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Teaching Design for Environment through Critique within a Project-Based Product Design Course*

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Future environmental regulations are creating new employment requirements within traditional engineering organizations. These organizations require recent graduates to have a strong handle on environmental issues related to new product development. Since mechanical engineering curricula are saturated with courses covering a broad spectrum of engineering fundamentals, there is little room to develop a separate course to teach principles related to sustainable product design. This manuscript presents a novel method for teaching Design for Environment (DfE) strategies within a mechanical engineering product design course through the use of expert critiques. The results from this study indicate that integration of a critique based module within an existing design project is an effective medium for teaching sustainable product design. Also, receiving feedback in the form of disruptive design critiques breeds innovative design modifications that lower the energy and carbon footprints of the design across multiple lifecycle stages. More importantly, the results indicate that after participating in this teaching module, students are more likely to apply the learned DfE principles within academia and industry.

Keywords: design learning; project critique; design for environment; contextual learning

1. Introduction

1.1 Motivation

Future regulations regarding stricter environmental standards for production systems may cause a paradigm shift in organizational culture from voluntary participation to compulsory compliance. To be prepared for these fundamental changes, engineering firms must hire new talent who are aware of the principles, methods, and tools that can mitigate the environmental impact of their products and production systems. In 2010, the American Society of Mechanical Engineers (ASME) conducted a large-scale survey of over 4,000 practicing engineers and engineering students regarding their views on the subject of sustainable engineering. As evident in the survey, 60% of the respondents expected that their organization's involvement in incorporating sustainable and/or green design specifications would increase in the coming year [1]. Additionally, 67% of the overall respondents suggested that, even currently, they are involved with sustainability or sustainable technologies. Related studies, however, have shown that recent engineering graduates lack the fundamentals to successfully engage in sustainable design thinking. The results of a worldwide survey of over 3000 engineering students suggested that the 'level of knowledge and understanding of environmental and sustainability issues by engineering students is not satisfactory and that relatively large knowledge gaps exist' [2].

To bridge this knowledge gap, there have been many educational initiatives aimed at providing opportunities for both undergraduate and graduate engineering students to study sustainability related issues and their relevance to engineering design [3]. In fact, the United States Environmental Protection Agency (USEPA) funded a research grant with the University of Texas at Austin, Carnegie Mellon University, and Arizona State University in order to benchmark efforts of American engineering programs to incorporate sustainability concepts into engineering curricula [4]. These efforts have been focused on the development of degree-level curricula [5–9], the formation of individual courses entirely centered on sustainability topics [10–12], as well as the incorporation of principles related to sustainability in already existing engineering courses [13–15]. To support similar initiatives, Purdue University created the Division of Environmental and Ecological Engineering (EEE) in 2006, in order to support all efforts and programs across Purdue's College of Engineering related to environmental and ecological engineering [16]. This manuscript presents one of these initiatives, which aims to incorporate Design for Environment (DfE) principles within a product design course via an expert-based critique module.

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In general, product design courses as well as capstone project requirements are meant to introduce various engineering focused conceptual design tools, such as quality function deployment (QFD), functional modeling and morphological matrices that industry requires for entry level design engineers [17]. According to Jonassen et al. (2006), most issues that industrial engineering teams face in real word scenarios are very rarely directly related to traditional engineering principles [18]. Soft design and management skills, such as teamwork, cost issues, market placement and problem identification are all vital considerations to launch innovative and successful products. Additionally, there has been a plethora of examples that alternatively motivate Project Based Learning (PBL) as a key enabler of engineering design learning [19]. These factors have become key drivers for engineering schools around the world adopting capstone and project-based courses for their students.

In the current education landscape, sustainability-related courses lack the necessary integration with traditional mechanical engineering courses and thus do not heavily transfer into engineering practice. Also, project-centered courses that embed sustainability topics are primarily focused on quite narrow issues such as waste treatment, sludge and water purification, and general urban infrastructure planning. Furthermore, their curricula are often not applicable for broad, knowledge-based engineers that require completing an extensive list of courses covering mechanical engineering fundamentals. The challenge here is to teach environmentally conscious principles at the course-level in a compact manner and, at the same time, be relevant across a variety of multi-disciplinary student projects. Thus, product design courses, in which students participate in diverse project types and topics, provide an appropriate medium to study teaching scenarios related to design for sustainability.

1.2 Literature review

Recently, there have been efforts directed at incorporating sustainable design principles into PBL engineering courses. However, most of these projects have been centered on important yet narrow environmental issues, such as water waste management, sludge treatment, and alternative or clean energy. For example, Hmelo et al. (1995) introduced sustainability-related problems such as chemical spill cleanup, impact reduction opportunities in sheet molding, and effect of chlorine use in lakes within an engineering elective for research study [20]. Steinemann (2003) developed a civil engineering course that involves student projects directly related to environmental auditing, developing energy and water conservation programs, sustainable landscaping, as well as other sustainability projects [21]. Schafer et al. (2007) conducted a sustainable engineering course with a central PBL module focused on solving the water provision crisis in a sustainable manner by bringing together research expertise in the areas of water treatment and renewable energy [12]. Bremer et al. (2010) introduced sustainability as a key driver in innovation and creativity through student group projects regarding erosion control, wind-energy generation, and energy distribution control of AC systems in automobiles [22]. Again, these projects demonstrate very important and relevant perspectives on dealing specifically with projects related to sustainability. On the other hand, these modified courses lack teaching general DfE (Design for Environment) strategies that can be applied to the design of any new product, processe and service. Also, since the project content is fixed for each group, the design space is significantly reduced and, as a result, design innovation as well as creativity is affected.

