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EXPLORING THE EFFECTIVENESS OF PROVIDING STRUCTURED DfE DESIGN STRATEGIES DURING CONCEPTUAL DESIGN

Donovan Ross
School of Mechanical, Industrial, and Manufacturing Engineering
Oregon State University
Corvallis, OR, 97331

Vincenzo Ferrero
School of Mechanical, Industrial, and Manufacturing Engineering
Oregon State University
Corvallis, OR, 97331

Bryony DuPont
School of Mechanical, Industrial, and Manufacturing Engineering
Oregon State University
Corvallis, OR, 97331

ABSTRACT

The *fuzzy front end* of engineering design can present a difficult challenge, and as such, recent engineering design research has focused on guiding and influencing the way a designer ideates. Early ideation can be especially difficult when attempting to integrate specific design objectives in product design, called *Design for X* (DfX). Some examples of DfX are Design for Manufacturing (DfM), Design for Assembly (DfA), Design for Function (DfF), and Design for Safety (DfS). This paper will present two experiments exploring the efficacy of a structured Design for the Environment (DfE) design method called the GREEn Quiz (**G**uidelines and **R**egulations for **E**arly design for the **En**vironment) that provides designers with sustainable design knowledge during the conceptual design phase. The GREEn Quiz operates on a web-based platform and queries the designer about their design concepts; an end-of-quiz report provides abstract DfE knowledge to designers. While this abstract knowledge was able to be applied by designers in a former study, we hypothesize that providing targeted, specific design strategies during conceptual design may enable better integration in concept generation by novice designers. In this study, we created these DfE strategies, embedded these in the GREEn Quiz, and studied the efficacy of these strategies when presented to designers at both the expert and novice levels. Experimental results suggest that respondents with access to the strategy-based GREEn Quiz produced concepts with evidence of more sustainable design decisions and higher solution quality scores when compared to previous respondents and the control groups. This research encourages the consideration of downstream environmental impact knowledge during conceptual design, resulting in lower-impact products regardless of the previous DfE expertise of the designer.

INTRODUCTION

Since the turn of the century, sustainability has risen to the forefront of research in engineering design [1], yet there exist very few design tools that provide engineers insight on the downstream effects of certain design decisions. This is especially detrimental in the realm of sustainable design, as 80% of the environmental impact of a product is determined after only 20% of the design process is complete [2]. The first 20% of the design process generally consists of problem identification, research, and brainstorming that leads into conceptual design [3]. The lack of sustainability knowledge—or the inability to apply this knowledge—in the early design phase typically necessitates redesign further along on the design process, which is a costly monetary and time barrier. Developing *DfE* tools to inform designers early on about the environmental effects of a potential product will help promote the paradigm shift towards sustainable product design.

Eco-design tools are the current means through which designers can integrate DfE principles into product design; these tools generally fall into one of these categories: *Life Cycle Assessments* (LCAs), *CAD-integrated tools*, *Checklists and Guidelines*, and *General Methodologies* [4]. The most extensive tools currently available to analyze the environmental impacts of products are LCAs [5]. Defined by the ISO 14040 standard, an LCA is a "compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle" [6]. LCAs are immensely valuable in assessing the potential environmental impacts of products, but they are only able to be applied in the late stages of the design process, after functions, materials, and manufacturing plans have been solidified. Attempting to utilize them during conceptual design would require a designer to make extensive assumptions about a design in order to run the calculations, dramatically increasing the uncertainty in the assessment. Integrating Design for the Environment principles into the early design phase entails influencing designers by using more abstracted tools than LCAs, generally falling into the *Checklists and Guidelines* categories. Our work has centered on accessing higher-fidelity downstream DfE knowledge and finding means for designers to understand and integrate this knowledge despite the generally abstract nature of conceptual design.

This paper will present two experiments performed at Oregon State University, in which we hypothesize that providing structured DfE strategies during conceptual design using the GREEn Quiz leads to a more effective integration of eco-design principles during concept generation. The GREEn Quiz has been updated to provide users with clear design strategies that can be integrated during concept generation through the end-of-quiz report. Metrics such as number of sustainable design decisions, solution quality, and ratio of sustainable design decisions to non-sustainable design decisions were used to assess how well designers were able to integrate these strategies.

