Learning to Waste and Wasting to Learn?
How to Use Cradle to Cradle Principles to Improve the Teaching of Design

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Abstract

Engineers of the future are expected to be knowledgeable about the principles and practices needed to develop eco-effective products and manufacturing processes, yet it is challenging to integrate these principles and practices into undergraduate engineering design education. Our research explored one approach for beginning this process to help first-year students understand and apply cradle to cradle design practices in a user-centered, project-based design course. We used McDonough and Braungart's 5-step model of cradle to cradle design as a framework to guide students through several exercises and reflections related to the prototyping activity in the course. The results of the research showed that through limited exposure to cradle to cradle design, students made some progress toward developing adaptive expertise in this area, although they had difficulty reconciling their new-found interest in cradle to cradle design principles with the competing demands of client wishes, time constraints, and limited access to and knowledge of materials.

Keywords: Design education; cradle to cradle design; sustainable design; reflection

I. Introduction

According to *The Engineer of 2020*, "The present generation [of engineering educators] has the obligation to leave a legacy to those who follow . . . to appreciate the unrestrained beauty of nature, the full diversity of the world's flora and fauna, and ancient and modern cultures and their artifacts. The world's future engineers are expected to be "leaders in the movement toward use of wise, informed, and economical sustainable development," and their training toward these ends "should begin in our educational institutions and be founded in the basic tenets of the engineering profession and its actions" [1].

Obviously, educational institutions will play a pivotal role in teaching these future engineers the principles and practices needed to develop innovative strategies and techniques for designing eco-effective products and manufacturing processes. Yet, currently, within any given educational institution, only a handful of advanced engineering students are exposed to these principles and practices [2]. Further, researchers question whether engineering students are able to integrate the principles taught in discussion-based classes into their engineering practices and technical

designs. To help bridge the divide between theory and application, researchers and practitioners suggest instructors integrate principles and practices of eco-effective design into engineering courses in fields such as design, materials, and processing [3, 4]. But how is this to be done?

Our research aimed to explore whether the process of understanding and applying cradle to cradle design principles can begin in a student's first year within courses that offer a project-based introduction to design. In fact, it grew out of our concern that if a focus on protecting the environment does *not* begin in an introduction to design, engineering design educators risk teaching first-year students an unintended but negative lesson: that attention to the environment—and to materials and waste in general—is not an essential part of the initial stages of design.

Working with McDonough and Braungart's definitions, we conceive of cradle to cradle design as designing products from the outset that provide nourishment for something new [5]. Products can be thought of as "technical nutrients" that can circulate as value materials within closed-loop industrial cycles or as "biological nutrients" that easily reenter the water and soil without leaving harmful toxins. To achieve cradle to cradle design, according to McDonough and Braungart, five steps must be taken:

Table 1: Five Steps Towards Cradle to Cradle Design [5]

Step	Explanation
1	Identify and then reduce hazardous materials that make up a product
2	Identify how materials may be reutilized at the end of the product's life
3	Assess and then reduce the amount of energy required for production
4	Assess and improve water usage and discharge quality
5	Engage in socially responsible and ethical corporate practices

Thus, we distinguish cradle to cradle from sustainability. Sustainable design aims to make systems, products, and practices more efficient, while cradle to cradle aims to make them waste free. Committed to this distinction, we believe that if we don't help students see that cradle to cradle design is an extension of sustainability, and not just a synonym for it, we will not be preparing them for the magnitude of the environmental challenges that they must soon face.

Our research investigated whether reflective instructional strategies can help students understand cradle to cradle design and apply it to their own design practice through

iterative prototyping in a project-based class where students design user-centered solutions for clients' real-world problems. Iterative prototyping is the act of making physical or virtual manifestations of concepts to test their viability and communicate ideas to others [6]. Such prototypes are intended to be inexpensive, easy to modify, and quickly made representations of ideas that can be tested against the actual use environment [7].