One method to seamlessly integrate a teaching module into a design course is through critique. Critique has been used in both a structured and a free-flowing manner to successfully coach students through project-centered courses and activities. Riggs et al. (1998) developed a CAD-embedded module that dynamically critiques a plastic design with respect to its complexity and manufacturability via injection molding [23]. Little et al. (2001) introduced a studio method for critiquing students' design exercises in weekly meetings as the studio leaders actively tracked each group's activities and progress [24]. Powers et al. (2009) assigned graduate engineering students as 'coaches,' who actively guided each team's design of an injection molding machine [17]. It was argued that incorporating design coaches allowed the undergraduate students to focus more on the engineering design aspects of their project. Sagun et al. (2007) implemented an online framework for both students and instructors to provide real-time critiques on detailed drawings [25]. It should be noted that there have been efforts in incorporating methods related to environmental sustainability within an already existing course. Yost and Lane (2007) developed a 'contemporary issues' module, which included an environmental assessment of students' engineering design capstone projects [26]. Chau (2007) implemented sustainable design thinking (e.g. utilizing recycled materials, undertaking impact assessments, minimizing waste, etc.) into team based civil engineering capstone design projects, such as the design of a footbridge [7]. To the best of the authors' knowledge, no studies have been conducted in which experts critique student projects specifically with regards to sustainability within a traditional product design course. This motivated the authors to supplement a traditional product development course at Purdue University (ME553: Product & Process Design) with a sustainable development learning module through the medium of design critique. The teaching module consisted of several surveys and an intervention by sustainable design experts, culminating in a redesign for sustainability assignment.

The critique module, in effect, introduces a contextual learning experience with regards to sustainable engineering while remaining in-line with each student groups' design process. Recognizing that students enter the product design course with preconceptions on DfE principles gathered from prior experiences, this teaching critique serves as an enabler of self-reflection. Competent performances are built, by dispelling some of these false concepts and introducing new factual knowledge. This is accomplished within a design project chosen by the students themselves. Contextualizing the learning process in such a manner, leads to increased levels of self-motivation, innovation and knowledge retention [27].

The following sections will describe this study and summarize the lessons learned from the effort.

2. Presentation

2.1 Course description

Product and Process Design (ME553), a graduate-level course in the School of Mechanical Engineering at Purdue University, has become a staple in the master's design program. The course caters to both on-campus and distance learning students. The off-campus students come from a wide spectrum of companies, representing the aerospace industry, the automobile industry and other major contributors to product development today. ME553 emphasizes on identifying existing market opportunities and developing innovative products addressing those specific needs. The course contains a mix of theoretical lectures as well as guest lectures that address specific topics pertaining to product development such as design innovation, creativity, product planning, supply networks, product platforming, among others. Accompanying each topic are various business reviews such as publications from the Harvard School of Business, the Sloan School of Management as well as insightful online open-source videos related to design.

Intricate to the course is a group project, in which each group conceptualizes, formalizes, and designs a product, process or service. Design principles such as Design for Manufacturing, Value Analysis and Design for Modularity learned throughout the course are meant to be incorporated into the design process for each project. All design activities are tracked throughout the semester via an online wiki module, hosted by GlobalHUB™ [28]. Data collection through a wiki module has been an effective teaching tool apparent throughout recent literature [29]. Throughout the course, student-teams regularly update their group wiki page with any decisions or progress made. Apart from the individual group, only the course instructors and teaching assistants can view each design wiki page. This measure ensures that the groups are not influenced by any other groups in the course. Data in the form of team dialogue, completed assignments, and any other team activities is mined from the wiki and analyzed, for use in this study.

Figure 1 details the timeline for the student group design project. The students are exposed to the wiki module in the first couple of weeks of the course. Following this, the class is divided into groups of 4–5 students. The on-campus groups are formed purely by student preferences, while there is moderation with regards to the distance learning groups. Next, each group is given a needs assignment which requires them to identify existing product opportu-

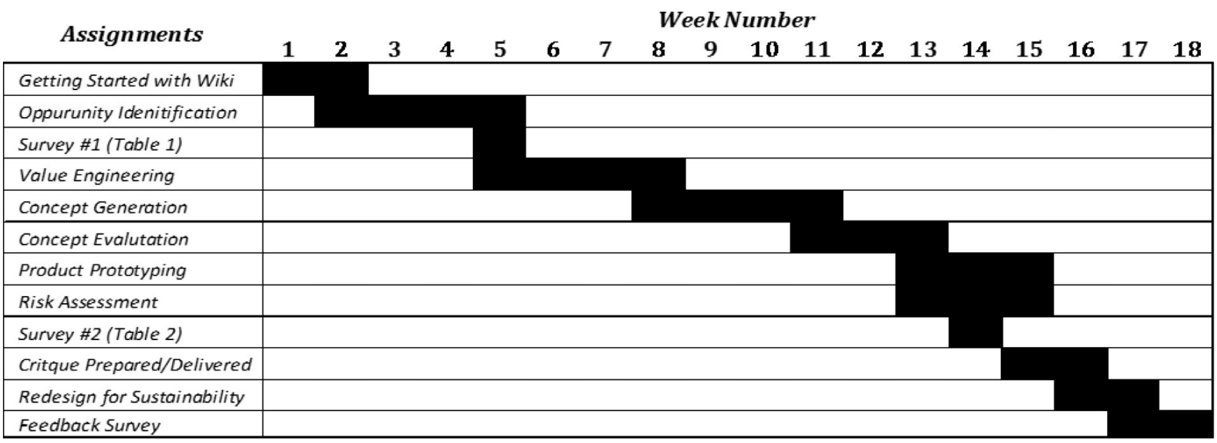

Fig. 1. Gantt chart outlining group project of ME553 including all critique module activities.

nities and rank each project choice by qualitative methods. After each design group chooses a specific project, the students are then put through a set of exercises that expose them to various tools and methodologies involved in the product design process, including value engineering, concept generation and evaluation, prototyping [30], risk assessment, among other auxiliary lessons [31]. The final stage of the design assignment involves a twenty minute presentation where the groups showcase their designs.

