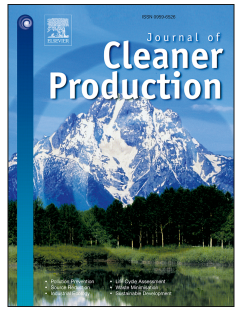

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Integrating environmental sustainability in undergraduate mechanical engineering courses using guided discovery instruction

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Abstract

In this paper we discuss a guided discovery instruction approach for integrating environmental sustainability in undergraduate mechanical engineering courses. To validate the proposed approach, we conducted two studies with students in a computer-aided design and prototyping course. The first study verified the feasibility of incorporating guided discovery instruction for teaching environmental sustainability using a structural shape synthesis design task. The second study compared the influences of the guided discovery instruction approach and traditional lecture-based instruction on students' understanding of environmental sustainability concepts. Results show the guided discovery instruction approach facilitated a better understanding of interactions among design parameters and the resulting environmental impact. We also found that students in the guided discovery instruction group gave more prominence to modifying design parameters specific to mechanical engineering concepts taught in the course. These findings suggest that using guided discovery instruction to teach environmental sustainability in undergraduate mechanical engineering courses is beneficial for promoting students' understanding of complex relationships between domain-specific design parameters and environmental sustainability.

Keywords: Guided discovery, Engineering education, Environmental sustainability

LIST OF ACRONYMS & ABBREVIATIONS

Al: Aluminum 2036
ANCOVA: Analysis of covariance
ASME: American Society of Mechanical Engineering
C#: design constraint number #
CAD: computer-aided design
CI: cast iron GGL-NiCuCr
CNC: computer numerical control
CS: carbon steel 35S20
EI: cradle-to-gate environmental indicator
ES: environmental sustainability
ESBP survey: survey on students' background in environmental sustainability and perception of environmental sustainability concepts
ESDQ: environmental sustainability design questionnaire
ESIP survey: survey on students' perception of instruction approaches used in teaching environmental sustainability

FEA: finite-element analysis
HSS: high speed steel
LCA: life cycle assessment
ME: mechanical engineering
ME444: undergraduate mechanical engineering course on computer-aided design and prototyping at Purdue University
RQ#: research question number #
S1: study 1
S2: study 2
Wt: weight

1. INTRODUCTION

Incorporating ES learning has become one of the primary goals of engineering curricula (Accreditation Board for Engineering & Technology, 2013). In a survey of institutions with engineering programs conducted in 2009, 80% of respondents reported some level of activity with regards to ES (Murphy et al., 2009). There is also a growing demand in industry for engineers with skills in sustainable technologies. A survey by the ASME and Autodesk research has shown that approximately 60% of the 4000 respondents from engineering organizations expected an increase in their organizations' involvement in sustainable design the following year (American Society of Mechanical Engineering, 2010). Along similar lines, the Green Technologies and Practices survey conducted by the United States Department of Labor in 2011 indicates that three-quarters of business establishments use at least one green technology or practice (Bureau of Labor Statistics, United States Department of Labor, 2011). To promote engineering students' ES skills, they need to learn to consider ES as an integral part of the engineering design process. This requires ES to be integrated into the fundamental engineering courses in a manner that enables students to explore complex relationships between domain-specific design parameters and the resulting ES outcomes. To this end, instructional approaches in such courses need to facilitate deep understanding of such relationships and support conceptual change in students' mental models of ES.

Building on theories in constructivism, guided discovery has been advocated as an effective approach for promoting conceptual understanding of theories and principles (de Jong, 1991). Different from lecture-based instruction that directly provides target information to students, guided discovery instruction encourages students to construct knowledge through guided inquiry processes (de Jong & Lazonder, 2014). The discovery learning process resembles real-world science knowledge acquisition, where students go through the hypothesis generation, planning, experimentation, and evaluation stages (Rivers & Vockell, 1987). The presence of guidance is indispensable in discovery learning: students achieved greater learning gains in classrooms with a greater degree of guidance compared with unguided discovery or direct instruction approaches (Furtak et al., 2012).

Previous research has shown that guided discovery instruction can be a more effective means for learning relationships across concepts compared to direct instruction (Alfieri et al., 2011). This is relevant for ES learning as it also involves understanding complex and often implicit relationships across domains. To this end, our work focuses on developing a guided discovery instruction approach for teaching ES within existing undergraduate ME courses. Using the proposed guided discovery approach, we conducted two studies with students in an undergraduate ME course and explored the following research questions.

RQ1: Is there a need for contextualizing ES learning to specific undergraduate ME courses?

RQ2: What are students' perceptions on using the guided discovery instruction approach to teach ES in undergraduate ME courses?

RQ3: What are the influences of the guided discovery instruction approach and traditional lecture-based instruction on students' understanding of ES?

The contributions of this paper, include (1) a guided discovery instruction approach for teaching ES in undergraduate ME courses, (2) an example application of the instruction approach using a shape synthesis design task that allows students to explore inter-dependencies in ES and domain-specific design variables, and (3) study setup, analyses, and results comparing guided discovery and lecture-based instruction for teaching ES in an undergraduate CAD and prototyping course.

2. RELATED LITERATURE

In this section we review previous work that has developed ES-focused instruction approaches within engineering curricula. We also discuss previous research on guided discovery instruction.

2.1. Instruction Approaches for Integrating ES Learning in Engineering Curricula

ES has been incorporated into engineering curricula by developing new engineering courses focused on ES (i.e., courses on sustainable product design, renewable energy, etc…), integrating ES concepts into traditional engineering courses, introducing self-directed learning modules on ES (e.g. Autodesk Sustainability Workshop (Faludi & Menter, 2013)), and allowing students to opt for ES-related electives offered in other departments.

Pioneering efforts in sustainability learning focused on developing holistic approaches to increase awareness of interdependencies at the system level. Tilbury (1995) states that environmental education for sustainability should focus on developing closer links between environmental quality, ecology, socio-economics, and the underlying political threads. Reorienting education for promoting sustainable development is discussed by Fien & Tilbury (2002). Their primary focus is the development of an educational system for learning the knowledge, skills, perspectives, and values, that motivate people to lead sustainable livelihoods. Similarly, Ashford (2004) argues that sustainability learning should be interdisciplinary in nature to broaden the "design space" for engineers.

Previous research has also focused on developing courses, workshops, games, and practical experiences that promote active learning of ES concepts (Brundiers et al., 2010; Dieleman & Huisingh, 2006; Brewer et al., 2011; Gennett et al., 2010). Such efforts make ES learning more immersive, which is seen as an important focus for sustainability education (Pappas et al., 2013). Approaches such as learning through reverse engineering products (Hesketh et al., 1997) and cyberlearning modules based on constructionism (Kim et al., 2017) have also been explored for better integrating ES concepts into product design. Project-based learning and problem-based learning have also been used by researchers to integrate ES in university curricula (Steinemann, 2003; Ameta et al., 2010; Bernstein et al., 2012). A comparison of goals and approaches in problem-based learning adopted by multiple universities is discussed by Huntzinger et al. (2007). A majority of such approaches focus on introducing systems-level problems, such as spill cleanup (Hmelo et al., 1995), water conservation (Steinemann, 2003), and energy management (Bremer et al., 2010). Therefore, they are more suitable for teaching systems modeling and life-cycle thinking, rather than teaching relationships between specific design parameters and the resulting environmental performance. To bridge this gap, researchers have argued ES learning should be integrated into fundamental engineering classes.