Our focus on prototyping stemmed from a consideration of the nature of project-based design courses. Since project-based learning typically teaches students how to integrate theory into practical design work [8], students generally build and test prototypes as part of the design process, an activity ideally suited to our research questions. Traditionally, design educators encourage students to select materials—such as modeling clay and foam core—that allow them to build prototypes as easily and rapidly as possible. Since the emphasis is on rapid assembly, little regard is given to how the raw material is manufactured, acquired, disassembled, disposed, and reused. While the material consumed in students' prototyping activity is minimal compared to the material consumed during manufacturing processes, we are concerned about the habits we may be encouraging in students if in our courses they are "learning to waste." Thus, the project-based design course offers an opportune time to investigate what students already know and think about sustainability and to introduce principles of and steps toward cradle to cradle design that emphasize reuse from the outset. We wanted to know whether, by adding more reflective strategies to the prototyping process and motivating students to see their knowledge take meaningful, tangible form through design practice, we can start to move them on a trajectory of "adaptive expertise" in cradle to cradle design [9, 10]. That is, as a result of these instructional practices, can students start to develop into experts who have not only deeper subject matter knowledge about cradle to cradle design but also the ability to apply that knowledge adaptively, or in innovative ways?

This paper describes the pedagogical interventions we developed to promote this dimension of adaptive expertise in our first year design course, including the theory behind those interventions; describes the methods we used to track their awareness and application of cradle to cradle principles; presents our results; and recommends ways to improve this dimension of the first year engineering design experience for the engineer of 2020.

II.   Study Rationale and Plan

Study context. We began our study by distributing a survey to the 264 first and second year engineering students who participated in a two-term required introductory course, Engineering Design and Communication (EDC) [11, 12]. In EDC, students learn engineering design and writing as parallel, inter-related, iterative processes, and receive credit for both engineering and writing as they work in teams to solve problems and write reports for real clients. Student teams design solutions for everything from cutting devices for patients recovering from strokes to book delivery systems for intercity library loan programs. EDC is the pre-requisite undergraduate design course for students pursuing the certificate in engineering design offered by the Segal Design Institute. The certificate program provides opportunities for students to develop skills they will need for professional practice in design and the habits of mind required for leadership and human centered innovation in engineering [13].

Theoretical framework. Since the EDC curriculum is already crowded and students are asked within a 10-week period to develop functional prototypes based on a rigorous process of research, user testing, and iteration, one of our goals was to see if we could expand students' understanding of cradle to cradle design with only modest additions to the coursework and a limited use of class time. Two frameworks underlie the interventions that we decided to use: the adaptive expertise framework mentioned above and Kolb's model of experiential learning [14]. In the adaptive expertise framework, performance is described along two axes representing efficiency and innovation (see Figure 1):
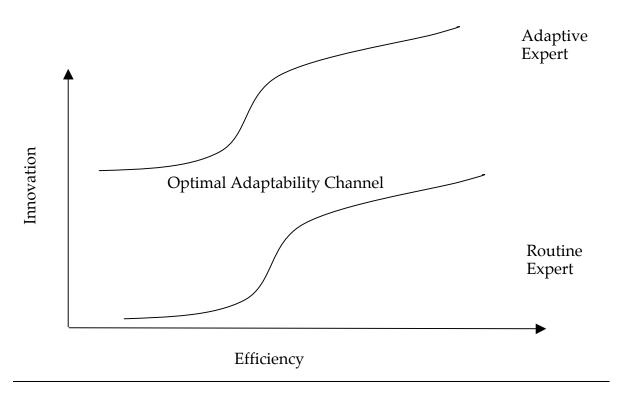
Figure 1: Relationship of efficiency and innovation in adaptive expertise. The "function of the 'optimal adaptability corridor' is to help insure that innovation and efficiency develop together" [9].

Unlike some "routine experts," who develop more and more skill in a narrow area (efficiency), the adaptive expert simultaneously develops the ability to apply his or her expertise to new situations (innovation). Students in a first-year design course are not expected to make tremendous advances in expertise since they are just beginning their technical education, but they can make some progress along both axes because they apply whatever expertise they develop flexibly in real time, from early stage design, through mock-ups, to final design recommendations. We wanted to find out whether adding cradle to cradle knowledge into this mix would allow them to develop adaptive expertise in the early stages of design process.

In addition to using the framework of adaptive expertise, our instructional approach followed Kolb's model of experiential learning [14] by embedding reflective and concrete activities throughout the course. Kolb states that learning is best conceived as a process, not as outcomes; that is, "ideas are not fixed and immutable elements of thought but are formed and re-formed based on experience." Kolb has suggested that learning is a four-stage process involving the four learning modes of concrete experience, reflective observation, abstract conceptualization, and active experimentation. The team-based projects and the interventions described below would serve as concrete experiences where students could actively engage in cradle to cradle design practices. In addition, the planned interventions would enhance learning because, as Kolb suggests, it is not just experience that contributes to learning but the coupling of experience and experimentation with reflection and abstraction. This combination forms a holistic adaptive learning process.

