IMPLEMENTING DESIGN CRITIQUE FOR TEACHING SUSTAINABLE CONCEPT GENERATION

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ABSTRACT
Product design is one of the most important activities that can influence sustainability. Therefore, it is critical to educate students about these methodologies as they are the next generation of engineers. This paper details a study conducted among engineering graduate students for teaching sustainability through design critique. The students were part of a graduate level design course and were required to conceptualize designs of novel products. Upon completion of their designs, questionnaires which assessed their familiarity with sustainable design and its relation to product design were handed out. A team of design experts reviewed the final design concepts along with these questionnaires and offered a detailed design critique focused on redesign with regards to sustainability. The students then revised their design based on the feedback. A post-evaluation questionnaire and the modified design concepts were then collected to assess the success of the design critiques. Although student projects are limited in scope, and simplify real world problems, the learning through this project will enable them to design products that consider environmental sustainability.

Keywords: Sustainable Design, Project-based Learning, Design Critique, Engineering Education

1 INTRODUCTION
Increasing environmental concerns, coupled with public pressure and stricter regulations, are fundamentally impacting the way companies design and launch new products across the world [1]. Therefore, companies are confronted with the responsibility of producing products in an environmentally friendly manner. This requires that the next generation of engineers be trained in the concept of sustainability with an international perspective in order to solve complex problems at both local and global scales [2]. As pointed out in a recent survey conducted by ASME, 60% of respondents expected their organization's involvement in incorporating sustainable and/or green design specifications would increase in the coming year [3]. Studies, however, have shown that recent graduates lack the fundamentals to successfully engage in sustainable design activities. 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" [4]. Thus, embedding relevant education initiatives within existing engineering curricula is essential for addressing these knowledge inadequacies and ultimately realizing a more environmentally benign future. The corporate push for more sustainable products and the respective lack of organizational knowledge regarding sustainability has created a significant need for educating the next generation of engineers to understand environmental challenges [5].
The literature is replete with studies that demonstrate that project-based learning (PBL) is an effective method for providing engineering students with a simulated framework for industrial practices with regards to product design. According to Dym et al., assessment criteria of design projects within engineering produce results that are indistinguishable from those obtained from typical US industrial approaches [6]. Additionally, Shekar suggests that PBL within product design requires a blend of marketing, manufacturing and design thinking throughout the active learning process, qualities that are all essential for success in business practices. PBL also creates a learning environment that spurs a holistic design approach that considers "product context, the end-user, environment, sustainable strategies and regulations" [7]. In general, PBL has become a staple in engineering design courses for undergraduate seniors along with graduate students [8-10].

Recently, there have been efforts directed at incorporating sustainable design principles into PBL-themed engineering courses. Most of these projects have been centered on important yet narrow environmental issues, such as water waste management, sludge treatment, and alternative energy. Hmelo et al. (1995) introduced sustainability-related problems (e.g. chemical spill cleanup, impact reduction opportunities in sheet molding, and effect of chlorine use in lakes) within an engineering elective for research study [11]. 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 [12]. 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" [13]. 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 [14].
Though all the above-mentioned topics play a significant role in the effort to minimize society's ecological footprint, there have been few examples in the literature which holistically incorporate sustainability thinking into all facets of the traditional product development process. Yost and Lane (2007) developed a "contemporary issues" module, which included an environmental assessment of students' engineering design capstone projects [15]. 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 [16]. Sustainability should be treated as a global constraint that must be incorporated in design related decision-making for any product (e.g. kitchen blender, computer monitor, and an automobile engine). This gap in research has motivated the authors to supplement a traditional product development course at Purdue University (ME553: Product & Process Design) with sustainable development learning modules. In short, these modules will come in two forms: (1) a one hour lecture from a professor in the Department of Environmental & Ecological Engineering (DEEE) and (2) an intervention by sustainable design experts that will independently assess each group's designs.

