerable populations as future generations cannot vote or speak out, have no political or financial power, and can not actively challenge the decisions made by the current generation [11, p. 8]. It stems directly from the original Brundtland definition's concern with sustaining the ability of future generations to meet their needs using the natural resources provided by our planet. *Intra*generational equity follows from the logic that underpins intergenerational equity, in that if the capacity of future generations to meet their needs is worthy of concern then so is the capacity of current generations [11, p. 43].

Further secondary dimensions of sustainability, subordinate to the primary dimensions, have been identified, which include preserving nature's intrinsic value, promoting protection of the environment, promoting public participation and satisfying aspirations for an improved standard of living [13].

Despite being the core of most sustainable development discourses, the vagueness within the Brundtland definition has been criticized for being open to interpretation, which has facilitated claims of sustainability by companies and products based on specifically selected metrics while their underlying nature remains unsustainable [7, 16].

2.1.3 The 3 'Pillars' of Sustainability: People, Planet and Profit

The definition of sustainability provided by the Brundtland report has been clarified to include what are now accepted as the three "pillars" of sustainability: society, environment, and economy [17–19]. Sometimes referred to as people, planet and profit, their inclusion has been used to distinguish sustainable development from other approaches to environmental protection and social justice, as sustainability takes a more holistic systems approach to measuring success.

These pillars both unite different definitions of sustainability and differentiate sustainability from other ways of looking at environmental and social problems. From a sustainability perspective, none of these three has priority over the others [20]. For example, neither economic growth nor social development are allowed to ignore ecological affects, or conversely environmental preservation cannot take associated economic or social impacts for granted [6].

2.2 Operationalization of Sustainability

By adopting such a broad scope, sustainability has been criticized as being an umbrella term for anything good or desired in society [7, 13]. Like the concepts of democracy, liberty or social justice, sustainability can be considered a contested concept [7]: universally desired, diversely understood, and extremely difficult to achieve [21, p. 26].

Being a contested concept means that sustainability is normative and complex, and the definition has two levels of "meaning". The first level of meaning is vague but generally accepted. This first level is where the Brundtland definition lays and has reached a rough consensus. The second level is where the diversity of interpretations arises, where methods of operationalization and implementation are determined.

This paper sets out to assess the different ways sustainability and sustainable development goals have been operationalized in the context of design. As design and its outcomes have such an intrinsic tie to the general global trend towards unsustainable outcomes, there have been many attempts over the years in both academia and industry to operationalize the goals of sustainability in the activity of design.

The various approaches to sustainable design discussed in the literature can be roughly classified according to three main levels: frameworks, methodologies, and tools. Further, each approach can be classified according to its generality, depending on whether it was developed for sustainable design in general, or for application to specific domains or problems. Table 1 presents some examples from the literature arranged along these classifications.

2.2.1 Frameworks for Sustainable Design

At the framework level, approaches primarily attempt to operationalize a definition of sustainability for design, so that approaches at the lower levels can work towards these definitions of sustainability. A key distinction between frameworks and methodologies is that frameworks do not provide procedural guidance to designers. Examples of this type of approach include the Framework for Strategic Sustainable Development (FSSD) and the 9 Principles of Sustainable Engineering from the Sandestin declaration [23, 28–31]. At this level, frameworks can still be quite vague and overarching, with the intent being to maximize generalizability.

For instance, the principles of the FSSD outline desired outcomes for sustainable design through eight axioms that define what makes a society sustainable [29, p. 23]. The first three axioms operationalize the environmental aspect of sustainability by stating that nature must not be subjected to systematically increasing concentrations of substances from the Earth's crust, waste by-products, and physical destruction. The remaining five axioms operationalize the social aspect of sustainability by stating that people must not be subjected to structural obstacles to health, influence, competence, impartiality, and meaning making.

Other approaches at this level include concepts like Design for Sustainability (DfS) [32, 33] and Design for Circular Economy (DfCE) [25–27], which have evolved to also refer to collections of methodologies that reflect their particular operationalizations of sustainable design. DfS for example is an evolution from a previous approach called EcoDesign, but introduces a more explicit focus on all dimensions of sustainability instead of just the environmental impacts [32, 33]. DfS also prescribes an approach that questions the need for physical products and seeks alternative methods of satisfying needs [32].