Pedagogical interventions. Two sections of EDC, with 16 students in one and 15 in the other, were selected as treatment groups for the cradle to cradle interventions. At the beginning of the first term of EDC—before the prototyping stage of their design process—we asked all students in EDC, including those in the treatment sections, to complete a 15 minute online survey asking them to define cradle to cradle designed products and practices and to describe how they might use cradle to cradle principles to design solutions for their projects. The survey was intended primarily to investigate this question:

• What do engineering design students understand about cradle to cradle designed products and practices and from where do they get their information?

Because we planned to use the survey as a pre- and post-course measure in the treatment sections, we also wanted to know the following:

• Does their knowledge of cradle to cradle design influence the way they design products and systems, and if so, how?
• What is the impact of our reflective instructional strategies on students' development of adaptive expertise in cradle to cradle design?

Once we received the surveys, all students in the course were given access to McDonough & Braungart's "Five Steps Towards Reinventing the World" [15], which outlines the principles of cradle to cradle design, and to the Designer's Accord website [16], which describes the work of a coalition of designers, educators, researchers, engineers, and corporate leaders, working to create environmental and social impact. Thus, those students whose curiosity about cradle to cradle design was piqued by the surveys had an opportunity to familiarize themselves with these ideas and to discuss them with their instructors, if they wished to do so.

For the treatment sections we designed two specific interventions, based on the initial steps in McDonough &Braungart's model for cradle to cradle design: identifying hazardous materials that make up a product and methods for reutilizing materials at the end of the product's life. As described below, the first intervention was an exercise based on the assigned reading and discussion, and the second was an effort through coaching and written reflections to help students apply their new knowledge to their projects.

1. The <u>first intervention</u> began with a 15 minute discussion of the readings, focusing on the nature of cradle to cradle design and the five steps toward achieving it. The students were given examples of cradle to cradle products and services. They were encouraged to consider the steps toward cradle to cradle design as much as possible as they prototyped solutions for their designs.

    One week later, in light of their new knowledge, the students were asked to redesign a prototyping exercise that all EDC students had completed a week earlier. This 15 minute exercise, which involves building a small house and bracket out of foam core, is used with all EDC students to introduce them to physical prototyping and give them practice in communicating ideas visually. For the new exercise in the

treatment sections, students were asked to research the life cycle of foam core, which, they learned, passes through such stages as raw material extraction, material products, production of parts, assembly, use, and disposal. Specifically, they learned that foam core production involves hazardous materials and does not provide "nutrients" back to the environment when disposed of. Approximately half of the students in the treatment sections completed this research and shared their findings with their classmates in another 15 minute discussion with their section classmates.

Then these students in the treatment section worked in small teams to re-design the prototyping activity to be waste free, consistent with cradle to cradle design principles, and described their new ideas to the rest of the class. Suggestions included practicing prototyping with reusable materials such as recycled cardboard and making objects that might have functional use in their daily lives. While the proposed solutions were not 100% waste free, they did consider the first two steps towards cradle to cradle design: minimizing the hazardous materials and reutilizing the materials after the exercise. Also, all teams considered how the EDC exercise could be re-designed to maintain the original learning goals while being more eco-efficient. Excited about the idea of modifying EDC, one student from each treatment section presented the new ideas directly to the faculty at the weekly faculty meeting.

2. The second intervention began one week after the first. Students in the treatment sections were urged to consider cradle to cradle design as they completed their project work. This intervention took two forms:

   a. Student teams in the treatment sections were coached informally on cradle to cradle principles as they addressed challenges, such as material selection, in their projects, and in some cases this resulted in additional class discussion. For example, in one case, where a student team was proposing use of a resource-intensive plastic material that was toxic to produce and dispose of, the whole class was encouraged to think of materials that might be less harmful to the environment and human health.

   b. Students were given two opportunities to submit written reflections about how cradle to cradle principles and practices applied to EDC course work: (1) they had the option of choosing this subject as a topic for an individual essay, and (2) they were required, as teams, to include an appendix on cradle to cradle design as it related to their own projects in their final reports.