2 METHODOLOGY

2.1 Course Layout

ME553, a graduate-level course in the School of Mechanical Engineering at Purdue University, caters to both on-campus and distance learning students. The off-campus students come from a wide spectrum of companies, representing the aerospace industry (e.g. Rolls Royce), automobile industry (e.g. Toyota) and other major contributors to product development today. The course emphasizes on identifying existing market opportunities and developing innovative products to address these needs. Critiquing students' designs with regard to sustainability was introduced as an integral part of the course. Furthermore, ME553 contains a mix of theoretical lectures, guest lectures which address specific aspects with regards to product development (e.g., sustainability and customer feedback), an individual design assignment and a group project (e.g., customer requirements identification, target costing and design for manufacturability). The group project runs in parallel with the above-mentioned

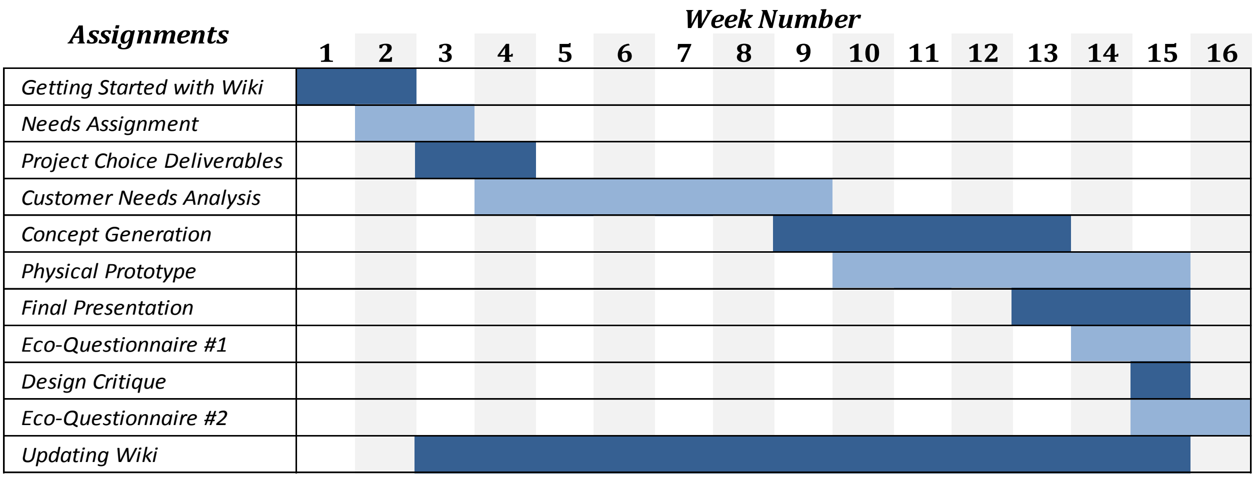


Figure 1. Course Schedule for the Student Group Design Project

aspects of the course. At the end of the fifteen week course, students are expected to develop a tangible prototype of their specific product. Throughout the course, student-teams regularly update their personal 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. 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 opportunities 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 [17]. The final stage of the design assignment involves a twenty minute presentation where the groups showcase their designs.

2.2 Data Collection

The wiki module, hosted by GlobalHUB™ [18], is a key component of the students' work. Data in the form of team dialogue, completed assignments, and any other team activities was extracted from the wiki and analyzed for use in this study. To understand whether on-campus and off-campus groups could be analyzed in the same sample, an independent t-test comparison was conducted to assess whether there is a statistically significant difference in project grades between the two groups. Table 1 shows the statistical values for the t-test. Figure 2 illustrates a boxplot of the project grades for each group from the class. The mean grades were 88.31 (N=8, σ_x = 6.28) and 87.67 (N=9, σ_x = 4.29) for the on-campus and off-campus students, respectively. The data for the on and off campus students were analyzed, and the hypothesis that there was a significant difference in scores was rejected.