Peet et al. (2004) noted that students find it difficult to integrate sustainable development into engineering practice unless the learning activities are incorporated in regular course work. Olsen et al. (2015) agreed that ideally engineering students should learn to consider sustainability in everything they do. However, the authors argue that time constraints, consideration of sustainability as a soft skill, organizational challenges, and academic cultural hurdles preclude this possibility. Kumar et al. (2005) concluded that sustainability education should be integrated into the design and manufacturing courses, and infusing ES into engineering curricula is essential for equipping students with the tools for achieving a sustainable future.

2.2. Guided Discovery Instruction

Guided discovery instruction has been proposed as an effective approach for teaching complex concepts in scientific domains (de Jong & Lazonder, 2014). In this instruction process, students are guided through the cycles of inquiry resembling scientific discovery: investigating questions, designing experimentation, observing outcomes, interpreting results and communicating findings (Alfieri et al., 2011; de Jong, 2006).

The advantages of guided discovery instruction over direct instruction are based on the premise of a knowledge "generation effect", which suggests that knowledge generated by students is more effective for learning than knowledge directly given to students (Bertsch et al., 2007). Also, constructivism theory, which emphasizes the benefits of knowledge construction, suggests that guided discovery can promote the conceptual understanding of theories and principles, especially on issues involving intertwined complex factors and trade-offs in the systems (de Jong, 1991). Previous research has also found guided discovery learning provides motivational benefits for students since constructing knowledge is generally more engaging and more likely to sustain student interest compared with lecture-based direct instruction (de Jong & Lazonder, 2014). However, it is important to note that when discovery learning is conducted by the students without any guidance, the outcomes are likely to be ineffective due to limitations in students' knowledge and skills to adjust and monitor the discovery process (de Jong & van Joolingen, 1998). Therefore, the guidance provided in discovery learning is crucial for promoting students' learning and motivation (Walker et al., 2014). This is further emphasized by a meta-analysis of research in science education that showed guided discovery instruction is more beneficial for learning compared to both unguided discovery and direct instruction (Alfieri et al., 2011).

Previous research has identified several issues that need to be considered while applying guided discovery instruction. When students lack prior domain knowledge on a topic, it is beneficial to directly present relevant information to students before or during the inquiry to promote the prior knowledge that the students can draw upon (Hmelo-Silver et al., 2007). In the current study, because the students indicated that they lack prior knowledge in sustainable design, we introduced relevant background information in the pre-activity sessions. Another issue is that the degree of guidance needed varies with the age of the students. Such guidance can be provided as either directive or non-directive support (de Jong & Njoo, 1992). Directive support provides students with direct instruction on the actions to be taken or the hypothesis to be tested. Non-directive support focuses on providing the main elements needed for conducting a discovery process, such as giving students the necessary elements to propose a hypothesis (de Jong & Lazonder, 2014). While younger (e.g., elementary and middle school) students may benefit from detailed and step-by-step directive support guidance, older students have been found to gain more with the non-directive and open type of guidance, such as question prompts and heuristics methods (Blanchard et al., 2010). In our study, we implemented open-ended question prompts to guide the undergraduate students to reflect on the heuristics and principles used in making the sustainable design decisions.

As some of the beneficial types of guidance in discovery processes coincide with the features afforded by computer supported environments, previous research has examined guided discovery learning in computer simulation settings structured as either conceptual models or operational models (de Jong & Lazonder, 2014). In our study, conceptual models that focus on the major principles and concepts (e.g., relationships between design variables and ES performance) are more relevant than operational models that focus on procedural knowledge. Examples of using such conceptual models in computer simulation environments include encouraging students to manipulate values in input variables and make inferences about principles based on observations of corresponding changes in the output variables (van Joolingen et al., 2005). In this study, we structure the simulation activities as encouraging students to discover the rules that apply to the sustainable design search space through manipulating variables and observe outcomes in the experiment space.

Despite the discussed benefits of guided discovery learning, such inductive learning approaches have found limited use in engineering education settings. As previous research has suggested, engineering education is traditionally carried out in a deductive fashion, where theories are learned and applied to relevant problem solving processes (Prince & Felder, 2006). Considering the potential of guided discovery learning and the lack of research in this area within engineering education, the current study intends to explore the integration of guided discovery learning in ES learning within an undergraduate mechanical engineering course. To the best of our knowledge, previous research has not explored the use of guided discovery instruction to contextualize ES to such undergraduate engineering courses.

3. METHODOLOGY

3.1. Study Design

The goal of this work was to explore the research questions outlined in the introduction section. We conducted two separate studies in ME444, a course on CAD and prototyping at Purdue University. The reasons for choosing ME444 over other ME courses, included (1) presence of two class sessions that yielded two groups of students, (2) presence of a homework assignment that could be adapted to integrate guided discovery instruction, and (3) need for involving ES-based learning in the course. As shown in Fig. 1, we compared two instruction approaches for teaching ES in ME444, (1) the proposed guided discovery instruction approach which centers on helping students explore relationships among material, geometry, & ES, and (2) traditional lecture-based instruction on ES.

First, we conducted a study (S1) to check if the proposed guided discovery instruction approach could be integrated into ME444 within the existing course objectives and schedule. After the completion of S1, we conducted a more complex study (S2) in a subsequent semester (with a different student cohort) which compared students' learning of ES concepts in the proposed guided discovery approach to that in lecture-based instruction. Thus, S1 served to confirm that the guided discovery instruction approach was viable in ME444 and S2 provided insights on comparing guided discovery instruction and lecture-based instruction. The procedures for implementing the two studies (S1 & S2) are described in Section 3.5.

3.2. Participants

The participants in S1 and S2 were full-time undergraduate students enrolled in ME444. This course is offered as a technical elective and is open to students enrolled in their junior and senior years. The total enrollment in the class was 71 in the semester S1 was conducted and 61 for S2. Please note that S1 and S2 had different student cohorts as they were conducted in different semesters of ME444. For both studies, we administered a voluntary demographics survey in which we received 59 responses in S1 (response rate: 83%) and 40 responses in S2 (response rate: 71%). From the surveys we found that in both studies a majority of the respondents were, in the ME program $(S1 = 81\%;\ S2 = 68\%)$, in their senior year $(S1 = 72\%;\ S2 = 69\%)$, and male $(S1 = 83\%;\ S2 = 55\%)$.

In S2, we split the students into two groups (Group 1 & Group 2) to compare guided discovery instruction with lecture based instruction. This was possible as ME444 had two separate sessions–a morning session and an afternoon session. Students self-selected which class session they would attend while enrolling for ME444. For S2, all ME44 students in the morning class session were considered as Group 1 and all students in the afternoon class session were considered as Group 2. The allocation of guided discovery instruction to Group 1 and lecture based instruction to Group 2 was made by random selection at the start of the semester before the enrollment deadline.