In all, the total in-class time devoted to cradle to cradle instruction was less than 1 hour out of a possible 40 hours of instruction.

The readings, in-class discussions, surveys, and reasoning about their own designed solutions all emphasized reflection and abstraction, consistent with Kolb's ideas about experiential learning. Furthermore, as Schon has explained, reflection is embedded as a natural part of the design process, i.e., to "educate the reflective practitioner" [17] in our classes, we had students engage in reflection-in-action, which includes thinking critically about the present situation and generating on-the-spot experiments to test ideas and refine one's thinking. In our study, the critical thinking emphasis was on

how to make well-reasoned decisions about cradle to cradle design practices, explain those decisions clearly to others, and revise their approach when necessary.

Data Collection. Throughout the quarter, we collected observations of students' attitudes and actions related to the pedagogical interventions in the treatment sections. Additionally, we collected written reflections in their final group reports and individual writing about how they used cradle to cradle principles in their project work. To compare the treatment and control conditions, all of the EDC students who completed the initial survey (117 students in total) were asked to fill out the post-version of the online survey about cradle to cradle design. We received a response rate of 51% for the post-survey. The post version included all of the questions from the first survey as well as four questions asking what kind of cradle to cradle instruction they received, if any, throughout the course. From this we learned, that no other instructors offered instruction in cradle to cradle design to students in the control condition and few students in the non intervention section read the available readings. This collection method served to gather some baseline information from the first-year students as a whole and to look more closely at the progress made and problems encountered by thirty-one students in the treatment sections.

Data Analysis. We evaluated the students' written work in the treatment sections as well as their pre and post survey responses to investigate the impact of our pedagogical approach of embedding specific reflective activities to facilitate the development of students' cradle to cradle design adaptive expertise. Only two of the thirty-one students chose cradle to cradle design as a topic for their individual essays. However, in their report appendices, all seven teams described (1) in what ways, if any, their team considered cradle-to-cradle design principles during their design process, (2) how these principles might have influenced their design, (3) as an engineer/designer what they might do differently in future design situations, and (4) from an instructional perspective what EDC might do differently in the future to address this topic. The appendices varied in length from one paragraph to one page.

We analyzed the data by reading through all of the responses and listing what the participants reported. At this stage of the research we were also interested in capturing students' overall conceptions of cradle to cradle design practices, and how these conceptions may have evolved as a result of our interventions. Our analysis, therefore, is primarily qualitative, and our approach here is to report the data in the original form as provided by the students.

We did not have a categorization scheme a priori since we did not know what students' ideas were regarding cradle to cradle design practices, nor has there been much research in this area that would have suggested any particular framework for analysis. Once we read through the data and documented the range of comments we developed general categories that captured the meaning of the corresponding comments. Table 2 provides an overview of the main categories we found and some representative comments for each category. We used these categories as a way to organize the responses, and as a starting point to help interpret the data. Also, we documented those participants who did not provide any response to the question(s) since this serves as a benchmark for comparing pre and post responses, and whether there has been any change in students' conceptions. For the required appendices for their project reports,

we considered if and how the students understood and followed the five steps toward cradle to cradle design as a way of categorizing actions. We analyzed each attempt to follow the steps of cradle to cradle design in their design process and final prototype design.

III. Findings

From this study, we discovered three main findings: 1. Prior knowledge of sustainable design provides an entry point for instruction in cradle to cradle design; 2. Minimal pedagogical interventions result in greater awareness of cradle to cradle design; and 3. Students have difficulty applying cradle to cradle principles to their own design work, despite their greater understanding of the principles. We discuss each finding in detail below.

Finding 1: Few students had specific knowledge of cradle to cradle design, but their prior knowledge of sustainable design provides an entry point for instruction in cradle to cradle design. The data reveal the type of knowledge students bring to the classroom and how they use this prior knowledge to make sense of the new concept of cradle-to-cradle design.

Of the 117 students who completed our general pre-survey, 63 (54%) had nothing to say about what cradle to cradle meant. Those who offered an explanation of cradle to cradle design often said it meant being environmentally friendly or recyclable. Others seemed to be making educated guesses.   Table 2 provides example responses from each of these three categories.

Table 2: Typical Student Responses at the Beginning of the EDC course as to what "Cradle to Cradle" Design Means.