2.2 Critique module description

The main purpose of the critique module was to seamlessly incorporate a teaching module in regards to DfE within the ME553 course. The module consisted of three surveys handed out to the students as well as a project-specific critique conducted by two PhD students. The PhD students have extensive experience in research related to sustainable design, ecodesign tools as well as DfE principles, concepts and practices [32]. It should be noted that the ME553 students were unaware of the critique module until after finalizing their product designs. This was needed, to ensure that their preliminary designs were not biased towards incorporating more ecodesign concepts than what they would have in a regular project design course. Fig. 2 summarizes the pipeline for the present case study.

To gain a baseline understanding of the student's initial self-perceived knowledge of the broad topic of sustainability, an extensive survey of each ME553 student was conducted. The primary purpose of this survey was to track any irregularities or outliers in responses to the critique. In other words, if a particular group incorporated an unusual amount of DfE considerations throughout their design process before the critique, the survey might reveal that their experiences prior to their enrollment in the course could be a significant factor. The survey was based on a similar survey conducted in Azapagic et al. (2005) [2]. Table 1 includes the topics related to sustainability, in which each student ranked their respective knowledge on a Likert scale, i.e. 'never heard of it', 'heard of it but cannot explain it', 'average knowledge', 'significant (above average)

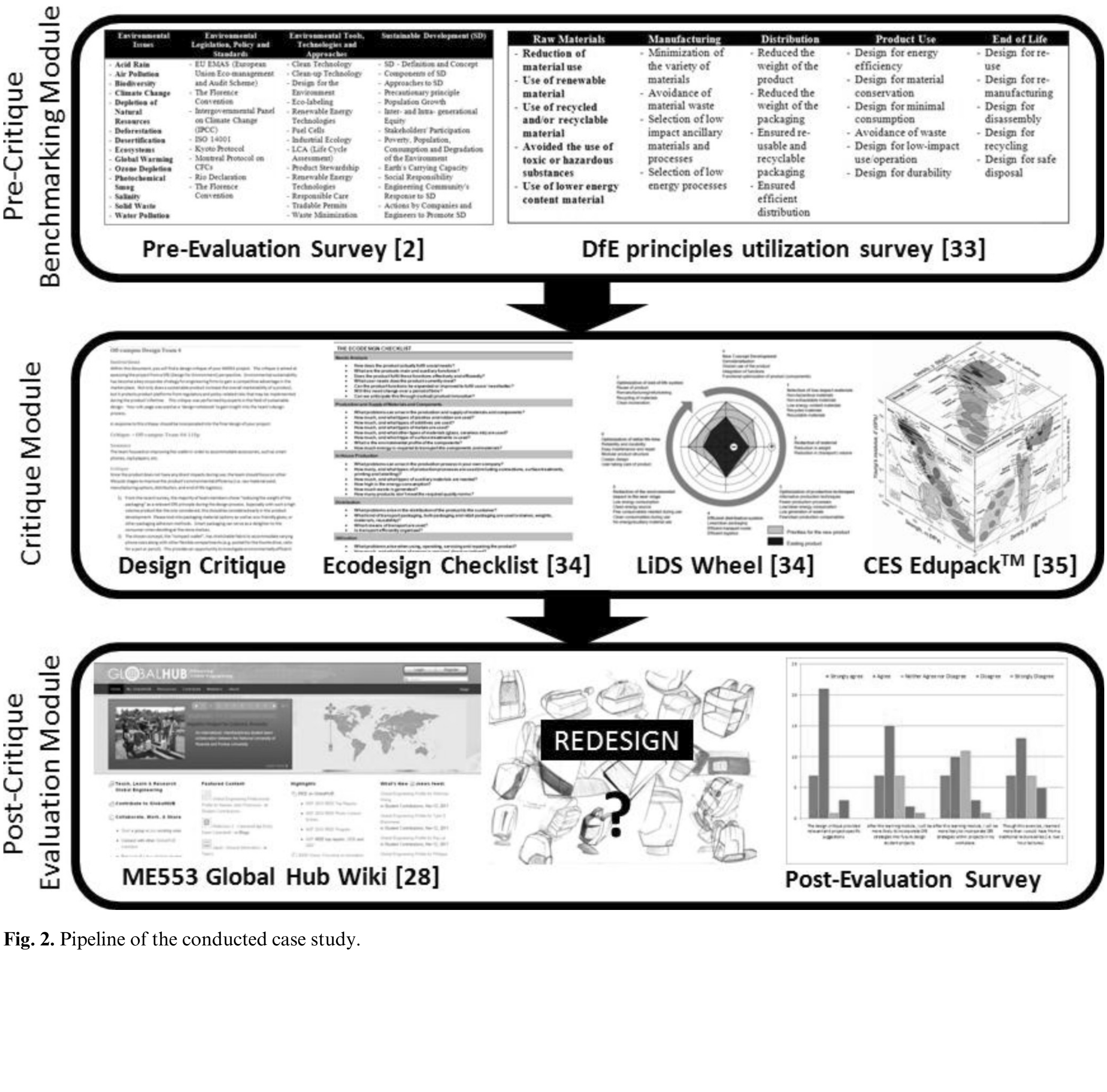

Fig. 2. Pipeline of the conducted case study.