3.3. Materials

The materials and measures used in S1 & S2 are illustrated in Fig. 2. The materials consisted of the proposed guided discovery based instruction approach, lecture-based instruction, and a shape synthesis design task. The measures included surveys on, (1) students' background in ES and their perception of ES concepts, and (2) students' perception of the two ES instruction approaches, and (3) an ES design questionnaire that measured students' learning of ES concepts prior to and after the instruction approaches.

As shown in Fig. 2, the first study (S1) was not modeled to be comparative. The second study (S2) compared the two instruction approaches by splitting them across the two groups in ME444. S2

Group 1 solved the shape synthesis design task using the proposed guided discovery based instruction approach. On the other hand, S2 Group 2 solved the shape synthesis design task using lecture-based instruction.

3.3.1. Shape synthesis design task

The shape synthesis design task contextualizes ES to ME concepts taught in ME444. It was developed by modifying a homework assignment that required students to analyze a brake pedal capable of carrying a specified load without failure. The modified shape synthesis design task required students to simultaneously minimize the final weight and the environmental impact of the brake pedal. This is a challenging design task as weight and environmental impact were setup to be conflicting design parameters. The task was also setup such that the output performance in ES, stress, and weight varied considerably with both material and geometry. Thus students had to consider inter-relatedness among design parameters and the resulting performance parameters, similar to real-world design tasks.

Students were required to synthesize different geometries starting from an initial blank shown in Fig. 3. Two additional design constraints (C5 & C6) were added to the list of physical constraints provided in the original assignment. C5 increased the complexity of the task as the choice of material significantly impacted the weight and the computed environmental indicator. C6 was setup so that the initial and final volumes of the CAD model could be used to compute an environmental indicator. The entire list of constraints given is shown below.

C1: A load of 5 psi is uniformly distributed on the pedal face.

C2: Friction between all surfaces can be neglected.

C3: The pedal is attached to a frame (not shown) using two bolts which holds the bolt face against that frame.

C4: The equivalent Von Mises stress cannot not exceed the maximum allowable stress.

C5: The design should use one of the three specified materials: CI, Al, or CS.

C6: All CAD modeling operations should only involve material removal.

Students solving the design task using guided discovery were required to perform three or more design iterations. When they performed these design iterations, they were guided by a human expert. They were also given access to a spreadsheet-based environmental indicator calculator. This calculator was provided as training the students on environmental impact calculation using LCA software was not practical due to time constraints in ME444. The calculator approximates the environmental impact of the design using a single score cradle-to-gate environmental indicator. Students were also provided with expert-estimated uncertainties in the computed indicator. Equation 1 describes the calculation of of the single score cradle-to-gate environmental indicator (EI). It accounts for environmental impacts of material extraction, formation of blank, manufacturing, and material recovery. Unit impacts related to resource extraction, ecosystem quality, and human health were estimated using the Ecoinvent 99 (I) method available in SimaPro®.

$$EI = k_1^{Sum} * W_b + \left(k_2^{Sum} - f * k_3^{Sum}\right) * \sum_{i=0}^{n} MRW_i \qquad (1)$$

Here,

W_b : weight of the starting shape (blank)

MRW_i : weight of material removed in the i^{th} manf. step

n : total number of manufacturing steps

f : fraction of material recycled from the total material removed in the machining processes.

k_1^{Sum}, k_2^{Sum}, k_3^{Sum} : respective single score unit process impacts for material extraction, manufacturing, and material recycling

Table 1 shows the values for k_1^{Sum} and k_2^{Sum} for materials in the shape synthesis design task. They are calculated by summing the unit process impacts on three impact categories: resource consumption (*R*), ecosystem quality (*E*), and human health (*H*). All material removal operations for the part $(i:1,2,\ldots,n)$ were assumed to be CNC milling. For calculating k_3^{Sum} we assumed a 100% recycling credit (i.e. $k_3^{Sum}=k_1^{Sum}$) and that all machined material was recycled ($f=1.0$). In our previous work (Ramanujan et al., 2014), we found these simplifications were necessary for keeping the structural shape synthesis problem at a reasonable level of complexity. As shown in Tbl. 1, the unit process impacts are expressed in Pt/lb where 1 Pt represents one thousandth of the yearly environmental load of an average European inhabitant. To compute the EI for a given design, students input the current volume of the design in the spreadsheet. For each iteration, MRW_i is calculated by multiplying the difference in volume from the previous step by the density of the chosen material. The spreadsheet computes the EI based on the input MRW_i and Eq. 1.

Students using lecture-based instruction (S2 Group 2) solved the design task based on ES concepts taught in a traditional lecture setting. While they were allowed to seek further clarifications on the design task, no guidance or support material for ES was provided. Additionally, students in this group were not required to perform a minimum number of design iterations.

3.3.2. Guided discovery instruction approach

The guided discovery instruction approach was developed for integrating ES in existing undergraduate ME courses. It aligns with the primary propositions of constructivism (Savery & Duffy, 1995) and focuses on fostering student learning through the exploration of authentic design problems. Students are guided by a mentor with expertise in both the ME and relevant ES concepts. The processes in our guided discovery approach and their relation to constructivism principles are shown in Table 2. The five steps shown in this table form the basis for applying guided discovery instruction to a structural shape synthesis design task in ME444. While we only discuss the application of the proposed guided discovery approach to one context (structural shape synthesis), the framework is developed in a general manner so that it can be adapted to other undergraduate ME courses in the future.

3.3.3. Lecture-Based instruction

The lecture content was developed and delivered by a senior faculty member in the School of Mechanical Engineering at Purdue University with expertise in sustainable design and manufacturing. The faculty member has used similar lectures to introduce ES in undergraduate and graduate-level design courses in ME. The 50 minute lecture covers concepts in designing for ES, including (1) definition of ES, environmental impact, and ecological footprint, (2) design for environment and life cycle thinking, (3) principles in eco-design and sustainable design, (4) tools for sustainable product design, and (5) introduction to LCA The lecture also provides concrete examples on environmental impact estimation and redesigning products to lower their environmental impacts.

3.4. Measures

3.4.1. ESBP survey

The ESBP survey asked students about their prior background in ES-related training and their perception of integrating ES in ME instruction. This survey included questions about their experience in ES, plans for enrolling in ES-related courses in the future, and self-perceived importance of learning ES concepts in engineering curricula. The survey also contained demographic questions related to students' degree program, current standing, and completed courses.

3.4.2. ESIP survey

The ESIP survey assessed students' attitudes towards the instructional approaches used to teach ES concepts in ME444. We also asked students if introducing a similar instruction approach in other undergraduate ME courses would be help them better contextualize ES to ME. In the ESIP survey, students rated on a 3-point scale (0–no, 1–maybe, 2–yes) on whether the instruction approach should be integrated as part of the regular component of ME444. Students also rated on a 5 point scale (ranging from 1 to 5) the necessity to extend the instruction approach to other ME courses as well as the likelihood of using ES in future designs.