Category	Example Responses
Environmentally friendly	"Cradle to cradle designs means designing a product that is environmentally friendly." "Using environmentally-friendly materials in designing, building and manufacturing." "Design that is intended to be environmentally friendly."
Recyclable	"A product that is 100% recyclable" "Cradle to cradle is regarding recycle products. With design it refers to creating something that can be reused or at least that have its parts recycled individually to create a new product after it has been used." "This means that a product is easily recyclable and can be used again without wasting resources, as opposed to cradle to grave."

Logical guesses	• "'Cradle to cradle'" sounds like another buzzword, like "Blue Ocean Strategy" and "Six Sigma" • "from the beginning to the beginning" • "It's the process of remaking the way we design things such that we factor in human interaction and safety, etc." • "Something designed for the users, by the users." • "I have never heard of "cradle to cradle" design. I might guess that it could be related to the saying "cradle to grave', which would then indicate that it has to be about someone guiding you throughout the entire design."

From these pre survey responses, we note that students do use prior knowledge and that some of their responses provide notions that are closely related to, or in some ways part of, the concept of cradle-to-cradle design. For example, recycling is a first step towards building awareness of cradle to cradle design practice, but is not necessarily part of its practice since recycling often assumes that the products and the materials from which they are made are being downgraded and that energy is being wasted to do so. In addition, the notion of being environmentally friendly is consistent with the concept of cradle-to-cradle but not sufficient to explain the full premise. The pre responses indicate that students do have relevant ideas that can serve as entry points into introducing the more sophisticated concept of cradle-to-cradle. The nature of the pre responses provides insights into how instruction can be refined to be more learner-centered such that it will take into account and build on prior knowledge [18].

Finding 2: Our pedagogical interventions resulted in a greater awareness of cradle to cradle design. We analyzed students' pre and post responses to see how their responses evolved from using common sense explanations to providing more precise explanations that include normative language from the community of design practitioners. This analysis shows an interesting evolution of students' understanding and how they build on previous knowledge.

In the post responses in the treatment sections, 27 of the 27 respondents provided an explanation, and the explanations included more nuanced ideas about cradle-to-cradle design. In addition to the three categories most common in the pre responses – environmentally friendly, recyclable, and logical guesses—a fourth category emerged: students introduce ideas such as life cycle and energy consumption, showing a greater understanding of cradle to cradle and the concept of waste throughout various stages of the design process. Examples of post responses from students in the treatment sections showing a greater understanding of cradle to cradle are below.

- "Cradle to cradle design means to have designs using products that could be used over and over again without ever becoming waste. Cradle to cradle designs use materials that could be recycled forever without ever losing their contributions to designs. Cradle to cradle design means keeping from having materials 'wasted'."

- "The ability to make something in a way that will make it reusable to a future product, therefore eliminating intermediary energy and production waste."

- "When I think of 'Cradle to Cradle' design, I imagine careful consideration being given to the environmental impact of the materials used in a design. To me, it suggests a lifecycle of materials that extends beyond the lifetime of the design they are a part of."

- "Cradle to Cradle design is a process that involves designing products with the environment in mind. This does not only include the materials being used during the design process, but also the way one thinks about designs. It is a design process that shifts the focus to not only how will this design have less of an impact on our environment, but also, how can this design actually give back to our environment."

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The students recall the first three and the fifth steps of cradle to cradle design: identifying and then reducing hazardous materials that make up a product; identifying how materials may be reutilized at the end of the product's life; assessing and then reducing the amount of energy required for production; and engaging in socially responsible and ethical corporate practices. They do not speak directly to cradle to cradle step 4: assessing and improving water usage and discharge quality. A possible explanation may be that step 4 requires knowledge beyond that of a freshman or sophomore engineering student and thus less likely to be considered when asked about cradle to cradle design.