Table 1. Covered topics in the pre-project survey to asses student's self-perceived knowledge of sustainability

Environmental Issues	Environmental Legislation, Policy and Standards	Environmental Tools, Technologies and Approaches	Sustainable Development (SD)
– Acid Rain – Air Pollution – Biodiversity – Climate Change – Depletion of Natural Resources – Deforestation – Desertification – Ecosystems – Global Warming – Ozone Depletion – Photochemical Smog – Salinity – Solid Waste – Water Pollution	– EU EMAS (European Union Eco-management and Audit Scheme) – The Florence Convention – Intergovernmental Panel on Climate Change (IPCC) – ISO 14001 – Kyoto Protocol – Montreal Protocol on CFCs – Rio Declaration – The Florence Convention	– Clean Technology – Clean-up Technology – Design for the Environment – Eco-labeling – Renewable Energy Technologies – Fuel Cells – Industrial Ecology – LCA (Life Cycle Assessment) – Product Stewardship – Renewable Energy Technologies – Responsible Care – Tradable Permits – Waste Minimization	– SD—Definition and Concept – Components of SD – Approaches to SD – Precautionary principle – Population Growth – Inter- and Intra- generational Equity – Stakeholders' Participation – Poverty, Population, Consumption and Degradation of the Environment – Earth's Carrying Capacity – Social Responsibility – Engineering Community's Response to SD – Actions by Companies and Engineers to Promote SD

knowledge', and 'expert in area'. The authors also plan to utilize the responses from this survey in comparing self-perceived knowledge towards sustainability with other student groups such as undergraduate students and student populations from other institutions for future work.

Before the critique, the students were also subjected to a project-specific survey during Week 14, when each groups' designs were conceptually mature. The intention of this survey was to estimate the number of specific DfE principles that the teams had incorporated into their preliminary material and manufacturing decisions and structural design embodiments. Here, the students were exposed to a list of DfE principles based on a compilation by [33]. Each team member was asked to input a 'checkmark' next to each principle if it was considered at any point throughout their design process. All DfE principles that were included in the survey can be seen in Table 2. This study enabled the PhD students' responsible for each team's critique to understand exactly how each design objective was carried out. Though the wiki provided most of the information necessary for the critique, additional comments and responses from each team member accelerated the general critique process. Additionally, if a DfE principle such as the use of renewable material was left unchecked by all team members, the critiquers identified the DfE strategy as underutilized, which further directed the critique.

Utilizing the second survey and the wiki content, each project was analyzed on the basis of each DfE principle in Table 2 and various methods to include more sustainable considerations into their design were suggested. There were 13 participating design groups, each comprising of 4–5 team members and totaling 57 participants. All projects analyzed were from off-campus groups, who attended each class via the internet. On-campus groups were excluded from the study for two main reasons. (1) In general, conditions on-campus throughout the course would be quite different considering that students might be more likely to pass ideas between groups before and after class. (2) Since many of the off-campus students currently hold engineering positions within industry, a more significant snapshot of how DfE

Table 2. Pre-critique survey contents

Raw Materials	Manufacturing	Distribution	Product Use	End of Life
– Reduction of material use – Use of renewable material – Use of recycled and/or recyclable material – Avoided the use of toxic or hazardous substances – Use of lower energy content material	– Minimization of the variety of materials – Avoidance of material waste – Selection of low impact ancillary materials and processes – Selection of low energy processes	– Reduced the weight of the product – Reduced the weight of the packaging – Ensured re-usable and recyclable packaging – Ensured efficient distribution	– Design for energy efficiency – Design for material conservation – Design for minimal consumption – Avoidance of waste – Design for low-impact use/operation – Design for durability	– Design for re-use – Design for re-manufacturing – Design for disassembly – Design for recycling – Design for safe disposal

principles are used within design teams could be assessed. In fact, some participants had over 10 years of relevant experience.

Each critique was written in paragraph form ranging from 3–4 pages, including five main design suggestions directly addressing survey responses and Wiki content from each team. Additionally, for every team, the critiques presented three commonly used tools in industry: (1) a URL link to a Granta CES Edupack^{TM}; an online material database with relevant information categorized for each material (2) an ecodesign checklist [34] that provides a list of questions that qualitatively assess different aspects of the design's lifecycle and (3) an explanation of how to use the Lifecycle Design Strategy Wheel (LiDS Wheel). The LiDS Wheel comprises of 8 criteria such as low impact materials, reduction of materials, low eco-impact production, optimize lifetime, optimize end-of-life system, etc., in which the designer is meant to score each concept on a 0–5 linear scale [34]. This tool was chosen because it was seen as an easy-to-use, quick way of qualitatively assessing any design changes, specifically for sustainability, the team had made. It should be noted that the 2011 version of Granta CES Edupack^{TM} offers qualitative recyclability, toxicity, biodegradability ratings as well as quantitative estimations for primary manufacturing energy consumption and carbon footprint data for all materials and their accompanying processes [35]. The students were asked to utilize such information to make decisive design modifications. Finally, all design modifications based on the critique were uploaded to each team's wiki page for assessment.