3.4.3. ESDQ

The ESDQ assessed students' learning of ES concepts by asking them to compare ES-related performance of design alternatives. There were four questions in ESDQ where students selected the most environmentally benign choice for a design situation and provided rationale for their choice. The questions covered ES-related design decision-making for, (1) manufacturing process selection of an external spur gear, (2) material and geometry selection of an end mill used in a CNC milling process, (3) material selection for a cable used for supporting a transmission line wire, and (4) comparing a leaf spring, air suspension spring, and a helical steel spring for a trailer suspension system. The focus of the questionnaire was to gather students' rationale for making ES-related evaluations. The ESDQ also served as a question prompt for motivating students to reflect on the concepts learned. Please note the same questionnaire was distributed to students in both instruction groups in S2, prior to and after the respective ES instruction approaches (see Fig. 2).

3.5. Procedures

The overall setup of the studies is shown in Fig. 2 and the timeline of tasks is shown in Fig. 4. The following sections describe the detailed procedure for the two studies.

3.5.1. S1 Procedure

S1 was conducted to check if the guided discovery instruction approach could be integrated into ME444 within the existing course objectives and schedule. As shown in Fig. 2, students in S1 were given, (1) the ESBP survey, (2) the shape synthesis design task using guided discovery instruction, and (3) the ESIP survey.

The shape synthesis design task was given as a week long take-home individual assignment. Before distributing this assignment, we conducted a 30 minute session that clarified the overall objectives, constraints, and the grading rubric for the assignment. We provided guidance for the assignment using a combination of guided discovery support (non-directive support) and instruction documents (directive support). Along with the assignment, we distributed (1) a step-by-step instruction document related to the CAD and FEA software, (2) a reference manual that explained the methodology behind ES assessment, and (3) a spreadsheet-based calculator for cradle-to-gate environmental indicator (discussed in Section 3.3.1). Students were offered guidance during the assignment through experts (in CAD, FEA, and ES) via two 90 minute lab sessions. The experts were instructed not to provide any direct design guidance. They helped students overcome problems with the software, conceptual understanding, and guided students' exploration processes. We refrained from counting the number of questions posed by students during the lab sessions as doing so would have encouraged performance goals rather than mastery goals, which is not beneficial for promoting the motivation and autonomy of the students (Ames, 1995).

Students were allowed to discuss and compare their results for Wt and EI, but were not allowed to share details about their actual designs. We also motivated students by including mastery-oriented learning objectives. Therefore, apart from final EI and Wt, students were asked to submit documentation on each design iteration. We asked students to perform a minimum of three design iterations in order to facilitate guided discovery instruction. However, students were free to iterate more than three times. At the end of each iteration, students were required to provide rationale for the change, selected material, Wt, EI, and assess whether their design met the constraints. Ninety percent of the assignment grade was based on correctly setting up design constraints and the FEA mesh. To encourage exploration of the design space, the remaining 10% grade was based on students' relative performance on the assignment. For this, final submissions were ranked using dominance-based sorting (i.e both EI and Wt are smaller than another solution) and binned into four quartiles. Students received either 100%, 75%, 50%, or 25% of the 10% grade, depending on their placement in the quartiles.

3.5.2. S2 Procedure

S2 was conducted in a subsequent semester and was setup to compare students' learning of ES concepts in the proposed guided discovery approach and lecture-based instruction. Therefore, students in the two class sessions were exposed to two different instruction approaches (see Fig. 2). Students in S2 Group 1 (morning session) solved the shape synthesis task using the guided discovery instruction approach. The study procedure for this group was the same as the one described in Section 3.5.1.

Students in S2 Group 2 (afternoon session) solved the shape synthesis task using lecture-based instruction. Therefore, students in S2 Group 2 received a 50 minute lecture on ES concepts before the shape synthesis design task (see Section 3.3.3). Students in S2 Group 2 were allowed to seek clarification from the course instructors during the task. However, no form of ES-related guidance or support material was provided during the task. Furthermore, students in S2 Group 2 were not required to perform a minimum number of design iterations. For both S2 Group 1 and S2 Group 2, the design task was given as a week-long, individual, take-home assignment. The grading rubric, mastery-based incentives, and submission protocols were also the same for both groups. As shown in Fig. 2, students from both S2 Group 1 & S2 Group 2 were given the same ESBP survey, ESIP survey and ESDQ (see Sections 3.4.1, 3.4.2, & 3.4.3).

3.6. Content Analysis of Open-Ended Responses to ESIP and ESDQ

To identify the students' understanding of ES concepts, we performed content analysis of the responses to an open-ended question in the ESIP survey, where the students described the insights they gained from the instructional approaches. For the same purpose, we also analyzed students' responses to the pre-ESDQ and post-ESDQ. In both cases, content analysis was conducted in the form of iterative open coding of the responses in order to identify emerging themes (Hsieh & Shannon, 2005; Krippendorff, 2004). In the first coding iteration, two researchers worked independently and generated preliminary codes for the same set of selected responses. Then the two researchers discussed and consolidated the preliminary codes.

Afterwards, one researcher coded the remaining responses using the consolidated codes. The researcher also generated new codes in the process when the existing codes did not fit with a particular category. In the second coding iteration, the researcher read all the text under each code and either combined or split the codes into categories or subcategories. Finally, a third coder randomly selected one third of the responses and applied the codes to check for inter-rater reliability.

In conducting the content analysis, we used the Dedoose qualitative data analysis software. As recommended by the Dedoose user guide (Dedoose, 2018) and other previous research (Greene et al., 2014), the percentage data resulting from the content analysis were normalized because there were unequal numbers of cases in each group. The normalization procedure in Dedoose operates by assigning a weight of "1" to the group with the largest number of members (basis group) and then assigns weights to the other groups as a function of the numeric relation between the number of members in the group to that of the number of members in the basis group (Dedoose, 2018). These weights were then used to adjust the number of raw counts to accomplish ratio equivalence across group and the weighted percentage was calculated based on these adjusted counts. Such normalization is deemed necessary because the percentage of code application by group is relatively meaningless if there are unequal numbers of individual cases across each sub-group (Dedoose, 2018).

4. Results

4.1. Students' Performance on the Shape Synthesis Design Task:

Table 3 details key statistics related to the shape synthesis design task for S1, S2 Group 1, and S2 Group 2. Please note Tbl. 3 only displays summative statistics for valid submissions, i.e. submissions that correctly setup and solved the assignment. As shown in Tbl. 3, a majority of students performed more than the minimum of 3 iterations in the guided discovery instruction approach. In S1, 28/43 students performed over 3 iterations while in S2 Group 1, all students performed over 3 iterations. We found a significant negative correlation between the total number of iterations and final weight in both S1 ($Pearson\ r(41) = -0.35$, $p = .021$) and S2 Group 1 ($Pearson\ r(17) = -0.488$, $p = .0341$). However, the number of iterations was not correlated to the final EI.

We compared the EI and Wt for the final designs and did not find a significant difference between S1 & S2 Group 1 as well as S1 & S2 Group 2. However, the EI for S2 Group 1 and S2 Group 2 shows a significant difference ($t(33) = 2.3756$, $p = .0235$). We also found a significant difference in final Wt between S2 Group 1 and S2 Group 2 ($t(33) = 2.5558$, $p = .0154$). As mentioned in Section 3.3.1, the shape synthesis design task was setup such that EI significantly varied with material choice. We found students in S2 Group 1 displayed more uniformity in materials used in their final design ($Al = 31.58\%$, $CI = 36.84\%$, $CS = 31.58\%$), as compared to S2 Group 2 ($Al = 43.75\%$, $CI = 18.75\%$, $CS = 37.50\%$).