Students in the treatment sections showed a greater awareness of examples of cradle to cradle products and processes. Whereas only 7 out of 27 students initially explained cradle to cradle design accurately or even connected it to eco-friendliness, 17 out of 27 respondents from those sections identified cradle to cradle products, or types of products, or provided explanations of cradle to cradle design practices by the end of the course. Examples of products they mentioned included "junk metal that is melted down and reconfigured to create something new," products "that can biodegrade," "backpacks made out of old Publix bags," "paper bags made out of recycled papers." Examples of cradle to cradle design practice highlighted efforts to reduce waste, mentioning design that uses recyclable materials, considers the issue of disposal, builds a new product out of an old one, or reduces environmental impact and energy use. Students did not often cite examples of cradle to cradle design that were waste free, but this response should be expected since few cradle to cradle designs exist. The lack of examples has been identified as a current challenge in teaching cradle to cradle design; instructors and practitioners are actively working to create case studies to provide examples for students [4]. A few students gave examples of large systems, showing their ability to think beyond the design of individual products. Consistent with Peet et al.'s expectations [3], the few students who read the offered readings but did not participate in the intervention or do any activities related to cradle to cradle design, could explain cradle to cradle design but did not attempt to implement the practices into their own design work.

These more nuanced explanations are encouraging given the modest exposure and limited class time devoted to cradle to cradle design in the treatment sections. Viewed through the adaptive expertise framework, these more accurate explanations suggest that students are making a first step in "efficiency"; that is, if the aim is to have students be innovative with their knowledge and apply the concepts of cradle-to-cradle to their design practice, then as a first step they need to develop awareness of the concept.

It is reasonable to assume that growth in the treatment sections stemmed from the interventions. In particular, since students in these sections were asked to redesign one of their prototyping activities, the intervention modeled the larger goal of the course to have students learn about design by engaging in design process. In the intervention, students used this process by first doing research about materials and energy required for the production and disposal of foam core, then brainstorming alternatives, and finally developing a new solution, but their goal, instead of solving a problem for a client, was to learn about cradle to cradle design. We believe that this replication of the main course goal promoted understanding.

Finding 3: Students have difficulty applying cradle to cradle principles to their own design work, despite their greater understanding of the principles. Although our survey results show that students in the treatment sections demonstrate an understanding of basic cradle to cradle principles, they had difficulty applying those principles to their design projects. In the post surveys, when asked whether they used cradle to cradle principles in prototyping or in deciding on their final design, half of the students said they did not. There are at least three possible reasons that they chose not to use these criteria.

1. *Projects are complex and demanding.* This ten-week introductory course requires that students learn a wide array of concepts and skills related to design and apply those to open-ended design problems. Thus, they must do various kinds of research in order to understand ill-defined design problems given to them by their clients, observe users in order to account for their needs in the design, build and test multiple mockups, and so forth. As a result, they often feel overwhelmed by the complexity and demands of the projects. As one student put it, "We didn't consider 'cradle to cradle' ideas during the prototyping process. Giving considerable, serious consideration to these ideas was difficult given our time frame (10 weeks)…" Another wrote, "Time was a critical factor; we wanted to build quickly."

2. *Students give priority to the needs of the client and users*. The EDC curriculum and instructors repeatedly emphasize that designers must understand and respond to client and user needs. Thus, if the client and users do not say that cradle to cradle criteria are important, the students are unlikely to impose the criteria on them. As one student commented, "The criterion that was most important for us while designing was to create a prototype that will be both satisfactory for the user and the client. We mainly focused on what the client desired since he was the one with the most experience about the users and had knowledge about what they needed." Other comments included, "We based the ideas of our prototypes and mock-ups off of the requirements and recommendations from the user," and "My team and I used what the user said was the best design."

3. *The availability of materials for prototyping and the students' understanding of those materials are very limited.* Students are provided with foam core and various kinds of wood, metal, plastic, but they are given no instruction on alternatives to those materials. Two students commented,

for instance, that the availability of materials in the prototyping shop was a key consideration in their decisions about how to build their prototypes. Another wrote, "For prototyping, we used what was available in the shop and what would be easy to use from McMaster-Carr."

Despite these constraints, however, half of the students in the two sections who completed the survey did report that in prototyping their concepts and/or in designing their final design for the client they took first steps towards including cradle to cradle criteria: choosing recyclable or reusable materials that used less energy to produce, avoiding wasteful use of materials and environmentally harmful products like foam core, and considering reutilization of the materials when disassembled. For example, one student group created a small book carrying case out of recycled wood. They considered the source of the wood as well as disassembly of the case back into its original materials for remanufacture. It is unclear, however, how intentional students were in applying these criteria. For instance, the materials used in their final prototypes—generally, wood and aluminum—were frequently recommended to them by the mentors in the prototyping lab because these materials are inexpensive, readily available, and easy to work with; thus, students may not have considered the cradle to cradle advantages of wood and aluminum until after the fact.