Table 1. Results of two tail two sample t-test (t- value = 0.24, p-value = 0.811)

	student teams (N)	mean project grade	std. deviation project grade	std. error in mean project grade
on-campus	8	88.31	6.28	2.2
off-campus	9	87.67	4.29	1.4

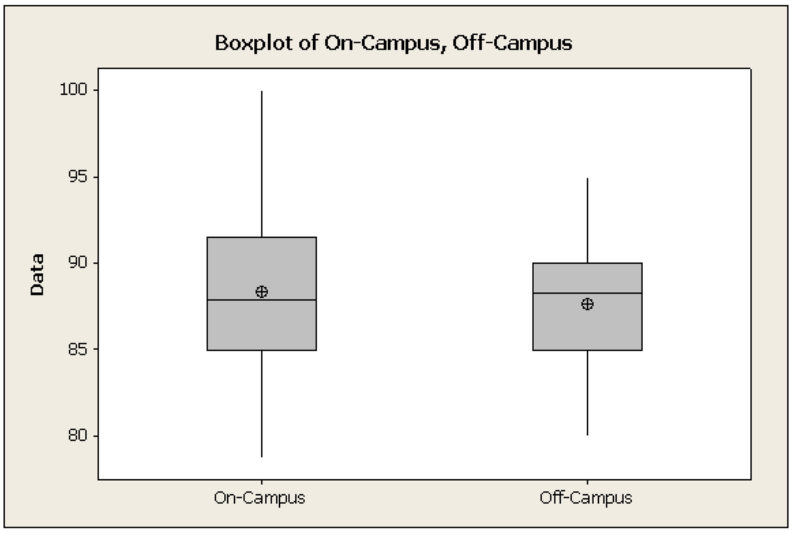


Figure 2. Boxplot of project grades comparing on-campus and off-campus groups

Because there is no significant difference in project grades between off-campus and on-campus students, information posted on the wiki was grouped into a single sample set (N=17). Next, a separate research question was posed. Does adopting a holistic lifecycle view of the product's lifecycle create a more elegant and innovative product? Based on an hour-long lecture from a DEEE professor, an expert on sustainable product development, students within the class had a basic understanding of sustainability issues as they relate to product design. Figure 3 illustrates the main

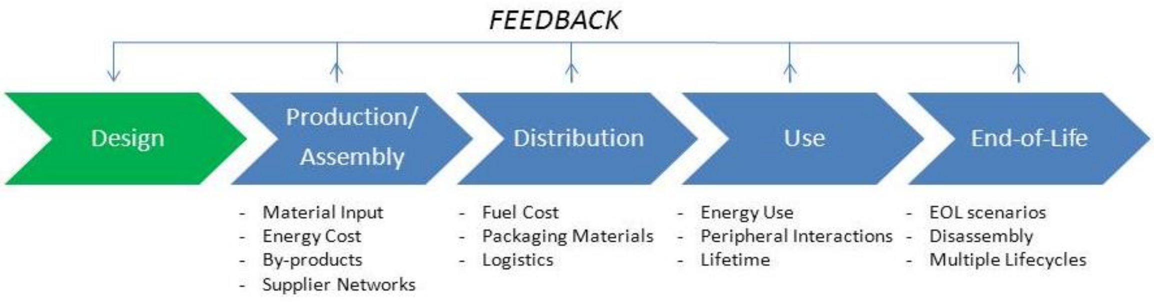


Figure 3. Map of product development representing critical stages that affect sustainable design

message of the guest professor's lecture. Because sustainability is a global constraint, ecological factors interact with the product at every stage of its lifecycle (i.e. production, assembly, distribution, use and end of life). Thus, there is a significant need for novel design methods that project these complex interactions in a condensed, easy-to-use form to the designer. The same applies within a design engineering education setting. Students have limited access to the necessary tools and methods to design a product or process that is greener from a holistic perspective.

The wiki pages of each group were analyzed based on a binary criterion (Y/N): were the impacts of any downstream issues considered in the team's design. This could come in the form of a customer requirement embedded within a lean QFD, information regarding specific packaging or distribution of the product, energy requirements for specific processes, among other topics. Approximately 41% (7/17) of the student groups used some downstream knowledge or representation to aid their design. Since the projects were graded based on feasibility and creativity, the grades for each project were separated based on the above criteria and compared using a one-sided t-test. It should be noted that sustainability was not a grading criterion. Interestingly, there was an outlier by the 1.5-IQR (interquartile range) rule in the group of projects that did not consider sustainability in the design phase. In other words, the highest project grade in the class belonged to a group that did not consider sustainability when developing concepts. This illustrates that if a talented, innovative group develops an exceptional idea, downstream considerations might have little to no impact on the product's success.