4.2. Students' Background and Perceptions in ES

To identify the need for integrating ES in ME courses, we examined student responses to the ESBP survey. We received 59 responses in S1 (response rate: 83%) and 40 responses in S2 (response rate: 71%). We found that the students had little training on ES either from coursework or project experiences. Only 1/59 respondents in S1, and 1/19 in S2 Group 1, and 4/21 in S2 Group 2 reported having prior experience related to ES. Students ratings on the importance of learning about ES concepts in engineering (1: "not important" and 5: "very important") showed that the average rating for students in S1 was 3.67, with standard deviation 0.64. For students in S2, the average rating was 4.18, with standard deviation 0.93. There was no significant difference in student ratings between S2 Group 1 and S2 Group 2 ($t(38) = 1.1355$, $p = 0.2633$). Thus, results show students in both studies gave higher than neutral ratings (mid-point value $= 3.0$ on the 1–5 scale) on average and indicated the importance of learning about ES in ME.

4.3. Students' Perception of ES Instruction Approaches

After experiencing the respective instruction approaches, students reported their perception of the guided discovery and the lecture approaches in the ESIP survey. We received 29 responses in S1 (response rate: 41%) and 40 responses in S2 (response rate: 71%). For S2, 19 responses were from the guided discovery group (S2 Group 1) and 21 from the lecture-based instruction group (S2 Group 2).

Table 4 presents the mean and standard deviation of S1 students' ratings on questions in the ESIP survey. The results show that on average, students in S1 gave ratings that are at or above the neutral ratings on the scales (mid-point value $= 1.0$ on 0–2 scale, or $= 3.0$ on a 1–5 scale). Thus, these results show that on average, students favored integrating ES in the ME444 course, other ME courses, and using ES in conducting sustainable design. In S2, because the students participated in either the guided-discovery instruction or the lecture-based instruction, we compared their ratings on the ESIP survey. Using one-way ANCOVA controlling for students' rating on the importance of learning about sustainable design concepts, we compared the students' ratings on the survey items and found that there was no significant difference between students in the guided-discovery instruction (S2 Group 1) and lecture-based instruction (S2 Group 2) on ME444 integration ($F=0.28$, $p=0.60$), other ME courses integration ($F=0.43$, $p=0.52$), and the likelihood of using sustainable design in the future ($F=1.41$, $p=0.24$). The descriptive statistics of the students ratings is shown in Tbl. 5.

Students in S2 also reflected on the insights that they gained on ES-based design after exposures to the instructional approaches. The results showed that 63.2% of the students who were exposed to the guided-discovery instruction approach and 52.4% of the students in the lecture-based approach reported having developed new insights about ES-based design. In the next section, we provide more details about the insights that the students described.

4.4. Students' Understanding of ES Concepts in Guided Discovery and Lecture-Based Instruction

To identify students' understanding of ES concepts, we analyzed the results from the content analysis of the open-ended responses to the ESIP and ESDQ. The methodology is described in Section 3.6. The inter-rater agreement for the two analysis reached 93% and 92% respectively.

4.4.1. Results from the ESIP survey:

In the ESIP survey, students in S2 reflected on the insights they developed from engaging in the guided-discovery and the lecture-based instructional approaches . The major coding categories that emerged from the content analysis are shown in Fig. 5 and in Tbl. 6.

Students in the guided-discovery group (S2 Group 1) referred to the "multi-factor" and "complex" nature of ES-based design more frequently than those in the lecture-based group (S2 Group 2). For example, as shown in Fig. 5, 100% of *Complexity & Multi-Factors in ES Design* category belonged to students in the guided-discovery group. On the other hand, none of the students in the lecture-based instruction group commented about this aspect of ES-based design. More specifically, we found that students in the guided-discovery group mentioned that it is necessary to consider "multiple design factors during ES-based design" and the "trade-offs in ES-based design". Additionally, students in the guided-discovery group had more instances of discussing the impact of the designs' shape and geometry on ES (as shown by the category *Correlations in Materials & Geometry* in Fig. 5). They talked about the inter-relatedness among material weight, volume, and shape on the environmental impact. Students in the lecture-based instruction group discussed about changes to material more frequently without being specific of the nature of the change (*Unspecified material changes* category in Fig. 5). For example, "reducing the impact of the material" and "switching to greener materials". In comparison to students in the guided-discovery group, students in the lecture-based instruction group also had more discussions in the *Unspecified design changes* category (see Fig. 5). They talked about "maintaining a balance between design functions and environmental impact", "reducing the impact of the design", and "reducing energy consumption". Such insights were more general and did not contextualize their ES learning to domain-specific design parameters such as type of material, part weight, and part volume. Students in both groups reported gaining insights on relationships between the manufacturing process and ES-based design.

4.4.2. Results from pre- and post-ESDQ:

We also examined students' design rationale in the pre- and post-ESDQ. Fig. 6 illustrates one of the questions in the ESDQ as well as students' pre- and post-ESDQ choices for this question. The percentages in Fig. 6 indicate students who switched their design choices from the pre- to post-ESDQ. The percentages in blue are for students in the guided-discovery instruction (S2 Group 1) and the percentages in green are for students in the lecture-based instruction (S2 Group 2) . For all four questions, there were more students who retained the same choice compared to students who switched choices. However, the rationale provided by the students significantly changed in this process. To provide a complete picture of students' understanding of ES concepts, we conducted content analysis of the students' rationale for the design choices.

The major coding categories generated from content analysis include, *Design*, *Impacts*, *Manufacturing*, and *Material* (see Tbl. 7). Upon examining the subcategories under *Materials*, we found that the frequencies of making references to *Material Strength* increased from the pre-ESDQ to the post-ESDQ for students in the guided discovery group. In comparison, the frequencies in these categories decreased for students in the lecture-based instruction group (see Fig. 7). We also found that the frequency of describing the role of *Material Shape* and *Material Weight* in ES-based design increased from the pre-ESDQ to the post-ESDQ for both the groups. However, the increase for students in the guided discovery group is more than that of the students in the lecture-based instruction group. We found students in the guided discovery group decreased in referring to the *Material Properties*, students in the lecture-based instruction group increased in discussing this aspect. The *Material Properties* category includes aspects of ES-based design that are less contextualized to ME concepts taught in the course. For example students' responses mentioned arguments such as, “Because it is made of high strength steel”, “HSS is cheaper and less environmentally costly to produce”, and “This is the softest material to produce and it is readily available”. Thus, these results indicate students in the lecture-based instruction group focused on broader strategies in ES-based design, whereas students in the guided discovery group gave more prominence to the specific design factors and the changes in design parameters such as shape, geometry, and weight change. Similar patterns were also observed in the category of *Design Performance* and the subcategories of *Manufacturability* and *Machinability* under *Manufacturing* (see Fig. 7).

5. DISCUSSIONS

In this section we discuss the three research questions outlined in the beginning of the paper based on results from our studies. We also discuss our observations about the feasibility of incorporating ES-related guided discovery instruction in undergraduate ME courses.