Alternatively, DfCE operationalizes sustainability through the principles of the Circular Economy, focusing on the resource flows involved in design. Sustainable design under the DfCE framework involves "narrowing", "extending" or "slowing",

Table 1. Examples of sustainable design approaches

Level	Generality	Approach	Sources
Framework	General	Ecological Engineering	[22]
		Sandestin Declaration	[23]
		10 Principles of Sustainability (Engineers Canada)	[24]
		Design for Circular Economy (DfCE)	[25–27]
		Framework for Strategic Sustainable Development (FSSD)	[28–31]
		Design for Sustainability (DfS)	[32, 33]
		Product-Service System (PSS) Design for Sustainability	[34]
		Systems Design for Complex Societal Problems	[35]
		Ecodesign	[36, 37]
	Domain Specific	Social Sustainability for Urban Design	[38]
	Problem Specific	Principles for Sustainable Palm Oil	[39]
Methodology	General	Method for Sustainable Product Development (MSPD)	[40]
		Methodology for PSS Innovation (MePSS)	[41]
		Systemic Innovation for Sustainability (SCENARIO)	[42]
		Multilevel Design Model (MDM)	[43]
		Design of Eco-Efficient Services	[44]
		Sustainable Design Thinking	[45]
		Sustainable Product and/or Service Development (SPSD)	[46, 47]
		User-centered design for sustainable behaviour	[48]
Tool	General	Product Sustainability Index (ProdSI)	[49]
		Sustainability Footprint	[50]
		Sustainable Life Cycle Assessment (LCA)	[51, 52]
		Sustainability Compliance Index	[53]
	Domain Specific	Formal Indicators of Social Urban Sustainability	[54]
		Building Information Modelling (BIM) Sustainable Design Tool	[55]
	Problem Specific	Sustainability Indicators for Wastewater Treatments	[56]

and "closing" resource flows. Designing for narrowing of resource flows entails improving the resource efficiency of products and production, which is not unique to DfCE and appears in other approaches like EcoDesign [57]. Designing for extending or slowing of resource flows targets extending product lifespans by improving durability, reliability, consumer attachment, ease of maintenance and repair, upgradability and adaptability [57]. The last focus of DfCE is the most unique to its framework, which is the concept of closing resource flows through biological and technological cycles [57].

2.2.2 Methodologies for Sustainable Design

Approaches at the methodology level are more structured than those at the framework level and provide specific guidelines and often stepwise procedures for designers to follow with the goal of creating sustainable design outcomes. Examples include the Method for Sustainable Product Development (MSPD), the Sustainable Product and/or Service Development (SPSD), and the systemic double-flow scenario method for companies (SCENARIO) [40, 42, 46, 47].

As an example, the SCENARIO approach guides designers through a multi-step workshop process covering topics such as the analysis of interactions between the environment, society and economy in relation to a company's products or services; developing a vision that mitigates sustainability risk; exploring scenarios to identify necessary changes; and preparing an action plan to achieve the vision [42, p. 107].

2.2.3 Tools for Sustainable Design

The final level identified in the literature includes specific tools that facilitate and support designers' attempts to design sustainably, such as life-cycle assessment (LCA), product sustainability indicators (PSI), and the sustainability compliance index (SCI) [53, 54, 56, 58, 59]. These approaches do not define complete design methodologies, but often reflect the assumptions and definitions of higher-level approaches that they were built to support.

An example of this can be seen with the development of LCA. Initially developed to support green design and Ecodesign approaches, most implementations of LCA do not consider the social impacts of sustainability [58]. Attempts to incorporate social impacts into LCA tools have struggled due to the difficulty of quantifying many social impacts into dimensions that can be analyzed alongside economic and environmental impacts [52].

2.2.4 Generality of Sustainable Design Approaches

In addition to the level of approach, prescriptive sustainable design approaches can also be classified by how general or specific they are to certain domains and types of design problems. A large portion of the approaches (e.g., DfS, LCA, SPSD, etc.) attempt to have some level of generality, so that designers can apply them to many design problems, while others are developed specifically for application in certain domains or even specific design problems. An example of a domain-specific approach is the attempt by Dempsey et al. [38] to define social sustainability in the context of urban design, while a problem-specific approach may look like Muga and Mihelcic's [56] sustainability indicators for wastewater treatment. It is fairly evident that the latter's indicators are highly specific to wastewater treatment and would provide little guidance to designers outside that domain.