RELEVANT LITERATURE

In order to gain a better understanding of the experiments, this section will outline relevant literature encompassing current Design for the Environment tools and concept generation.

Design for the Environment Tools

Design for X (DfX) imperatives encompass the notion of fragmenting the design process into specific categories of product design objectives and enabling focus on these objectives. DfX tools generally reduce the iterative nature of the design process by embedding design decisions that aim for a specific goal or optimize specific areas of product engineering [7]. Some examples of DfX categories are Design for Manufacturing (DfM), Design for Assembly (DfA), Design for Function (DfF), and Design for Safety (DfS); Figure 1 lists many examples of DfX [8].

FIGURE 1: DESIGN FOR X CATEGORIES [8]

Design for the Environment (DfE) is integrating environmental knowledge during the product design process using strategies to reduce negative environmental impacts during a product's life cycle [9]. DfE knowledge is also called eco-design and product sustainability. The National Environmental Policy Act of 1969 defined the notion of sustainability "to create and maintain conditions under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic and other requirements of present and future generations" [10]. Current tools aiding in DfE generally fall into one of the following categories: Life Cycle Assessments (LCAs), CAD integrated tools, Checklists and Guidelines, and General Methodologies [4].

LCAs operate as a framework quantifying the impact of a product through its life-cycle phases [11]. They are usually manifested as software tools with user interfaces built upon impact databases related to a product's life-cycle impact. The largest proprietors of LCA software are GaBi and SimaPro; these are most commonly used by researchers and practitioners [4]. This software is comprehensive enough to be utilized in sector-specific applications, meaning they can aid in improving the entire design of a product, but their shortcoming is the requirement of a great deal of practitioner skill and experience. Along with the fact that LCAs can only be implemented in the later design stages, they typically require multiple design-test iterations to embed sustainability in a design concept.

CAD-integrated tools are one solution to embed DfE knowledge earlier in the design process by merging impact analysis tools with computer-aided design. They utilize CAD models to calculate environmental impact through reciprocal data transfers [12], geometries and features [13], and plugins embedded in CAD software [14]. They can be thought of as a consolidation of LCAs and CAD software, as almost all are based on the environmental impact databases utilized in LCAs [4]. These CAD-integrated tools allow designers to estimate the potential impacts of modeled design concepts and compare and contrast design solutions. However, their shortcomings are similar to LCAs, in that an established design (in this case, a dimensioned CAD model) needs to be present for analysis, rendering it impossible to use these approaches during early conceptual design.

Checklists and Guidelines are approaches that are more useful during the early design phases. Unlike LCAs or CAD-integrated tools, these approaches ask designers questions and offer strategies to improve environmental performance. In order for these approaches to work, information must be presented to designers at an appropriate level of abstraction to be incorporated into the existing design processes, inadvertently giving them the advantage to be used by non-experts [4]. Examples of these design checklists and guidelines are The Ten Golden Rules, Volvo's White, Grey, and Black Lists for material selection, and Compilations of Design for Environment Guidelines [15–17]. The abstract nature of the Checklist and Guidelines approaches allows an easier integration into the early design phases.

General Methodologies encompass the way DfE and eco-design are actually implemented in industrial practice. Whether these approaches are related to innovation, life cycle, user, or design tools, these methodologies are attempts to efficiently embed DfE into company practices. They have manifested as integration methods compiled with related software, product life cycle planning (PLC) methods, and combination techniques using multiple design tool programs and analyses [18–21]. These methodologies change the way companies employ the design process with respect to sustainability.

In our work, we use data-driven design principles to move high-fidelity downstream DfE knowledge (LCA and CAD-integrated DfE information) to the early design phases by abstracting this information and presenting it to users as they perform concept generation. In that way, our approach is at the intersection of all four of these presented categories.

Concept Generation

Creativity is an aspect of human nature that is highly complex and is often unable to be formally defined or managed. There has been recent interest in increasing the innovative abilities of engineering designers [22] but the "fuzzy front end" of the conceptual design process presents difficulties in integrating DfE methods. Trying to influence creativity to achieve specific DfE goals can add an unforeseen level of complexity to the design process, and even hinder or stifle creative ideas. A common method of generating concepts involves using function knowledge to generate solutions to a problem [3]. Common methods that can inform the conceptual design phase include brainstorming, designing from analogy, using design expertise, and morphologies.