RQ1: Is there a need for contextualizing ES learning to specific undergraduate ME courses?

Results from the ESBP survey (Section 4.2) show students from all three groups (S1, S2 Group 1, & S2 Group 2) had very limited prior exposure to ES through the ME program and personal experiences. Despite their lack of prior experiences, students from all three groups reported that it is important to learn ES concepts within engineering courses. However, this study was conducted in a junior-level course and students had limited avenues for gaining ES-related learning in the remainder of the curriculum. Furthermore, results from our survey of graduate-level ME students (Ramanujan et al., 2014) found similar knowledge gaps; particularly in applying known ES concepts into engineering practice. These studies indicate the need for undergraduate ME curricula to improve integration of ES concepts within existing and new courses.

Content analysis of the ESIP survey indicates that students in the guided-discovery group developed a more contextualized understanding of ES-based design in ME as they gave prominence to the complexity of the design process, and the necessity to consider multiple ES design factors (i.e material strength, weight) in the design process. We also found students in the guided discovery group were able to construct knowledge about the trade-offs and complexities involved in ES-based design. Furthermore, results from the content analysis of the ESDQ surveys indicate that guided discovery instruction leads to a positive impact on students’ understanding of ES concepts. Thus, our results suggest that facilitating the contextualization of ES concepts in ME through guided discovery instruction may promote better integration of ES into design courses in ME. Facilitating such integration is known to be a significant consideration in sustainable product design (Ramani et al., 2010). These findings, along with results by other researchers (Peet et al., 2004; Kumar et al., 2005; Staniškis & Katiliūtė, 2016), support the need for further research on contextualizing ES learning to undergraduate ME courses through approaches such as guided discovery instruction.

RQ2: What are students’ perceptions on using the guided discovery instruction approach to teach ES in undergraduate ME courses?

Results from the ESIP survey (Tbl. 4) show, students in S1 developed positive attitudes towards the guided-discovery instruction approach and reported a high likelihood of using learned ES principles in their future designs. Students were also in favor of extending the guided discovery instruction approach to teach ES in other ME courses. Similarly, students who used the guided-discovery instruction approach in S2 (S2 Group 1) reported positive attitudes towards integrating the ES-related instruction approaches in ME444, extending the approach for ES instruction in other ME courses, and high level of likelihood to use learned ES concepts in their future designs (see Tbl. 5).

We also found the potential benefits of guided discovery instruction for motivating students (S1 and S2 Group 1) to explore the relationships between ES and ME concepts in the shape synthesis design task. For instance, the survey results from ESIP showed that in S2, a higher percentage of students who used the guided-discovery approach (S2 Group 1) reported having gained insights related to ES design than those who used the lecture-based approach (S2 Group 2). These results lend support to other studies (de Jong & Lazonder, 2014) that suggest guided discovery instruction promotes student's motivation by allowing them to construct knowledge between multiple related concepts.

Furthermore, although the shape synthesis design task required the students to conduct a minimum of three design iterations, a majority of the students in both S1 and S2 Group 1 performed more than three design iterations as shown in Tbl. 3. This suggests that students in these groups were motivated to continue exploring the design space. However, it is important to note that our study collected student-reported iteration data from students in the guided discovery group only. Data on the number of design iterations were not available for students in the lecture-based group. Thus, this finding is not regarding the unique benefits of guided discovery approach compared to the lecture-based instruction approach. Findings from our study seem to reflect previous research (de Jong & Lazonder, 2014) that found motivational benefits of guided discovery instruction, wherein students demonstrated interest and persistence on the task. However, it is necessary to conduct future controlled experiments to compare the motivational outcomes in guided discovery and lecture-based instruction approaches in future studies.

In summary, results show that the students developed positive attitudes towards integrating the proposed guided discovery instruction approach in ME444 and other undergraduate ME courses. We also found guided discovery approach may also provide motivational benefits for students to explore the relationships between ES and ME concepts.

RQ3: What are the influences of the proposed guided discovery instruction approach and lecture-based instruction on students' understanding of ES?

Our findings extend the previous literature by showing that the guided discovery instruction approach aided students to develop a deeper understanding of the complexity and inter-relatedness of the domain-specific design variables and ES outcomes, compared to students who received the lecture-based instruction approach. Results from the content analysis of the ESDQ show students in the guided-discovery group (S2 Group 1) gave more prominence to the specific design parameters (i.e. shape, weight, strength) relevant to the concepts discussed in ME444 while solving the questions in the ESDQ. On the other hand, students in the lecture-based group (S2 Group 2) were more focused on broader design strategies (i.e. switch to a renewable energy) peripheral to ME concepts discussed in the course. This suggests guided discovery instruction was more beneficial in fostering a deep level understanding and contextualizing ES learning to ME concepts discussed in the course. This finding is consistent with previous research that found the use of guided discovery approach facilitated deep level understanding of issues involving complex factors and trade-offs in the system (de Jong, 1991). Based on prior literature discussed in Section 2.2, our results seem to indicate that the guided discovery approach helped students build on their prior knowledge and assimilate ES concepts while giving students ownership of the problem solving process by encouraging them to test ideas against alternative perspectives. Through these guided discovery processes, students seemed to have developed a more contextual understanding of ES concepts and recognized the necessity to consider factors in a richer combination of categories. In comparison, students in the lecture-based approach group received direct instructions and may not have access to the motivational and information processing benefits afforded by the guided discovery instruction (de Jong & Lazonder, 2014).

A potential reason for the benefits of the guided discovery approach observed in this study is, students reflected on their reasoning behind the design decisions through question prompts (in the ESDQ) distributed before and after working on the shape synthesis design task. This reflection could have helped them assimilate principles that apply to the ES design search space by manipulating design variables and observing corresponding outcomes in the experiment space. Additionally, previous research has shown simulation tools that use question prompts to encourage students to reflect on their comprehension of the problem space and justify the reasoning of the inquiry process are beneficial for promoting learning outcomes in guided discovery learning (van Joolingen et al., 2005). In our study, students in the guided discovery group, had access to question prompts and domain knowledge from experts. They were able to conduct iterative discovery cycles and discover the ways in which the material shape, strength, and Wt act together to affect EI. Such experiences may have contributed to the guided discovery group students' growing frequencies in considering these domain-specific design factors in ES design decisions.

In summary, our findings indicate students in the guided discovery group developed a deeper understanding of the complex interactions among design parameters and the resulting environmental impact. This understanding had the benefit of shifting students' focus away from the non-specific and general strategies for ES-based design (i.e. reducing energy consumption, obtaining greener materials) towards the domain-specific strategies (i.e. redesigning part geometry and choosing more machinable materials). Constructing a deep level understanding of the relationships among the domain-specific design parameters and the resulting ES outcomes would also enable students to integrate ES principles into engineering practice.