2.3 Other Classifications and Validations Of Sustainable Design Approaches

In response to the plethora of approaches developed in academia and industry there have also been attempts within the literature to compare and validate the sustainable design approaches. See the following for examples of reviews that have classified and compared sustainable design approaches within the frameworks of DfS [33, 60–62], EcoDesign [63], Sustainable Product-Service System Design [64–67], and DfCE [57, 68].

2.3.1 Technocentric vs. Ecocentric Sustainable Design Approaches

In addition to the level and generality of the approaches, the sustainable design literature also plays host to a debate on whether to target changing consumption patterns to lower impact or to reduce the impacts of current consumption patterns (typically through improved knowledge, technology or organization) [69]. These two categories of approaches have been referred to as eco-centric (alternatively, human need centered) versus techno-centric (or innovation centered) approaches respectively [70, 71].

While it is likely that a combination of both ecocentric and technocentric approaches will be necessary to successfully transition to a sustainable society, the technocentric approach is more susceptible to the rebound effect, whereby efficiency improvements lead to increased consumption and a larger overall impact despite the shrinking individual impact [72, 73]. The interventions designers create to make these improvements can vary in scope from redesigning existing products to developing entirely new life-styles, and as the scope and complexity of the design project grows so do the potential sustainability gains [71, 74, 75].

2.3.2 Attempts to Validate Sustainable Design Approaches

Finally, a growing body of work attempts to validate various sustainable design approaches. This typically takes the form of case studies, as the case study research method lends itself well to the complex and diverse nature of sustainable design projects [76]. Other forms of empirical validation such as experiments typically suffer from a lack of external validity due to the difficulty of replicating the conditions of design problems within an experimental setting [77]. However, the nature of case study research means that determining an empirically validated best approach to sustainable design has not been possible.

3. Implications for Engineering Design Education

3.1 Why is Sustainability Important to Design Education?

Critics of sustainable development and its perceived costs point to an alternative path to solving the ecological and social problems plaguing the world within the current paradigm. They argue that humanity will solve these problems through technological advancement and traditional economic development [6]. This is predicated on the assumption that improved products, services and infrastructure will reduce, eliminate or even reverse humanity's impact on the planet and that continued economic growth will raise the quality of life for all people globally.

While the technologies of the future cannot be accurately predicted, and there exists a potential for a technological solution to some of these issues, it is imperative that an increasingly active sustainable course be plotted to hedge against the catastrophic consequences if business-as-usual methods do not or cannot result in a sustainable society. The precautionary principle adopted by the 1992 Rio Convention [78] and the European Community Treaty [79] supports such a proactive approach, arguing that when there are threats of serious or irreversible damage, the lack of complete scientific certainty and consensus should not be used as a justification for postponing cost-effective measures to prevent environmental degradation.

The precautionary principle applied to design ethics would provide guidance to the role of design in a more sustainable world [73, 80–83]. The impetus for active engagement of designers with sustainability also derives from this principle as a response to the clear and pressing risks of the current production and consumption paradigm. Designers should be held responsible for the impacts and effects of their designs, as they introduce these designs into the world and shape the impacts of those designs through their design decisions.

The engineering profession has enshrined the importance of safety into its professional ethics [84], licensing [85], accreditation [86], and in some instances legal regulations [85], and this concern for safety is structurally analogous to the precautionary principle in many ways. It follows from this commitment to public safety that engineers and designers should also accept responsibility for the broader, more holistic safety of the public with respect to the impacts of their designs [24]. As some of the crises resulting from unsustainable consumption threaten lives, properties and societal institutions, there should be an ethical imperative upon designers to reduce or eliminate the unsustainable impacts of their designs.

Incorporating sustainability into engineering and design education is both an imperative and a boon for engineering education [87, 88]. Future engineering and design professionals will be responsible for developing the technologies, systems and services needed to transition to a sustainable society [89, 90] but today's graduates are not adequately prepared for the challenges involved [91, 92]. Barriers that have prevented the successful integration of sustainability concepts into engineering and design education include overcrowded curricula, indifference from faculty, limited faculty expertise and awareness, insufficient institutional motivation and support, and reservations about the normative nature of sustainability [93–95].