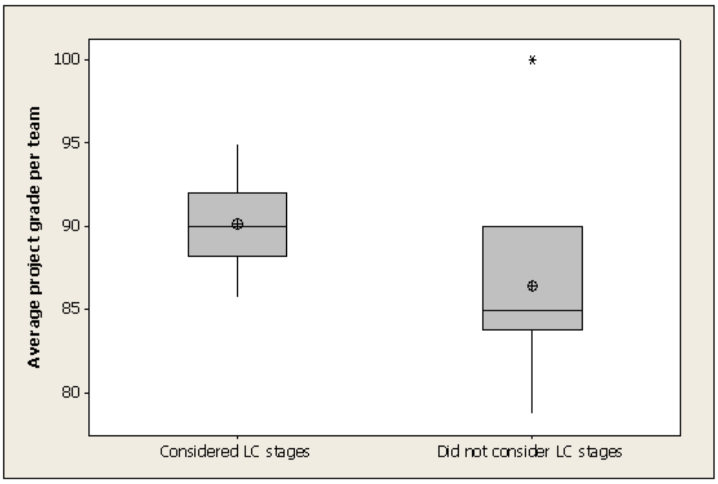


Figure 4. Boxplot of ME553 groups

Table 2. Grades of student groups that considered LC effects - results of one-tailed two sample t-test (t- value = 1.70, p-value = 0.057)

	Student teams (N)	mean project grade	std. deviation project grade	std. error in mean project grade
considered LC stages	7	90.14	2.89	1.1
did not consider LC stages	10	86.45	5.95	1.9

With the exception of the outlier, illustrated in Figure 4, there is a significant statistical difference between the two data sets. A one-tailed two sample t-test was performed to quantify this difference. Table 2 shows the results from the t-test. Since the testing hypothesis states that groups that considered issues within downstream lifecycle stages have a greater average score compared to the groups that did not consider them, a one-tailed t-test is appropriate. Even with the outlier, there is more than a 94% confidence that the two samples are statistically different. These findings motivate supplemental instruction to achieve broader reach within the class. An extra credit assignment was given out as a questionnaire related to how each team incorporated downstream issues or considerations regarding sustainability into conceptual design. 8 out of 17 groups participated in the study.

2.3 Questionnaire and Critique Layout

The eight groups that participated in the extra-credit exercise first were given a pre-evaluation questionnaire comprising of 18 detailed questions. The questions were focused on the team's design process (e.g. "List the primary objectives of your design" and "List all the production operations necessary to manufacture your product. How did you select each process") as well as on topics relevant to sustainability (e.g. "In your opinion, what is environmental sustainability?" and "Which phase of the process/product development of your project dominates the total environmental impact?"). The purpose of the questionnaire was two-fold: (1) to provide a baseline for the DfE experts to understand the team's design activities and (2) to assess the teams' knowledge level regarding sustainability.

Category	*Sample Checklist Item*
Material	*Product contains renewable materials. Yes ☐ No ☐* *Product contains recycled materials. Yes ☐ No ☐* *Materials use has been minimized. Yes ☐ No ☐*
Emissions	*Product contains no VOC's or CFC's. Yes ☐ No ☐* *Chemical emissions have been minimized. Yes ☐ No ☐*
Energy	*List sources of energy used in the product: ___________* *Energy consumption info is available. Yes ☐ No ☐* *Product is energy-star compliant. Yes ☐ No ☐*
Consumables	*Design has min. amount of consumables. Yes ☐ No ☐*
Packaging	*Packaging materials is reduced. Yes ☐ No ☐* *Recycled packaging materials are used. Yes ☐ No ☐*
End-of-Life	*Materials can be easily separated. Yes ☐ No ☐* *Plastic recycling no's are clearly indicated. Yes ☐ No ☐*
Product Life	*Product contains modular components. Yes ☐ No ☐* *Product contains standardized parts. Yes ☐ No ☐*
Hazardous Subs.	*Product is WEEE and RoHS compliant. Yes ☐ No ☐* *No parts contribute to hazardous waste. Yes ☐ No ☐*
Life Cycle Aspects	*No stage has adverse ecological effects. Yes ☐ No ☐* *All departments comply with eco-policies. Yes ☐ No ☐*
Misc.	*Product benchmarking has been done. Yes ☐ No ☐* *Product's eco-attributes are available. Yes ☐ No ☐*