The limited examples of students attempt to follow the steps towards cradle to cradle design are outlined in Table 3. Out of seven possible teams, only three attempted to pursue cradle to cradle design in their prototyping process or creation of their final prototype.

Table 3: Examples of Students' Attempts to Follow the Five Steps towards Cradle to Cradle Design while Prototyping

Step	Explanation	Examples of Team Actions
1	Identify and then reduce hazardous materials that make up a product	• Identified foam core as a hazardous material and used reclaimed cardboard for quick mock-ups • Identified a super glue as hazardous material and used a screw to affix a hinge instead
2	Identify how materials may be reutilized at the end of the product's life	• Repurposed materials from an unsuccessful prototype to create a new prototype • Designed final prototype to be used as a building block after it was no longer needed as a book carrier
3	Assess and then reduce the amount of energy required for production	• Chose to use reclaimed banner material to create a wall hanging book display • Chose reclaimed particle board to create a book box rather than new wood

4	Assess and improve water usage and discharge quality	• Not considered by any team
5	Engage in socially responsible and ethical corporate practices	• Identified local sewing leagues to manufacture their soft good and distribute it to local libraries in underprivileged neighborhoods

Our instructional approach was designed to balance the two dimensions of adaptive expertise: We created the learning experience (intervention) to develop students' efficiency (awareness and understanding) through a relevant prototyping redesign activity and then expected students to apply the concept of cradle-to-cradle in an adaptive or innovative way in their design solution. However, we did not achieve the desired co-development of efficiency and innovation. We learned instead that even though the students were acquiring their knowledge about cradle to cradle in a class that stresses application, as opposed to simply discussion, they still faced too many competing factors toward the end of the course to consistently prioritize cradle to cradle principles in an innovative project. In addition, they lacked sufficient knowledge about materials to make further progress in completing the 5-step process that McDonough and Braungart describe [15].

This suggests that the design knowledge that might be included on the efficiency axis is nuanced and complex, and that there are several supporting concepts and knowledge required for innovation with cradle to cradle design principles. In other words, from an efficiency perspective, the instructional content needs to include aspects of efficiency that might be more subtlety embedded in the larger concept of cradle to cradle design. Without the foundational knowledge to make sense of the broader concept, students struggle with recognizing when cradle to cradle design principles apply to their projects. This might be viewed as an "efficiency gap" that needs to be filled before students can make innovative use of cradle to cradle design principles. These stumbling blocks suggest some clear steps for refining the interventions in future classes.

IV. Conclusions and Next Steps

Given the success of the interventions in this study in building awareness of cradle to cradle principles, it is reasonable to assume that a small amount of reading and limited in-class discussion, combined with design exercises, is sufficient to start building a foundation upon which students can begin to develop adaptive expertise in cradle to cradle design. Based on what we learned in this study, we suggest the following

interventions to put students on the path to developing adaptive expertise in the five steps of cradle to cradle design throughout their design education. We also suggest interventions for faculty which allow them to support students as they develop adaptive expertise.

Recommended interventions with students. In an introductory design course, students seemed most able to consider the first two steps towards cradle to cradle design as outlined by McDonough and Braungart [5, 15]. Students were capable of researching and analyzing the environmental impact of materials (step 1) and consider the reuse of the materials in a product after the product is not longer needed (step 2). Steps 3 and 4, which involve more technically sophisticated knowledge and expertise of manufacturing processes, were more difficult and may be introduced later in the undergraduate education. Students were able to grasp, if only in a general sense, step 5, which considers socially and ethically responsible practices. Table 4 suggests future interventions to extend what introductory students learn about cradle to cradle design.

Table 4: Future Interventions with Introductory Students for each Step Toward Cradle to Cradle Design

Step	Explanation	Future Interventions
1	Identify and then reduce hazardous materials that make up a product	Assign students to analyze the materials used in their rapid prototypes Assign students to analyze the materials included in their final prototype
2	Identify how materials may be reutilized at the end of the product's life	Ask students to design all prototypes for disassembly Ask them to keep a record of materials used throughout course
3	Assess and then reduce the amount of energy required for production	Defer until advanced design course
4	Assess and improve water usage and discharge quality	Defer until advanced design course
5	Engage in socially	Ask students to analyze the impact of their

	responsible and ethical corporate practices	prototyping process and final prototype on the environment and human health and well-being. Ask students to consider the environment and human health and well-being as stakeholders in their stakeholder assessment

The idea would be not to ask students to do more than is possible in a 10-week period when they have to learn so much new material and please so many "masters" but to have them be more analytical about their decisions and explain what they decided to prioritize and why.