3.2 Common Skills and Attributes Required in Operationalizations of Sustainability

With a clear and pressing need to engage designers with sustainability, the multitude of definitions and operationalizations can often be an impediment to integrating sustainability into design education. This is compounded by the near impossibility of validating a single sustainable design approach as being the correct one. Furthermore, design problems are open-ended [96] and introducing sustainability considerations to design adds to the scope and complexity. These open-ended problems can represent a culture change within engineering education when compared to the well-defined problems with measurable and definable correct answers that comprise a large portion of most engineering programs [95].

In the interests of facilitating discussion and encouraging implementation within the engineering design curriculum, several common attributes and skills common to sustainable design operationalizations have been synthesized from the approaches summarized earlier in this paper. By focusing on common skills and attributes, educators can prepare students to engage with sustainable design in the field, regardless of what framework or methodology they or their firms choose to use. These skills and attributes fall roughly into the following categories: a systems approach, problem framing and reframing, interpersonal and communication skills, and domain knowledge. These attributes common to sustainable design approaches align well with previous attempts to develop sets of competencies for the incorporation of sustainable development into higher education in general [97–99].

3.2.1 Systems Approach

Common to all sustainable design approaches is an emphasis on extending the designer's perspective beyond just the design artefact in question, to also consider its interactions with the environmental, social, and economic systems in which it will function. Most approaches further advocate considering potential system interactions over the entire lifespan of the designed artefact, using terms such as lifecycle thinking, "cradle-to-grave" or even "cradle-to-cradle" in the language of Circular Economy. All of these perspectives involve taking a systems thinking approach to design, understanding that designs can be considered in relation to a larger system in which they operate, and that the larger system can have properties and impacts that emerge from the relationship between its constituent parts [100, 101].

3.2.2 Problem Framing and Reframing

Problem framing and reframing is the most design-specific key skillset that was distilled from the literature. Framing in design is the creation of a standpoint from which a problem can be understood and solved, which includes specific perceptions of the problem and a "working principle" that underpins the solution [102]. Sustainable design approaches require framing the problem in ways that focus on the need being satisfied instead of the design artifact itself. Also designated as "needs satisficing" or "functional thinking" within the literature, it entails the designer or design team focusing on meeting functional needs through whatever means best satisfies them [32, 47]. These means can cover the spectrum from traditional products, through product-service systems, to whole new social paradigms for consumption and needs satisficing. Designers can create more sustainable outcomes by re-envisioning and reinterpreting how users and consumers can meet their needs and desires without necessitating further increased resource consumption and waste outputs.

3.2.3 Interpersonal and Communication Skills

Interpersonal competences and communication skills are crucial to sustainable design due to a shift in thinking from solving problems to satisficing needs, the broad scope and scale of sustainability problems typically necessitating larger and more diverse design teams, as well as the need to engage stakeholders with new approaches to problems.

Shifting to a needs satisficing agenda will require designers to be better equipped to engage with users and stakeholders to identify what their real needs are. Approaches such as participatory design and codesign become more important when designing with a focus on meeting needs in ways that reduce environmental impact without negatively impacting quality of life or social structures.

Communication skills are also important for sustainable designers to be able to engage stakeholders crucial to the design's success. As many sustainable design approaches have the potential to involve the design of services, systems, and other non-physical product solutions to needs, designers need to have the necessary communication skills to get buy-in for these novel ideas from organizational, institutional, and societal gatekeepers.

3.2.4 Domain Knowledge

In addition to the other attributes discussed above, a designer needs sufficient domain knowledge in the relevant fields to understand and characterize the interactions their design will have with the environmental, social, and economic systems in which it will operate. Herein lies what is probably the biggest difficulty in teaching sustainable design, as the relevant domain knowledge will vary depending on the design problem in question. This is particularly challenging in the context of engineering education as many sustainability problems require transdisciplinary approaches supported by the social sciences and the humanities, which are subjects that engineers are typically uncomfortable with [103].