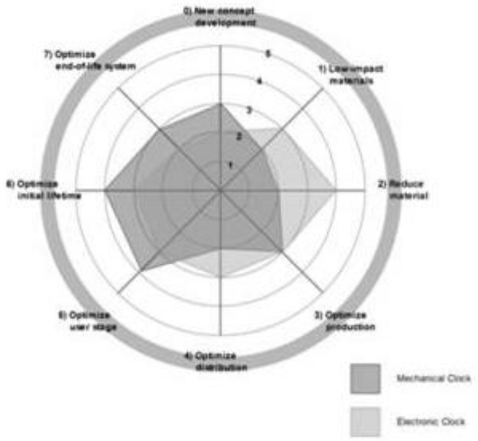


Figure 5. Eco-design tools suggested after first questionnaire. (Left) Abridged eco-design checklist. (Right) Example of the LiDS wheel.

Design critiques from two eco-design experts followed the collection of the pre-evaluation questionnaires. The critiques were developed based on how well each groups' design process incorporates sustainability with respect to production/assembly, distribution, product use, and end-of-life logistics. Specific to each respective project topic, the critiques were developed based on the completed questionnaires and the wiki modules. Each critique was accompanied with two ecodesign tools, (1) an ecodesign checklist and (2) the lifetime design strategy wheel (LiDS wheel) [19] seen in Figure 5. These specific methodologies were chosen because of their wide use in industry today. Instructions on how to use each tool was also provided in the critique. The teams were then asked to modify their design based on suggestions from the critique incorporating both a project-specific critique along with both eco-design tool frameworks.

Once design modifications were posted on the wiki, a post-evaluation questionnaire was handed out to assess the effectiveness of the redesign activity. The results from three groups will be described in detail as representative of significant learning with regards to DfE (Design for Environment) displayed by all participants.

3 CASE STUDIES

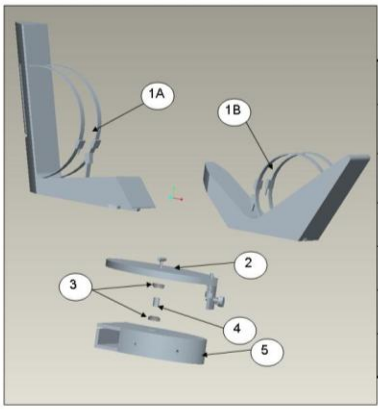
Retrospective learning is particularly applicable with respect to sustainable design. As sustainability affects every downstream stage of a product's life, designers are faced with the enormous challenge of weighing several factors at a time to make significant decisions in the early design phase.

Furthermore, biases, perceptions, and preconceptions from the designers themselves are difficult to overcome to achieve a truly green product. These misconceptions were consistently evident by the groups' responses within the pre-questionnaire. For example, when asked at what stage in the design process was sustainability considered, one group responded, "We did not consider sustainability in our design process. This is simply due to the disposable and inexpensive nature of our product". Most answers were focused on material substitutions that would aid recyclability. Though these are significant improvements towards a greener society, these answers show a limited understanding of a product's environmental impact. Only one team out of the eight participants even mentioned distribution, which in cases of high production volume and low quality contributes significantly to its footprint.

It should be noted that the same tools, the eco-checklist and LiDS wheel, were both discussed in the one hour lecture, but there was no evidence from the post-evaluation questionnaires or the wikis that any ecodesign tool was used by any team during their initial design processes. Analyzing questionnaire results and wiki input from several teams showed some very significant and interesting trends in education with regards to DfE topics. An overview of three of the groups' efforts is provided below.

3.1 CS1 - Luxury Car Seat

Team-1 identified a market opportunity for a new design for a child's car seat citing the difficulties for some parents to lift their children out of a traditional forward-facing car seat. The team suggested fixing a seat on a rotating platform that allows the seat to be turned 90 degrees in either direction without compromising safety during transport (Figure 6). Based on results from the team's pre-questionnaire, the team relied heavily on the modular design of their product to argue for its sustainability. Stating that material and manufacturing techniques within the safety seat industry are fixed due to regulations and standards, the team focused on extending the lifetime of the product itself.