A morphological chart is one method used to generate concepts based on their functional characteristics. These charts are created by listing functional characteristics and accompanying them with respective engineering solutions [23]. Following this, concepts are generated by combining these engineering solutions to solve the design problem. It has been shown that morphological charts with more engineering solutions than design characteristics produce better concepts [24]. One study on product function and environmental impact showed potential correlations between these attributes and that implementing DfE methods early in the design phase resulted in a product with reduced environmental impact [25].

Design by analogy is a method in which designers utilize previous solutions or solutions from other domains to generate inspiration or gain insight. Design by analogy is "the conscious and unconscious reliance on prior experience and knowledge" [26]. The impact of design by analogy shows that it plays an important role in increasing idea stimulation [27]. However, it is understood that introducing analogies beyond the scope of the problem at hand can be harmful in the design process [28]. In current DfE practice, designers are often reliant on their prior experience and knowledge in conducting sustainable design.

"The Theory of Inventive Machines" or TRIZ is another common ideation technique. TRIZ is based on the notion of *systematic innovation*, and encompasses two ideas: 1) many problems engineers faced have already been solved, potentially in an unrelated field, and 2) predictable patterns can be used to determine the most probable successful next steps [3]. Research on the use of TRIZ has shown success with integration of DfE methods during product development [29,30].

It is also important to mitigate the effects of design fixation, particularly when incorporating DfX/DfE objectives. Even experienced designers can succumb to design fixation, while also only partially perceiving the effects of fixation [31]. Attempting to mitigate the effects of design fixation is critical to the integration of DfE methods into early design phase techniques. The difficulty arises in coercing designers to make design choices with respect to sustainability, while at the same time not offering solutions on which designers could become fixated. Research has shown that fixation on potential solutions "is associated with a reduction in the variety, quantity and quality of solutions that designers generate" [32]. Generating DfE methods that guide rather than solve can help mitigate these effects and allow designers to fully explore a design space, rather than fixating on a potentially sub-optimal solution.

METHODOLOGY

In this research, we hypothesize that providing designers with DfE knowledge early in the design phase leads to more effective consideration of DfE information during concept generation. More specifically, designers given access to the GREEn Quiz will produce concepts with more inherent environmental impact considerations. The effectiveness was measured using several metrics found in concepts generated during two experiments. The purpose of the experiments was to see if providing designers with targeted DfE knowledge using the GREEn Quiz leads to more effective DfE integration within early design phase concepts.

The GREEn Quiz is a web-based design for the environment tool that provides designers with abstract DfE knowledge to make early design concepts more sustainable. The quiz has a total of 60 questions and utilizes an organized search tree to remove questions that do not pertain to the new design. It does this by asking a filtering question pertaining to specific areas of a potential product. Figure 2 shows an example of the search tree element; the quiz asks the designer if the product will produce waste and the answer given will dictate any future questions presented.

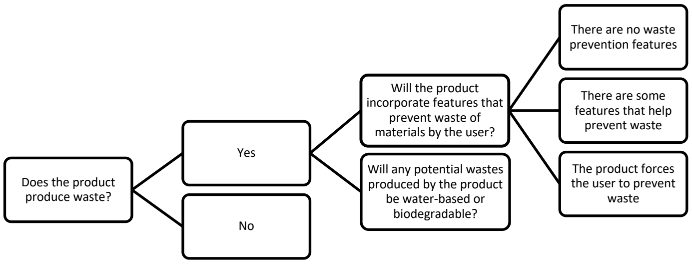


FIGURE 2: GREEN QUIZ SEARCH TREE EXAMPLE

These areas of interest in the GREEn Quiz relate to ten areas of product development: Comparison, Material Selection, Design/Structure, Manufacturing, Transportation, Use Phase, Maintenance, Hazardous Materials, Disassembly, and Disposal. The quiz is designed to ask all the filtering first followed by asking relevant questions related to these areas, akin to the flow shown in Figure 3. Once all related questions are answered, a report is generated that shows ten areas of the concept that scored poorly on potential environmental impact based on the user-provided responses; the report provides three respective design strategies to mitigate each of these ten impacts. Accompanying these strategies is an impact score of each of the ten design areas in Figure 3. These scores vary based on the filtered questions relevant to the design and operate as a quantification metric to allow the designer to see the areas of their design that contribute to higher environmental impact potential.