A way to approach this hurdle is through transdisciplinary design teams, relying on subject matter experts to provide the relevant domain knowledge. This reinforces the criticality of developing strong communication skills in sustainable designers and engineers to facilitate effective designing in the context of these transdisciplinary teams.

3.3 Pedagogical Approaches to Teaching Sustainable Design in Engineering Education

If the skills and attributes discussed above and elsewhere in the literature form the outcomes of sustainable design education, then the teaching techniques and pedagogical approaches are the process to instill those attributes in design students. There have been many attempts to incorporate sustainability values into design and engineering education, with varying degrees of success [104, 105]. Strategies range from adding sustainability topics to existing courses through to re-designing entire curricula with a sustainable underpinning [88, 106, 107]. The literature indicates that successful long-term integration relies on both top-down institutional support and bottom-up grassroots initiatives from both faculty and students [106, 108, 109].

Simply providing students with access to information about sustainability and sustainable design from textbooks or other sources is ineffective for instilling sustainable attributes, skills, and mindsets [104, 110]. It is necessary to engage the students with the real world context of the skills they are developing [111, 112].

A survey of case studies and implementations of sustainable design in education indicates that the preferred pedagogies are action-based learning through project-based courses, preferably interdisciplinary or transdisciplinary in nature, supplemented with experiential learning through field-based coursework, internships, site visits or other similar approaches [87, 105, 113–120]. Case studies can also help students connect theoretical knowledge of sustainable design principles and methods to real world contexts [121, 122].

4. Future Work

Sustainability has long been part of academic and popular discourses of design, and many frameworks, methodologies and tools have been developed. However, the implementation of sustainable design within industry and institutions has been slow. An area of research that warrants further exploration are the factors hindering widespread acceptance and implementation of sustainable design methods, both at an organizational/institutional level and at the level of individual designers.

There also exists a gap in the literature investigating what factors motivate designers to be more sustainable, how different motivating factors affect the sustainable approaches chosen and the relative success of those approaches. Further work also needs to be completed on whether instilling sustainability competencies and knowledge in engineering students actually leads to improved sustainability in their careers in practice, or if the normative nature of sustainability necessitates also instilling and teaching values.

Further research needs to study methods to successfully facilitate the successful integration of sustainability into established engineering design curricula. This is particularly important given the complexity of organizational change combined with the scale and urgency of some of the necessary changes.

5. Conclusion

Design has a goal of improving the quality of life through the meeting of needs. In this way, design is analogous to development, which is used to discuss well-being and quality of life at a national and societal level. Sustainable design is a crucial component in sustainable development, and as the anthropocentric pressures on the environment mount and the current economic paradigm strains social systems, the consequences of the current consumption and production system can no longer be ignored. Though design has contributed to the Western culture of consumption and bears its share of responsibility for the deterioration of environment and social structures, it also has the potential to mitigate those effects and create more sustainable products, services and systems.

Design educators play a crucial role in the transition to sustainable design, through the instilling of values, skills and attributes necessary to develop innovative and successful designers. While there are many definitions of sustainability and approaches to sustainable design, the majority share a limited set of common mindsets and aptitudes, allowing educators to prepare a foundation for their students to apply in practice.

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Jordan Nickel is a graduate student in the Department of Management Sciences at the University of Waterloo. His research focuses on requirement conflicts and trade-offs in design. Prior to entering academia, he has worked as a design engineer and consultant in a large variety of sectors including automotive, consumer apparel, building systems, manufacturing, and industrial electronics. He received a bachelor's degree in mechanical engineering from the University of Waterloo.

Rob Duimering is an Associate Professor in the Department of Management Sciences at the University of Waterloo. His research investigates social aspect of technical systems, as well as communication and cognitive processes in groups and organizations. Recent work includes field studies of product development decisions and team interactions, experiments on group problem solving and subjective probability, and applications of machine learning to improve medical information retrieval.

Ada Hurst is a Continuing Lecturer in the Department of Management Sciences at the University of Waterloo. Her research falls in the areas of design cognition, and design teaching and learning. She is interested in innovations in engineering design pedagogy and regularly teaches engineering capstone design courses. She received a bachelor's in electrical engineering, followed by master's and doctorate degrees in management sciences, all from the University of Waterloo.