Item	Description	Qty
1A	CHAIR, FORWARD FACING	1
1B	CHAIR REAR FACING	1
2	TOP BASE	1
3	BEARING	2
4	SHAFT	1
5	BOTTOM BASE	1

Figure 6. Team 1 CAD model and BOM of Luxury Car Seat

In this case, the team seemed relatively knowledgeable about sustainability in terms of product design from past experiences. The group used modularity to realize a sustainable design. Though there is no formal proof that modularity always leads to a more environmentally benign design, there is strong evidence to suggest that this is the case. Throughout their pre-questionnaire, there were however, a few fundamental misconceptions reflected from their definition and ideas regarding sustainability. The group stated that "a product that does not consume energy does not impact the environment during use." It is well known that energy is not the only input to the environment during use of products worldwide. Water consumption, land use, consumable materials and energy (e.g. oil and natural gas) can all be considered as consumables during the use phase of various products. Furthermore, some additional comments illustrated that the group did not possess an accurate definition or understanding of environmental sustainability. This specific group defined environmental sustainability as "the overall footprint [that] a product's cycle leaves on the environment. This includes not only its life cycle, but more importantly its manufacturing and eventual disposal." Apparently, in this case, the students failed to recognize that manufacturing processes and end-of-life logistics are inherently part of the product's lifecycle.

The outline of the design critique handed back to the students consisted of three main points: (1) the introduction of qualitative ecodesign tools (i.e. lifetime design strategy wheel and ecodesign checklist), (2) direction to more rigorously analyze whether modularity, in fact, has environmental benefits for this specific application by mapping out take-back logistics, and (3) the suggestion to map out all material and energy flows throughout the product's entire lifetime.

In response to the experts' critique of their design, the design team used both the LiDS wheel and eco-design checklist to begin an intragroup discussion about decisions to effectively lower the environmental footprint of their product. Using both these tools, the students displayed strong thinking in terms of sustainable product design. This group, in particular, described projects that would have been completed with more time, including the investigation of modular versus multi-functional units, more advanced materials and manufacturing process analysis, and the development of a simulated supply chain network. When asked of the design changes considered after the design critique, which modifications would be implemented in a real world scenario, the group provided a very telling, insightful answer.

"If all designers kept this in the back of their minds during the design cycle, drastic changes could be made in small steps that would make our world better for the future. Sadly, this concept is often a convenience that start-up companies cannot afford to spend too much time on. It is only with government funding that technology such as wind farms is expanding in this country. Until the American mentality changes to embrace sustainability as a product feature that affects their purchasing decision, most designers can do little more that keep the concept in the back of their minds."

3.2 CS2 - MP3 Headphone Storage Device

Team-2 developed a design which could store headphone cables for MP3 playing devices (Figure 7). In this specific case, the learning process was mostly dedicated to correcting misperceptions about sustainability and its implementation in design. Answers within the pre-questionnaire raised some questions. The group claimed that they did not consider sustainability in their design "due to the disposable and inexpensive nature of the product". Furthermore, they suggested that in order to achieve environmental sustainability within product design, one must introduce "a large set of modifications to the design process that can be taught separately from the generic process design flow." This group represents a microcosm of what is lacking throughout American engineering programs. There seems to be disconnect between education regarding environmental sciences and traditional engineering curricula. This group viewed DfE principles as a burden or inefficiency to the progress of their product's development.

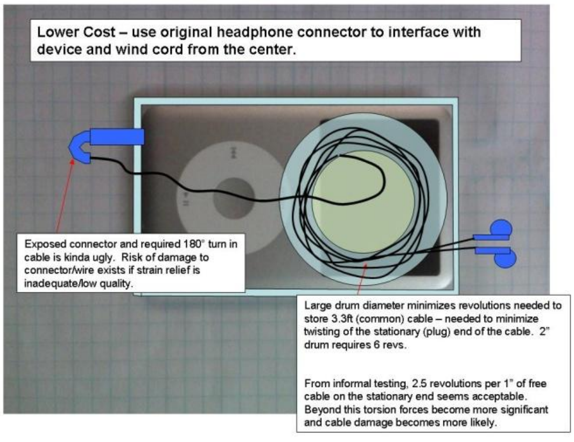


Figure 7. Team 2 Initial Sketch of their Design

The outline of the design critique handed back to the students suggested four main points: (1) the introduction of qualitative ecodesign tools (i.e., lifetime design strategy wheel and ecodesign checklist), (2) the motivation to study why sustainability must be considered for inexpensive, disposable products, (3) the direction to consider distribution and transportation of the product to reduce environmental impact, and (4) the push to understand take-back logistics of components/subassemblies to verify the environmental benefits of their modular design.