6. LIMITATIONS

Our study focuses on the specific ME domain of structural shape synthesis. We have not explored the effects of our instruction approach in other domains such as heat transfer or fluid mechanics. Therefore, without conducting further studies we cannot confirm the generalizability of our approach to these domains. We also found that feasibility of incorporating guided discovery instruction for teaching ES in undergraduate ME courses is significantly affected by course-specific constraints. For example, relevance to existing syllabus, time burden imposed on students, and instructor and organizational support towards ES teaching. In our study, the amount of time available was indicated as the reason for stopping the exploration process by a significant majority of the students. The course instructors for ME444 also pointed that it could be challenging to engage an ES expert every semester to run this module. Therefore, to be successful, the proposed guided discovery approach needs formal collaboration between faculty with expertise in ES and other undergraduate faculty. Previous research has shown making such changes can be difficult without organizational and cultural rethinking (Olsen et al., 2015).

7. CONCLUSIONS AND FUTURE WORK

This paper presents a guided discovery instruction approach for integrating ES in undergraduate ME courses. This instruction approach was tested in an undergraduate mechanical engineering course on CAD and prototyping by developing a ES-focused shape synthesis design task. We conducted two classroom-based studies that evaluated the need, learning, and limitations of our approach and also compared it to a lecture-based instruction of ES concepts. We found there is a significant need for contextualizing ES to undergraduate ME courses through development of more integrative course content. To this end, results show guided discovery instruction motivated students to explore interrelationships between ES and ME concepts and helped them construct knowledge about the trade-offs and complexities involved in ES-based design. This finding lends support to other previous studies (de Jong & Lazonder, 2014) that suggest allowing students to construct knowledge using guided discovery motivates their learning process. Additionally, students in the guided discovery instruction group were more aware of the complex and multi-factor nature of ES-based design when compared to students in the lecture-based instruction group. We also found guided discovery instruction had a positive impact on students' understanding of ES concepts and allowed students to explore ES-based design by changing domain-related design parameters specific to the course. This could enable students to better understand ES-related implications of specific design changes and lead towards framing ES as a necessary performance constraint during the mechanical design process. Finally, our results show students using the guided discovery instruction approach were in favor of using it to teach ES in other ME courses. Our results build on findings from previous studies (Alfieri et al., 2011; de Jong & Lazonder, 2014) and suggest that guided discovery instruction could enable better integration of ES concepts within undergraduate ME curricula.

In our future work, we will look at applying the discussed guided discovery instruction approach to other undergraduate ME courses, e.g. heat transfer and fluid mechanics. An important consideration in our future work will be studying students retention of learned concepts and their motivation to apply sustainability concepts to other engineering design problems. Holistic integration of ES with ME also requires work on instructional models that facilitate conceptual change while guarding against misconceptions developed in these processes (Vosniadou, 1994). Assessing such changes requires future studies that (1) provide a better understanding of students existing misconceptions related to environmental sustainability when they enter the undergraduate program through measures such as group interviews, and (2) conduct longitudinal studies to assess changes relative to the identified baseline through the undergraduate program.

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Figure 1: The current ME444 course does not incorporate any environmental sustainability related content. In order to do so, we compared the proposed guided discovery instruction approach and traditional lecture-based instruction.

Figure 2: Materials and measures used in Study 1 and Study 2. Please note Study 1 and Study 2 were conducted in different semesters and therefore with a separate student cohort. Completion of tasks marked with a black circle contributed towards a student's final grade in the class. All other tasks were not graded and completion was voluntary. In Study 2, Group 1 received guided discovery instruction and Group 2 received lecture-based instruction. Both groups received the surveys on background and perception of environmental sustainability concepts, environmental sustainability instruction perception, as well as the environmental sustainability design questionnaire.

Figure 3: Starting blank for the shape synthesis design task (blank.prt). The goal is to design a brake pedal attached to a frame using two bolts (on bolt face) that can support a 5 psi load uniformly distributed on the pedal face. A sample set of three design iterations are also shown.

Figure 4: Timeline of tasks for the Study 1, Study 2 Group 1, and Study 2 Group 2. In all three cases, the tasks began in week 8 and ended in the final week of instruction (week 15).

Figure 5: The major categories of the insights that the students obtained from the guided-discovery (Study 2 Group 1) and lecture-based (Study 2 Group 2) instruction approaches. The table shows the percentage of students in either the guided-discovery or lecture-based group who made statements in a certain category. For instance, the first column shows that for students who made statements in the manufacturing process category, 45.30% of students belonged to the guided-discovery group, whereas 54.70% of the students belonged to the lecture-based group. Please note the displayed percentages are computed using the normalization function available on the Dedoose software (Dedoose, 2018).

Figure 6: Sample design question from the pre- & post-environmental sustainability design questionnaire (pre-ESDQ & post-ESDQ) evaluating the environmental sustainability performance of end mill designs. The diagram below the question shows students' switch in selection of design alternatives from the pre-ESDQ to the post-ESDQ. Percentages in blue represent students from the guided discovery group (Study 2 Group 1) and those in green refer to students in the lecture-based instruction group (Study 2 Group 2). For example, 0% of students in Study 2 Group 1 and 18.75% of students in Study 2 Group 2 changed their selection from the high speed steel (HSS) ball end mill to the Titanium Aluminum Nitiride (TiAlN) coated carbide square end mill from the pre-ESDQ to the post-ESDQ.

Figure 7: Coded categories that showed a change in frequency from the pre-environmental sustainability design questionnaire (pre-ESDQ) to the post-environmental sustainability design

questionnaire (post-ESDQ). The numbers in the table below the figure represent the percentage of students who belonged to a certain group who also made statements that were coded as a certain category. For instance, first two rows of the first column mean that among the students who made statements coded as the material shape category, 25.00% of the students were in the pre-ESDQ of the guided-discovery group, whereas 75.00% of the students were in the post-ESDQ of the lecture-based group. Please note the pre-ESDQ and post-ESDQ percentages for a given code category sum to 100% for each instruction type. The displayed percentages are computed using the normalization function available on the Dedoose software (Dedoose, 2018).

Table 1: Material-specific unit process impacts for raw material extraction and computer numerical control (CNC) machining. The superscripts R, E, and H represent impacts for resource extraction, ecosystem quality, and human health. The subscripts 1 & 2 represents unit process impacts for material extraction and CNC machining respectively. The single score impacts for material extraction and CNC machining (k_1^{Sum} , k_2^{Sum}) are computed by summing impacts in the three corresponding impact categories (R,E,H). The values in this table were estimated based on the Ecoinvent 99(I) method available in SimaPro®.

	k_1^R (Pt/lb)	k_1^E (Pt/lb)	k_1^H (Pt/lb)	k_1^{Sum} (Pt/lb)	k_2^R (Pt/lb)	k_2^E (Pt/lb)	k_2^H (Pt/lb)	k_2^{Sum} (Pt/lb)
Cast Iron (GGL-NiCuCr)	1.230	0.0053	0.169	1.4043	0.0662	0.00536	0.0868	0.15836
Aluminum (Al 2036)	1.720	0.0138	0.190	1.9238	1.350	0.0098	0.251	1.6108
Carbon Steel (35S20)	0.0305	0.00307	0.0164	0.04997	1.080	0.00709	0.123	1.21009

Table 2: Detailed steps in our instruction framework and their relationship to principles in constructivism (Savery & Duffy, 1995).