For students to develop more fully toward adaptive expertise in cradle to cradle design, we would have to plan interventions to close the "efficiency gap" for upper level classes, where students are introduced to the knowledge that would help them consider steps 3 and 4 of the McDonough-Braungart model [5, 15]. This could be done through an audit of other required project-based classes to discover opportunities for intervention. Interventions in the other courses will help students view cradle to cradle design with increasing sophistication. For example, in an upper-level course at our school titled Interdisciplinary Design Projects, students begin by studying professional techniques for human observation. In preparation, when students are asked to identify stakeholders in the design, typically they focus on the primary user. We could again encourage students to consider the environment and future generations as stakeholders in the design. Following observation, students are taught rapid prototyping for idea generation. As in EDC, they are expected to assess the current solutions to the problem. Students could conduct life cycle analyses on the current solutions to understand the impact of these products on the environment. Existing solutions may be deficient because they fail to meet not only the immediate user needs, but also the broader set of stakeholders' environmental needs. Another opportunity for intervention may take place in a culminating course titled, Engineering Portfolio Design and Presentation. In this class, students are asked to reflect on their design process and the design objects, processes, and services they created while at Northwestern or in their broader undergraduate experience. As this is the final course in design that many students take as undergraduates, we may suggest that students reflect on the role of cradle to cradle design during their development as designers at Northwestern. In upper level design courses, there are numerous opportunities for intervention; the goal will be to intervene in a meaningful and efficient way that aligns with rather than distracts from a course's intentions.

Interventions with faculty: Teaching the first-year design engineering course EDC instructors are eager to provide a broad overview of human centered engineering design. Currently, the course teaches methods for ideation and brainstorming as well as skills such as technical drawing, clear written and oral communication, teamwork, and statistical analysis. However, the choice of topics to include in EDC is determined by other factors such as instructor expertise and preference, professional practice, and alignment with standards established by Northwestern and ABET for engineering education. Therefore, the following interventions should be considered:

1. To increase instructor expertise and preference to teach cradle to cradle design, we recommend hosting conversations with faculty about the basic principles and explain step by step the interventions we took in our classrooms and their impact on student learning. We expect that greater familiarity with cradle to cradle design principles will lead to greater confidence teaching the material in the approximately 48 sections of EDC that are taught each year.

2. We suggest familiarizing faculty with the expectations for practicing designers in this area. Designers are increasingly expected to be able to use tools such Life Cycle Analysis to assess the environmental impact of their design decisions. Eco-efficiency is being added to product specifications alongside traditional specifications such as functionality, cost, and product safety [19].

3. Design faculty and shop instructors need to be made aware of alternatives to foam core and other environmentally hazardous materials. Currently, foam core is the most readily available low fidelity prototyping material in the shop facilities where students begin their prototyping efforts. We envision making alternative materials available for students to use and reuse and educating them on site about the impact of their material selection.

Interventions like the ones described in this article should be explicitly aligned with the standards for engineering education as outlined in such documents as *The Engineer of 2020*. As noted in our introduction, engineers of the future are expected to be leaders in the movement toward "wise, informed, and economical sustainable development" [1]. Thus engineering students must know how to develop eco-designed products and development processes and must be committed to their importance.

VI.   Acknowledgments

VII. References

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Table 1: Five Steps Towards Cradle to Cradle Design (McDonough & Braungart, 2002)

Figure 1: Relationship of efficiency and innovation in adaptive expertise. The "function of the 'optimal adaptability corridor' is to help insure that innovation and efficiency develop together" (Schwartz, Bransford, and Sears, 2005).

Table 2: Typical Student Responses at the Beginning of the EDC course as to what "Cradle to Cradle" Design Means.

Table 3: Examples of Students' Attempts to Follow the Five Steps towards Cradle to Cradle Design while Prototyping

Table 4: Future Interventions with Introductory Students for each Step Toward Cradle to Cradle Design