FIGURE 3: FLOW OF CATEGORIES USED IN THE GREEN QUIZ

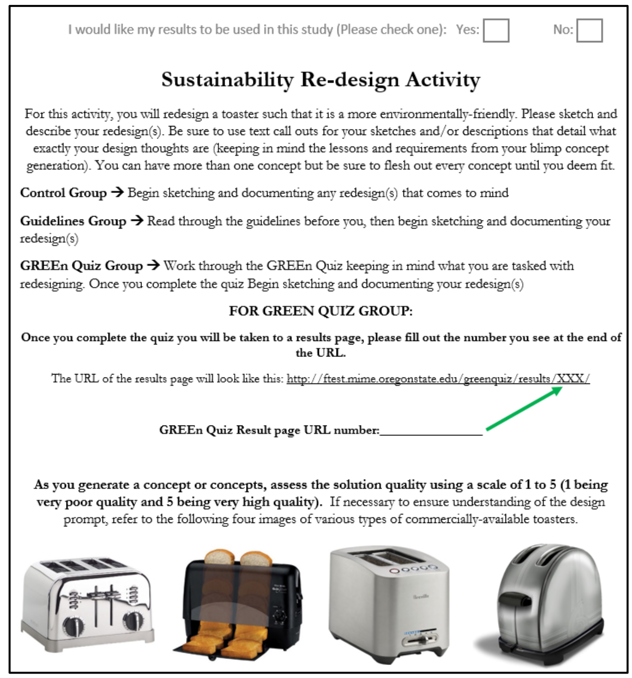
Examples of other questions asked in the GREEn Quiz include:

- Does the product require any form of resources to operate?
- Does the product's lifespan depend on the consumer's opinion on how the product appears?
- Does the product produce waste?
- Does the product have internal assemblies or components?

Two experiments were performed to analyze the effectiveness of providing designers with these DfE strategies after using the GREEn Quiz.

Experiment 1: Redesigning a Toaster (Novice DfE)

The design problem for this experiment involved redesigning an existing consumer product to be more sustainable. The toaster re-design problem is consistent with a previous study conducted at Oregon State University, which enables direct comparison of the results. This design problem was chosen due to familiarity of the product itself, along with the redesign — with or without DfE knowledge — being well within the realm of expertise of third-year mechanical engineering students. Figure 4 shows the re-design activity presented to the participants.


I would like my results to be used in this study (Please check one): Yes: ☐ No: ☐

Sustainability Re-design Activity

For this activity, you will redesign a toaster such that it is a more environmentally-friendly. Please sketch and describe your redesign(s). Be sure to use text call outs for your sketches and/or descriptions that detail what exactly your design thoughts are (keeping in mind the lessons and requirements from your blimp concept generation). You can have more than one concept but be sure to flesh out every concept until you deem fit.

Control Group → Begin sketching and documenting any redesign(s) that comes to mind

Guidelines Group → Read through the guidelines before you, then begin sketching and documenting your redesign(s)

GREEn Quiz Group → Work through the GREEn Quiz keeping in mind what you are tasked with redesigning. Once you complete the quiz Begin sketching and documenting your redesign(s)

FOR GREEN QUIZ GROUP:

Once you complete the quiz you will be taken to a results page, please fill out the number you see at the end of the URL.

The URL of the results page will look like this: http://ftest.mime.oregonstate.edu/greenquiz/results/XXX/

GREEn Quiz Result page URL number:_______________

As you generate a concept or concepts, assess the solution quality using a scale of 1 to 5 (1 being very poor quality and 5 being very high quality). If necessary to ensure understanding of the design prompt, refer to the following four images of various types of commercially-available toasters.