3. Discussion

Since there were a broad range of products that the teams focused on developing throughout the semester, the critiques themselves were quite different from one another. However, there were some clear trends that developed within the critiques. Eco-efficient material choice, which is possibly the simplest DfE principle to incorporate early in the design process, was a common theme throughout every critique. Depending on the specific project, biodegradable, recyclable, and/or renewable materials were suggested. It should be noted that the critiques did contain specific suggestions, but it was strongly encouraged to look through the CES Edupack^{TM} 2011 for any information relevant to material changes. This ensured that the students would learn how to use such a database through their own experiences.

One of the most common critiqued points was the DfE principle of selecting eco-efficient materials. This was mainly due to the fact that the ME553 focuses on front-end design principles especially relevant to concept and embodiment design such as functional requirements, customer requirements and product configuration rather than detailed design parameters such as manufacturing tolerances or production planning. Since the material makeup of possible components for most products is estimated early in design (i.e. during the concept and embodiment design phase), the groups were urged to conduct a deeper material search within Granta CES Edupack^{TM} 2011 so as to mitigate the energy and carbon footprint of their selections. Several groups substituted similar metals in order to lower carbon emissions and energy consumption. For example, upon referring to Granta CES Edupack^{TM} students realized that casting stainless steel consumes 427–472 kcal of energy per lb., while casting and aluminum consumes 256–283 kcal of energy per lb. Also, in terms of CO_2 content, casting stainless steel emits 0.236–0.262 lbs. of CO_2 per lb. material, while aluminum emits 0.142–0.157 lbs. of CO_2 per lb. of material. Though there are significant savings in terms of casting (nearly half in terms of CO_2 emissions and energy consumption), it should be noted that aluminum is not as eco-efficient compared with stainless steel when forging is considered. With regards to forging, stainless steel consumes 257–284 kcal of energy per lb. and emits 0.19-0.21 lbs. CO_2 per lb. material, while aluminum consumes 287–316 kcal of energy per lb. and emits 0.212–0.234 lbs. of CO_2 per lb. material. Design Group 7, substituted steel for aluminum in this case since there would be significant processing energy savings. The teams were thus motivated to analyze respective emission data and make tradeoffs between different processes, each with different energy and emissions outputs against varying mechanical properties of the corresponding materials. Each solution was case-specific and thus general rules or guidelines for 'eco-efficient' materials cannot be justified. Thus, on using the material database, students are able to analyze production considerations not only based on traditional decision factors such as batch size and cost, but also based on environmental considerations such as processing energy and emissions.

Aside from modifying the material makeup of the groups' designs, significant redesign was achieved specifically for material and component reduction. These DfE principles align strongly with Design for Manufacturing (DFM) and Design for Assembly (DFA) paradigms. Since graduate students, especially industry employed distance learning students are expected to have prior experience with DFM/DFA; it was of no surprise that material and component reduction was the most used DfE strategies before critique. After the critique, some of the teams revisited these design principles which lead to further reduction in the quantity of used material. For example, Design Group 3 integrated hooks with the main tub to the frame in their shopping cart design and redesigned the frame to achieve a 5% reduction in gross weight. Design Group 8 reduced the part count of their design by 67.4%. Some groups also focused on incorporating snap fit connectors to increase disssemblability. Reduction in part count and weight also improved the eco-friendliness of designs with respect to its distribution phase. Other redesigns presented different solutions to minimize environmental emissions during distribution, such as volume reduction (Design Group 9), biodegradable packaging materials (Design Group 1), and the development of recycling programs for used packaging materials (Design Group 10). Transportation within distribution of components and modules within the supply chain can also have a significant effect on the total environmental footprint of a specific product. Understanding the availability and location of outsourced modules can give a team insight into the possible emissions savings. Design Group 4, which developed a multi-functional mobile phone case which is an example of a simple, high-volume product, developed initial plans for in-house production to cut out an entire branch of a supply chain. Beyond mapping out preliminary supply chain plans, one team focused on reducing its product's envelope volume through structural changes. Design Group 8 significantly reduced its product's packaging volume by detaching the finger section of their hand assist tool and placing it inside the concave region of the sleeve, a particularity innovative solution.

Another common theme through the critiques was that the groups should develop some initial plans to enhance the end-of-life considerations of each of their products. There have been many studies throughout the literature that show how component and/or product takeback can be included in the early stages of design, e.g. [36–38]. Recyclable materials as well as remanufacturable and reusable modules are both design-relevant downstream considerations that can be implemented early, even at the concept design phase. It was strongly evident throughout the student's redesign projects that they incorporated end of life options throughout their design, post critiquing. Design Group 2 included appropriate labeling in the plastic mold design to influence customer recycling. The same team also constructed a comprehensive end of life scenario map detailing the material flow of each recyclable, reusable and disposable material. Design Group 4 identified specific components that will wear down before others and set-up a recovery system in order to institute a reuse program. Design Group 5 extensively investigated their product's structural modularity in order to increase its disassemblability. The group incorporated low profile castor wheels that can be easily detached along with adjustable and easily removable headrests and snap fit connectors on the chair's handles. Design Group 6 incorporated an in-house recycling program for safe disposal of both metal scrap from production, recovered metal and plastic components. Design Group 10 evaluated the economic feasibility of instituting distribution centers near their customers to coordinate recycling and reuse programs for the product itself as well as the packaging materials. Group 12 instituted a buy-back program where current users are given an incentive to return their worn-out gutter de-icing system.