In response to the critique, the team demonstrated a strong change in perception with regards to incorporating sustainable practices into the design process. The team completed both the LiDS wheel and checklist, which guided them in developing a more holistic view (i.e., incorporation of downstream concerns) of product development. In addition, the team had begun plans to develop a full recycling plan, which included preliminary logistics for a product take-back model.

When asked if this exercise had been helpful, the team responded, “This has been very helpful. When one thinks of sustainability it is usually of only using reasonable renewable resources in an efficient manner. Planning does not necessarily go into product packaging, shipping, and the technicalities of how the products can be reused or recycled. Our team can go forth in implementing more sustainable mindset in our design environments.”

3.3 CS3 - Automated Pill Bottle Opener

Team-3 chose to pursue a found market opportunity in developing an automated pill bottle opener (Figure 8) aimed at helping the elderly and those with low hand dexterity. Sustainability knowledge beforehand was only with respect to manufacturing process and material choice once the embodiment of the design is fixed. Most of the comments from the pre-questionnaire were primarily focused on material selection and environmentally benign manufacturing options.

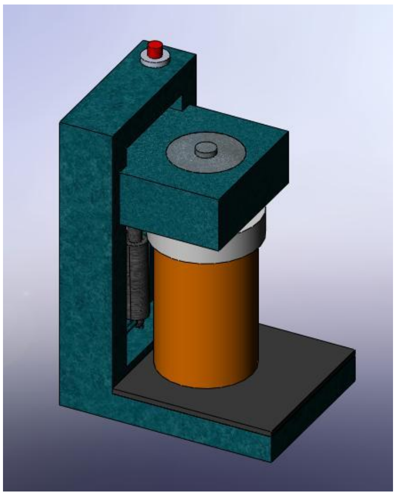


Figure 8. CAD model of final design of automated pill bottle opener

The critique team viewed this team as a nice case to experiment with redesign. Because the most critical feature of the product was to deliver torque to the medicine bottle cap, there were multiple concepts that could achieve this same function. The drive systems of both the lever subsystem as well as the knob design are both switch activated with an electro-mechanical system. The group’s design included preliminary plans for an electronic switchboard. It is known that it is environmentally burdensome to manufacture a functional wiring board. No answers within the pre-questionnaire focused on aspects of the actual design itself to be environmentally efficient, other than the possibilities of modularity.

The outline of the design critique handed back to the students had four principal components, including the following: (1) the motivation to investigate different concepts that utilize mechanical advantageous mechanisms to avoid settling on an electro-mechanical system that carries significant environmental impact in terms of manufacturing and rare element consumption, (2) the introduction of qualitative ecodesign tools (i.e. lifetime design strategy wheel and ecodesign checklist), (3) the direction to map in-house processing vs. outsourcing to understand supply chain logistics, and (4) the push to optimize material and process steps with regard to sustainability (e.g. dematerialization, reduction of steps, and gear design).

In response, the design team developed a thorough report responding to each suggestion. The team explored different embodiments to accomplish the same output functions of an automated pill bottle opener. A lever-crank mechanism and a slider-locking mechanism were both qualitatively compared to the original electro-mechanical subsystem. Here, the team judged the concepts based on sustainability metrics as well as cost efficiency. Similar to the teams from Case Studies 1 & 2, the design team completed both the LiDS wheel and the Eco-design Checklist to assess the current design.

In addition, the team mapped out possible supply chain pathways, including an in-house production network as well as an outsourcing supply chain loop (Figure 9).