FIGURE 4: SUSTAINABILITY REDESIGN ACTIVITY PRESENTED TO PARTICIPANTS

Participants

Participants in the study were third-year mechanical engineering students enrolled in the Introduction to Mechanical Design course at Oregon State University. They were used as a testbed of the effectiveness of the DfE tools using novice designers; most of these students have some familiarity with the design process but not with sustainability, and the GREEn Quiz was developed in the hopes of being utilized by all designers regardless of experience. Participation was voluntary, and the students could choose if they would like their results to be included in the study. They were divided into three groups: Group 1 acts as a control was given no extraneous tools, Group 2 was given a set of sustainable design guidelines developed by Telenko et al., and Group 3 was given access to the GREEn Quiz. A total of 98 student results were included in the study: 35 control group respondents, 31 guideline respondents, and 32 GREEn Quiz respondents.

Procedure

Participants were presented the re-design activity shown in Figure 4 during their Introduction to Design course lab time. The purpose of the experiment was explained to the participants and respondents were separated into each respective group. Although the term *group* implies cohesion during the redesign activity, each participant was instructed to work individually and without communication with other participants. The control group was tasked with generating a sustainable re-design without the use of any DfE methods to act as a baseline measurement. The group generating concepts using the sustainable design guidelines were given a printout of sustainable design guidelines developed by Telenko et al. [17]. The group utilizing the GREEn Quiz accessed it through personal computers and smartphones, as the quiz itself is hosted on a local server at Oregon State University and access is attained through a web browser.

The students were given 30 minutes of concept generation time to complete the study. In order to provide a comparable amount of time to each group, students were given specific instructions based on their group placement. Those using the GREEn Quiz were instructed to complete the quiz and save the end-of-quiz report. Once all GREEn Quiz completed the quiz, the 30-minute time limit on product ideation began. Those given the sustainable design guidelines were given 5 minutes to review the printout and then given the same 30-minute time limit. The control group was given just 30 minutes as they had no external resources in the study. During the activity the participants were asked to self-assess the solution quality of their generated concepts on a scale of one to five (one representing low solution quality, and five being high solution quality). When the 30 minutes concluded the re-design activity sheet was collected and sorted by group.

Metrics

We analyzed each participant's re-design activity using four metrics. The first metric was the *number of concepts generated* by each participant, and each following metric was measured with respect to these defined, individual concepts. These concepts were qualified as either sketches with callouts or lists detailing a single design. Figure 5 shows an example of a worksheet with three generated concepts. Following the number of concepts, we totaled number of design decisions.

The *number of evident design decisions* metric includes any design decision specified by the respondent, including any sustainable design decisions. In order to differentiate the *number of sustainable design decisions,* any word or description related to sustainability or specifically from the two DfE tools were counted as such. Defining what constituted a design decision presented another challenge in this analysis. Toasters are established products that have inherent design decisions that could influence their redesign; an example being that almost all toasters utilize electricity to operate. In order to analyze the novelty of the concepts generated in the experiment we established six status-quo design decisions to quantify novel design decisions made by the participants.

The status-quo design decisions were:

1. Even Number of Slots
2. Electrically Powered
3. Beveled Cube Shape
4. Spring Pop Up
5. Plunge Activated
6. Presence of Heat Settings
7. Presence of Cancel Button

These were used to filter out inherent designs present in toasters that could influence their redesign, allowing an analysis of the novel design decisions made as a result of the design tools to be compared.

The forth metric was quantifying the *solution quality* of each generated concept. This was done by appointing three judges—selected from a group of sustainable product design experts at OSU— to rate the solution quality of concepts. We instructed these researchers to score each concept based on performance in four categories on a scale of one to five. The categories were sustainability, level of detail, originality, and feasibility. These four scores were then be averaged to give an overall quality score for each concept to accompany the self-assessed solution quality generated by the respondents during the study for each of their concepts.