Steps in guided discovery instruction	**Principles in constructivism**	**Explanation of the relationship**
Identify design variables: Within an engineering domain, identify design variables that are commonly used for problem based learning. Among them, identify the relation between these variables to environmental performance. In theory, almost all variables will affect the environmental footprint of the resulting design.	Anchor learning activity to a larger task or problem.	Students should have a clear understanding of the purpose of the learning activity and how it relates to the domain context. It is important to align student expectations with the learning objectives. In our case, the design variables have a quantifiable relationship to environmental impact. Developing a direct correspondence between design variables and environmental sustainability allows students to better understand the purpose of the learning activity and relate to the larger context.
Setup design space exploration: Construct a problem that requires the selection/tuning of variables to meet domain dependent design requirements. The problem should require insights about relationships of the design variables to reach an	Design an authentic task. The problem should reflect complexities of real world tasks to prepare students.	Learning activities should reflect the level of cognitive demand required by the activities which we expect students to master at the end of learning. In our study, we setup a scenario involving complex trade-offs between multiple design

optimal solution through conflicting objectives and/or violations against rules of thumb.		variables. This helps us create cognitive conflicts for students by presenting scenarios that involve multiple conflicting objectives which are characteristic of real-world design problems.
Anchor the solution: Provide students access to domain experts and technical resources related to environmental sustainability and impact assessment. This will allow reflection on misconceptions and help students to develop a more comprehensive understanding of the relationships between environmental sustainability performance and relevant design variables.	Offer learner the ownership of the process. Support and challenge the learner's thinking.	We discouraged students from following predefined solutions or thinking strategies. Students were to anchor their solutions independently by adjusting design parameters and observing the resulting changes in environmental impact. Here, students developed solutions that met constraints and accounted for practical concerns, e.g. weight minimization. These strategies align with guided discovery learning, where students had ownership of the design.
Motivate the exploration process: Motivate students to create non-conventional solutions by encouraging them to document the iterations and exploration processes. We can also promote intrinsic motivation by helping students to develop interest in the learning tasks.	Encourage testing ideas against alternative perspectives.	It was critical that students did not stop after reaching a feasible solution. We motivated the students to search for viable alternatives and better performing solutions. This process encouraged students to construct new knowledge and help them bridge unfamiliar contexts.
Observe user behavior: Record mistakes as well as new insights gained by the students. When viable, store parameters for every unit iteration in the exploration process. Understanding the rationale of students' design decisions is critical for promoting conceptual change and environmental sustainability centered design.	Provide means for and support reflection on the content & the learning process.	Demonstrating methods for reflection (on the content learned & the learning processes) can help students self-regulate their learning in discovery learning contexts. We recorded the mistakes as well as new insights proposed by the students. Here, we tried to model reflection strategies that experts use to monitor problem solving processes specific to their field.

Table 3: Results from the shape synthesis design task conducted in Study 1 and Study 2. Please note that the environmental indicator for Study 2 Group 2 (lecture-based instruction) was computed by the authors using material and volumetric data from the submissions.

	Study 1	**Study 2 Group 1**	**Study 2 Group 2**
Total study population	71	29	32
Number of valid submissions	43	19	16
Number of valid submissions with over 3 *iterations*	28	19	N/A

$Total\ iterations$	$mean = 5.58$, $variance = 8.82$, $max = 12$	$mean = 7.00$, $variance = 6.33$, $max = 11$	N/A
$Environmental\ indicator\ (Pt)$	$mean = 15.74$, $variance = 152.6$, $min = 4.356$	$mean = 10.969$, $variance = 34.62$, $min = 4.202$	$mean = 19.848$, $variance = 225.$, $min = 4.432$
$Weight\ (lb)$	$mean = 1.62$, $variance = 3.5$, $min = 0.236$	$mean = 2.498$, $variance = 4.45$, $min = 0.277$	$mean = 1.112$, $variance = 0.28$, $min = 0.266$

Table 4: Descriptive statistics of students' ratings on the environmental sustainability instruction perception survey in Study 1.

Question Items	$Mean$	$Standard Deviation$
ME444 Integration[a]	1.59	0.57
Other Mechanical Engineering Courses Integration[b]	3.37	0.96
Conduct Sustainable Design[b]	3.00	1.22

[a]:On a 3-point scale, 0-No, 1-Maybe, 2-Yes.

[b]:On 5-point scale, 1 being Strongly Disagree, 5 being Strongly Agree.

Table 5: Descriptive statistics of students' ratings on the environmental sustainability instruction perception survey in Study 2

	Guided-Discovery		Lecture-Based	
	$Mean^a$	$Standard Error$	$Mean^a$	$Standard Error$
ME444 Integration[b]	1.47	0.23	1.29	0.23
Other Mechanical Engineering Courses Integration[c]	3.05	0.33	2.74	0.32
Conduct Sustainable Design[c]	2.66	0.29	3.17	0.29

[a] Mean is the estimated marginal means after controlling for students' ratings on the importance of learning about sustainable concepts in the environmental sustainability background & perception of environmental sustainability concepts survey. [b] On a 3-point scale, 0-No, 1-Maybe, 2-Yes. [c] On 5-point scale, 1 being Strongly Disagree, 5 being Strongly Agree.

Table 6: Major coding categories from the environmental sustainability instruction perception survey.

	Definition	Coded Examples
Manufacturing Process	Student discussed the role of the manufacturing process with regards to environmental sustainability.	I have not thought about the environmental impact of machinery parts. I usually just thought about the total mass of the part.
Unspecified Design Changes	Student discussed general design changes and did not contextualize environmental	There needs to be a good balance between

	sustainability learning to domain-specific design parameters such as type of material, part weight, and part volume.	environmental impact and how well the design will function.
Complexity and multi-factors in environmental sustainability design	Student recognized that there are multiple interrelated design factors involved in environmental sustainability based design. Discussed trade-offs among such factors in environmental sustainability based design	There are more factors related to environmental impact than I can confidently optimize in a design.
Unspecified Material Changes	Student discussed the changes made to materials without being specific of the nature of the change.	It depends a lot on the material.
Correlations in Materials and Geometry	Student discussed the inter-relatedness among material weight, volume, and shape on the environmental impact.	I learned the lighter products are not always better because sometimes it takes more energy to remove harder materials.

Table 7: Coded examples from the environmental sustainability design questionnaires. The major coding categories are indicated in bold font and sub-categories are in regular font.

	Definition	Coded Examples
Design performance	The durability or the strength of the design.	It is very strong and will last a longer time.
Impacts	The impact on the environment.	Casting, hobbing, forging require temperature operations which is potentially dangerous and definitely impact environment in a large scale.
Manufacturing		
Machinability	The ability of a material or design to be machined.	The air spring suspension is the easiest to machine.
Manufacturability	The ability of a material or design to be manufactured.	This is the simplest design to manufacture.
Material		
Shape	The shape of a part made of a given the material.	The material and the given shape allows it to last longer and therefore minimize the number of mills needed.
Weight	The weight of the material.	It’s the most sustainable as it takes off the most weight.
Strength	The strength of the material.	Titanium Aluminum Nitride has very high tensile strength and toughness.
Properties	The characteristics of the materials.	Hardened rubber has the smallest stiffness.