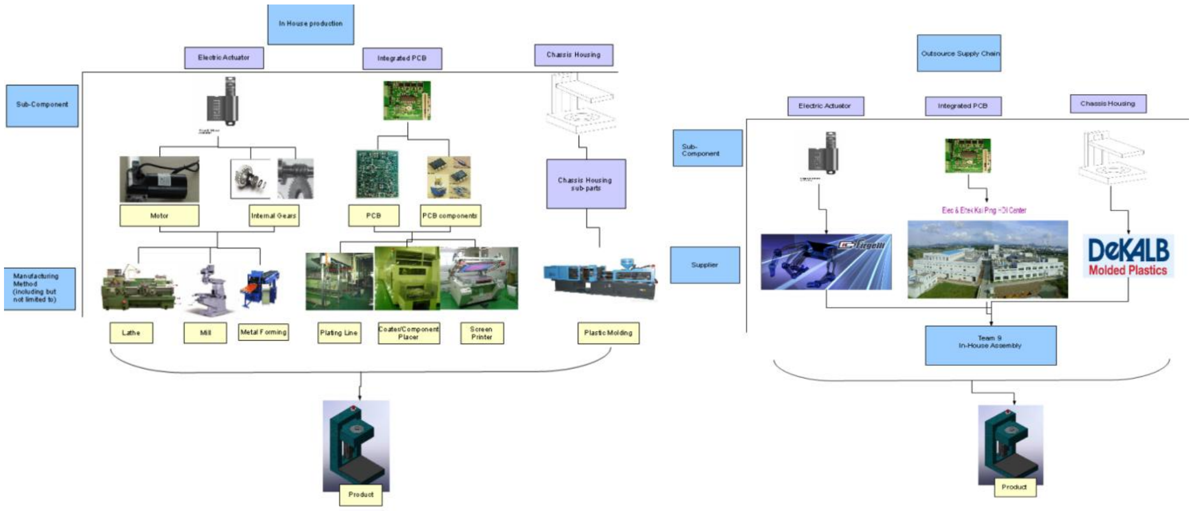


Figure 9. Preliminary Supply Chain Network Maps

When asked if this exercise was helpful, the team responded, that “it was helpful, as it forced the students to perform research and learn about sustainability through the questions presented. It also provided a focus to our specific product”.

4 CONCLUSIONS

Recently, the necessity of providing adequate education regarding sustainable design and production to engineering students has become clear. However, engineering curricula have become increasingly crowded with fundamental subjects (e.g., heat transfer and mechanics) that cannot be abridged. A new teaching method has been proposed in this manuscript to incorporate a critique module regarding sustainability within a pre-existing product design and development course. This, in turn, enables significant learning without reworking the entire curricula. Three student projects, in which the critique module was completed, were analyzed as case studies.

All the case studies in this pilot study represent different facets of incorporating sustainability into product design. Case Study 1 illustrated product modularity as a key driver in developing more environmentally efficient designs. The students learned to research, and further justify if modularity was actually environmentally beneficial in their particular application with the use of ecodesign tools. Case Study 2 focused on sustainability as a constraint within the distribution and disposal of a product. The design team developed strong learning after developing a recycling plan accompanied by a complete take-back logistical model. Case Study 3 proved that sustainability can also be a constraint applicable to the conceptual design phase. The design team compared different embodiments to achieve the same output function in order to qualitatively determine the most sustainable solution. The critique module provided flexibility to implement a unique and valuable learning exercise pertinent to each project.

In summary, similar to the product design process, true sustainable product development is a dynamic process. Understanding the material and energy inputs throughout a product’s lifecycle is essential in developing a green product. Intervening within students’ design processes and critiquing these designs from an environmental perspective provides an effective learning experience. Using a PBL approach effectively demonstrates that creating a sustainable product is very case specific. Similar design changes from one product concept to another may have drastically different effects. The dichotomy between the pre-evaluation and post-evaluation questionnaires (i.e. before and after the critique module) demonstrates that a critique-based learning module embedded in a design course can be an effective teaching tool. Particularly for curricula that are oversaturated with fundamental engineering courses, implementing a design critique module in a PBL-based course easily enables significant student learning with regards to sustainable design. After participating in this learning module, students will possess the necessary knowledge to apply environmentally responsible design practices as engineers in the industrial arena.

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