One of the more surprising outcomes of the critique module was that the critiques seemed to spur innovative solutions to design problems. Low levels of innovation such as part reduction, volume minimization for better distribution, disassemblability considerations were apparent in many of the above mentioned projects (Design Groups 1, 2, 3, 5 and 8). Furthermore, one group in particular displayed significantly innovative thinking in their redesign approach. Design Group 9 developed a separate methodology based on a mind map on eco-design principles to conceptualize environmentally efficient design alternatives. Utilizing this method, the group improved their design with respect to several lifecycle phases: the use phase, distribution, and end of life (see Table 3). The group then generated a detailed sustainability report via SolidWorks Sustainabiltiy Xpress™, a commercial environmental assessment tool, which would be made available to the eventual customers of their product [39]. This serves as a strong example of how the critique module can fortify lessons learned throughout the course by combining with a newly presented concept, design for sustainability. In future work, the authors plan to enhance this critique module with specific suggestions that may spur design innovation based on the results of this study.

All pre-mentioned results from the critique module are summarized in Table 3. The table consists of two columns detailing the significant case-specific critique points and the team's significant design improvements. It should be noted that the students provided extensive redesign reports and this table merely serves as a 'snapshot' highlighting some of the lessons learned through the critique module.

To assess the critique module itself, a third and final survey was presented to the students. Each

Table 3. Summary of project critiques and design improvement

Team	Project Title	Significant Critiqued Points	Significant Design Improvements
#1	Windshield De-icing System	Primary focus should be on material minimization and introducing recyclable materials with regards to the design. Material homogeneity should be increased to aid in the product's recyclability. Energy waste in the form of heat losses during product's operation must be addressed. Map out the potential suppliers and their physical locations to get an estimate of the environmental cost of part supply.	Tubing material switched from 304L to 409-Stainless Steel. Reduced pipe thickness to save weight. Added Slag Wool insulation. Use of molded foam packaging against the earlier styrofoam alternative. Explored use of bio degradable peanuts for packaging. Substituted brazing with mandrel bending to reduce emissions.
#2	Multi-use tool	Investigate the incorporation of recyclable plastics in the design through the CES Edupack 2011. Also utilize this tool to get energy and emission estimations for specific manufacturing processes per material Include modifications within the design that will aid the disassembly of the product to enable takeback logistics (product labeling, modularity, etc.). Create preliminary plans for supplier selection based on geo-location on sustainability concerns.	Used adhesives to bind the magnets to the exterior shell in order to allow them to be removable and recyclable. Included appropriate labeling in the injection molding cavities for the appropriate recycling indications. Estimated the total lifecycle carbon footprint and the corresponding energy requirements. Constructed a comprehensive end of life scenario map.
#3	Hands-free shopping basket	Material choices of the body of the cart and the cage should be carefully examined. Use design for manufacturing principles to reduce the total part count thereby simplifying the supply chain, the assembly and the ultimate end of life logistics. Team needs to get a deeper insight into process and machine tool selection. Also consider whether the product can be reused or recycled after its useful life and incorporate the necessary modifications for making that option feasible.	Main body material content changed to 100% recycled polypropylene. Hooks and plastic tub were integrated to the cart base to shorten the supply chain and assembly process. Reduction in material through the use of natural rubber and 500D cordura. Incorporated multi-use plastic bags. Reduction of mixed material by reducing metal content in the cart to <5% of the gross weight.
#4	Mobile Phone Protector Wallet	Reducing the weight of the packaging or the method of distribution itself is a critical parameter in this design scenario. Look into packaging material options as well as eco-friendly glues, or other packaging adhesion methods. Use CES Edupack 2011, a material database to search for possible material substitutions with regards to embodied energy. Prepare plans on supply chain logistics and discuss whether the product can be reused or recycled after its useful life.	Analyzed custom 3D printing vs. Build and Ship type production models using LiDS wheel. Incorporated recycled materials into the original design. Setup a product recovery system for collecting worn products. Created service map to analyze typical product failures. Eliminated distribution phase impact by on site production of parts.
#5	Transfer Solution for Disabled Users	The most impactful phase with respect to this product would be the manufacturing phase. Investigate environmentally benign material options and their associated manufacturing processes. Discuss specific modifications to parts that allow simple switching out of parts to extend overall product life and the aspect of product modularity for enabling easy disassembly. Also detail the changes to the design that could possibly make the supply chain pathways more efficient and reliable. Review aspects of lean production especially the concepts of waste reduction and cost efficiency.	Used recycled polymers for injection / cast molding. The new manufacturing process considered a disassembly station that will also serve to receive returned parts. Used a Hybrid Injection Molding Machine for reducing processing energy. New process included 28% scrap metal in Aluminum die casting process. Considered modularity and ease of disassembly by use low profile castor wheels that are easily attached to the product, adjustable and easily removable headrests and by using snap fit connectors on handles.
#6	Lifting System for an overhead attic	Proactively examine environmentally benign material substitutions and manufacturing process selection within the design for reducing embodied energy and the associated emission. Detail the trade-offs in this process (e.g. weight reduction vs. embodied energy). Discuss selection of supply chain strategies especially the policy of 100% outsourcing vs. in-house production. .Consider whether the product (or some components) can be reused or recycled after its useful life.	Substituted Aluminum 6061 T6 with 304 Stainless Steel to lower processing energy. High Density Polyethylene (HDPE) used as primary plastic material to lower carbon footprint of injection molding process. Changed to vendors with local warehouses for optimizing material sourcing impacts. Lean manufacturing techniques used during both the vacuum forming process, and the steel forming for waste reduction. Incorporated in-house recycling for safe disposal.
#7	User friendly gasoline station	Make estimations of the average emissions saved by the new system compared with a traditional gas station. Use material databases that contain energy and emission estimations for various materials and gain understanding of LEED certification for building projects .Look into whether to pursue an alternative design with a much simpler robot, possibly 3 axes.	Utilized building space to generate green energy by mounting wind turbines on the roof of the building to generate power. Changed to EnergyStar rated electronic components and LEED certified building standards to reduce use phase footprint. Used steel overhead beams for support instead of aluminum to reduce processing phase energy requirements.
#8	Hand Assist Tool	The team is strongly advised to look into the CES Edupack Material Database to explore other material possibilities for addressing DfE. Detail changes that will allow for an energy efficient design to reduce power requirements during use and consequently increase battery life. Explore whether the product can be reused or recycled after its useful life and incorporate the necessary modifications for making that option feasible. Also look into how you can increase product reliability or minimize maintenance during useful life.	Integrated the indexing portion of the tool and the support between the end effecter and the sleeve eliminated the need of additional components. Further design for assembly reduced part count by 67.4% . Food grade silicone was used as a substitution for Torlon to reduce embodied energy. Life of the rotation section was extended, by completely sealing it to increase overall product life. Long-life, low degradation lubrication oil specified to be used in the sealed assembly. The shipping volume of the device was significantly reduced by detaching the finger section and placing it inside the concave region of the sleeve.

Table 3 (*continued*)

Team	Project Title	Significant Critiqued Points	Significant Design Improvements
#9	Pack Your Everything—Luggage System	Innovation in material selection should be looked into. Particularly, homogeneity in material will greatly increase the possibility of disassembly and also reduce cost and the manufacturing footprint. Discuss the incorporation of usage/disposal modes post failure of the product. The tradeoff between using RFID chips versus a GPS in the luggage system should be thoroughly analyzed. Optimizing the weight of the product is the most important criterion in this design.	Embedded RFID chips to be used instead of GPS system for tracking of the bag to minimize use phase energy consumption. Polycarbonate resins that are biodegradable were substituted by ones that are recyclable. Packaging was minimized to a thin biodegradable bag. Created a mind map based on eco design principles to aid innovative design solutions which are also sustainable. Generated a detailed sustainability report using SolidWorks Sustainability Xpress(TM) which is accessible to customers.
#10	Lift Device for Disabled Transfer	The key concern with the product is the emissions involved in the use phase. Discuss the following aspects as related to the design: 1) Optimizing the weight of the product 2) Reducing the weight of packaging 3) Ensuring sustainable transportation systems. Assess whether the product is setup for ensuring reuse or recycling after its useful life. This product has a strong potential in addressing issues of social sustainability. Coupling this aspect, with an environmentally benign product and a responsible supply model will help the product design address all the three bottom lines of sustainability.	Included standard preventative maintenance (PM) and organizational certifications such as ISO to ensure standard practices and continued improvement w.r.t environmental declarations and practices. Evaluated feasibility of distribution centers to coordinate recycling and re-use program and establish customer support system for recycling packaging materials. Ensured no residual harmful chemical emissions from product and establish halogen free development practices. Ensured minimized raw material waste by minimizing storage time and evaluating materials that have long storage factors. Allowed for device refurbishing though standard part availability.
#11	Assistive goods' transporting device	Consider whether it is better to use a recycled Aluminum steering frame for lowering embodied energy or entirely switching to plastic for the sake of material homogeneity with regards to DfE. Map out the potential suppliers and their physical locations to get an estimate of the environmental cost of part supply. As the device is not in constant use, would leasing the product through the supermarket be a more sustainable model? Discuss the concepts of material homogeneity, ease of disassembly, modular design for reuse and ease of maintenance as per the design.	Switched to recycled polyethylene fabric for top cover. Spokes switched to Nylon6/6 with 33% glass reinforced fiber from virgin Aluminum for material homogeneity. Overall product weight reduced by 3.06 lbs. Reduced the products' life cycle impact through use of the LiDS wheel.
#12	YETI—Gutter deicing system	Discuss the possibility for using clean of energy and recovering the latent heat of phase transformation of water. The team is strongly encouraged to estimate the energy intensity and the carbon footprint in their material choice. Estimate of the environmental cost of part supply. Look into economic models for incentivizing product take back. Please go through the attached ecodesign checklist to assess the possible areas of improvement and benchmarking the design.	Changed the primary manufacturing process to injection molding from extrusion to lower manufacturing phase energy use. Instituted a buy-back program where current users are given an incentive to return their worn-out gutter de-icing system. Heating cables are to be encased in the PVC, and run through the length of the gutter cover. Clips and support arms will be injection molded as well, lowering their embodied energy. Reduced the products' life cycle impact through use of the LiDs wheel.
#13	Sliding Refrigerator Shelves	The team is strongly advised to look into other material possibilities. There is a strong potential for innovative selection strategies. On the other hand constructing sliders from the same material as existing shelves greatly aides the cause for ease of disassembly and consequent recycling. Such trade-offs must be proactively considered by the design team. Choosing the right injection molding machine can have a significant impact on manufacturing energy consumption. The team should also consider whether the product can be reused or recycled after its useful life. Use the attached LiDS wheel to benchmark the design w.r.t DfE.	Used the LiDs wheel to benchmark their current design versus other feasible material/manufacturing combinations. No changes made to the existing design.

participating student was asked to assess the following four statements based on a Likert scale with the options: 'strongly agree', 'agree', 'neither disagree nor agree', disagree', or 'strongly disagree'.

(1) The design critique provided relevant and project-specific suggestions.
(2) After this learning module, I will be more likely to incorporate DfE strategies into future design student projects.
(3) After this learning module, I will be more likely to incorporate DfE strategies within projects in my workplace.
(4) Though this exercise, I learned more than I would have from a traditional lecture series (i.e. two 1 hour lectures).

As seen in Fig. 3, the results of the critique assessment survey were positive and the critique module proved as an effective teaching tool of DfE strategies. An interesting outcome of the survey lies within the difference of responses

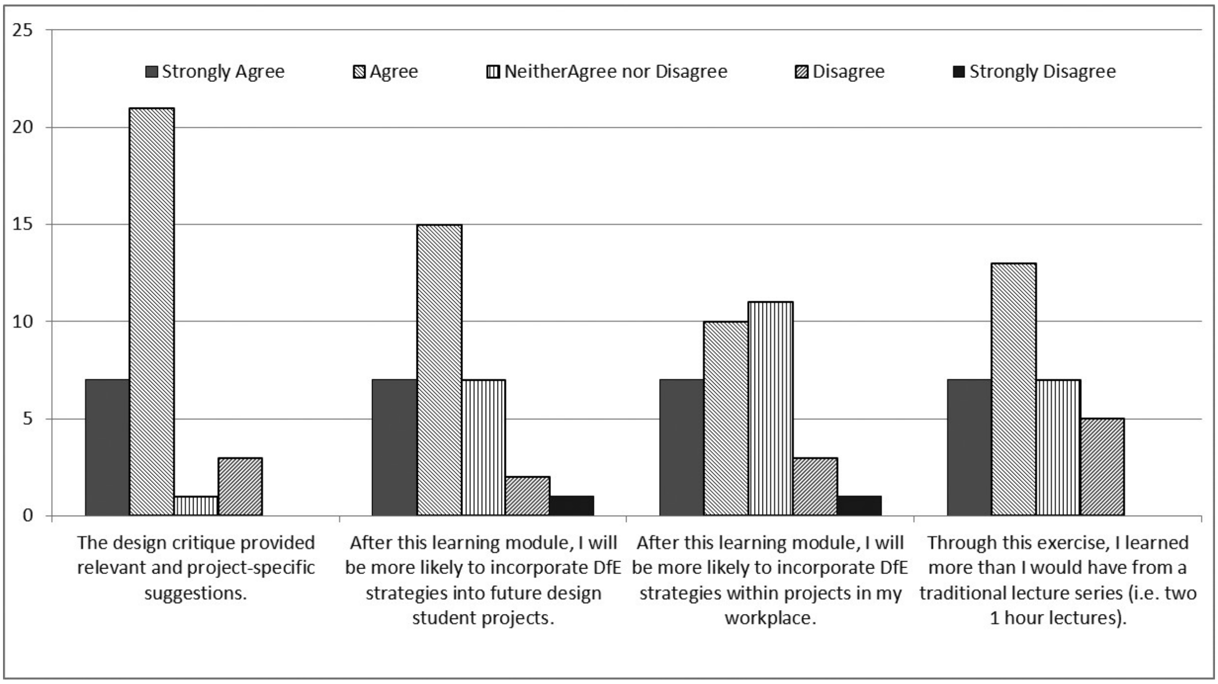

Fig. 3. Student Assessment of Critique Module.

between the second and third statements. As seen in the results, five more students agreed that they would be more likely to incorporate DfE strategies within academia compared with industry. This could be attributed to the front-end nature of the course. In most design engineering positions in industry, there are constant redesign related scenarios of subsystems within mature product platforms. Instituting radical changes of manufacturing and material considerations, for example, may be unfeasible in a real-world setting. Significant effects and risks within the supply chain as well as the customer experience would deter organizations from making such changes. It is also quite interesting to note that that the students generally agreed that the critique module was a more effective way of learning compared with a traditional lecture series. This provides a strong case for implementing similar critique methodologies on topics other than sustainability within other design related engineering courses. Instruction of secondary learning topics could utilize this general critique framework to embed these auxiliary lessons into a traditional course such as machine design. As mentioned before, the authors plan to continue this work by instituting an 'innovation critique' within a capstone design course.

4. Conclusions

The importance of training the next generation of design engineers in the context of sustainability and parallel issues (e.g. energy-efficient design, environmentally conscious supply chain) is increasing everyday due to end user demand. Therefore, developing new, effective learning scenarios about these key issues is vital. By participating in group projects related to product design, students develop problem solving abilities that can be translated to real-world scenarios. For this, students must apply more than one previously learned principle to produce a solution that can lead to the understanding of higher order principles of which he or she was formerly unaware [40]. By applying DfE principles in a project based setting, students not only develop the ability to reinforce their understanding of such principles through context, but they also translate this learning into subsequent real world design issues by repeated application. This effect is compounded, in the case of students already working in an industrial firm, as seen in the sample population in this study.

In this manuscript, a novel teaching methodology specifically for Design for Environment was presented. Utilizing project critiques by graduate student experts, a graduate-level product design course was supplemented with a redesign project with regards to sustainability. The results indicate that not only did students effectively make design modifications to lower the energy and carbon footprints of their design across multiple lifecycle stages, the teaching methodology led to design innovation. Results also indicated that after the teaching module, students will more likely to utilize learned DfE principles within academia and industry. Overall, the results of the study indicate that critiquing student projects within a specific context, such as sustainability, can be an effective learning strategy.

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