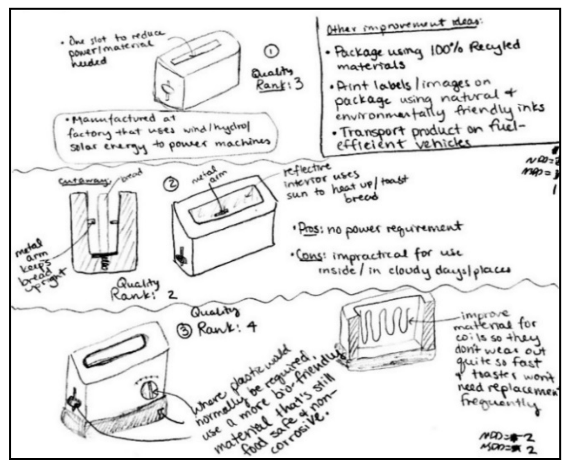


FIGURE 5: EXAMPLE OF SUBMITTED CONCEPT GENERATION FROM STUDY 1

Experiment 2: Redesigning Established Concepts

The design problem for this experiment involved redesigning concepts that were developed during Oregon State University's Sustainable Product Design course. This is a graduate-level engineering course that involved research and application of design for the environment principles. The goal of this course was to design a novel and sustainable product that would be beneficial for the graduate student market.

Participants

Participants in this study were graduate students enrolled in Oregon State University's Sustainable Product Design course in Spring 2018. These students were selected to test the effectiveness of the GREEn Quiz using more experienced designers; the students enrolled had an established understanding of the design process (through course prerequisites) and expertise in sustainable design gathered through the course itself. The study was also performed during the later weeks of the term, meaning that the participating students were able to utilize knowledge gained from weeks prior in the course. All students in the course elected to participate in the study, resulting in a total of 24 respondents.

Procedure

The course required students to be split into four teams of six students for their term-long design project. We conducted our study at the point in the design process where each team had converged onto three potential design solutions. For this study each team of six was then split into three pairs of students and instructed to select which of the three concepts each pair would analyze. Given that there were 24 respondents, a total of 12 teams participated in the study.

The students were provided the URL for the GREEn Quiz and instructed how to take it to perform a redesign of their respective concepts before the next lecture, giving them a total of 48 hours to redesign. They were instructed to include the before and after concept along with a printout of their final GREEn Quiz report.

Metrics

We analyzed each teams redesign activity using three metrics: number of evident design decisions, number of sustainable design decisions, and an itemized count of design decisions related to the following categories: Material Selection, Use, Maintenance, Manufacturing, Labeling, Design Layout, Disposal, and Transport. Unlike the first experiment where differences in groups were analyzed, this experiment was intended to show the GREEn Quiz's effect on established concepts and whether or not it increased potential sustainability. The metrics were analyzed based on the original concept developed by the teams and a redesigned concept the participants submitted after using the GREEn Quiz.

RESULTS

Experiment 1: Redesigning a Toaster

The following section will present the results of the experiment involving redesigning the toaster using three groups: Control, Guideline, and GREEn Quiz.

Number of Generated Concepts

Figure 6 shows a comparison of the total number of concepts generated between each respondent group. Similar to a previous study testing an initial version of the GREEn Quiz, the control group produced the largest number of concepts, followed by the guideline group and the GREEn Quiz group [33].

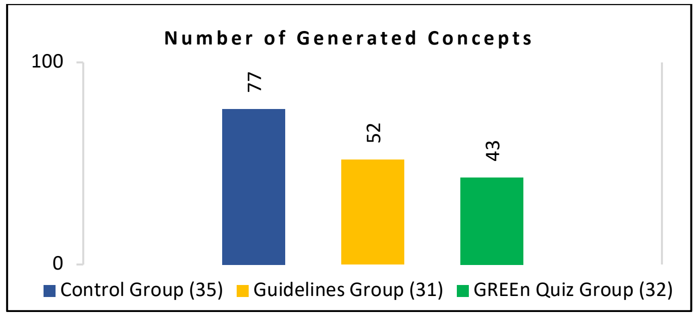


FIGURE 6: TOTAL NUMBER OF GENERATED CONCEPTS BY GROUP

Figure 7 shows the frequency of the number of concepts generated by each respondent within each group; the most common number of concepts generated being one by each respondent in each group. The control group showed the largest variation of total concepts generated per respondent and was the only group to have two respondents generating six concepts, the highest amount observed in the experiment. The GREEn Quiz respondents submitted the most redesigns of just a single concept with no GREEn Quiz respondent providing more than 3 concepts. Assuming a null hypothesis that the mean values of the three groups are equal, a single factor ANOVA test showed statistically significant differences in the number of generated concepts between groups. In this case, F_{crit}=3.09 at α=0.05, F=5.43 and the p-value is 0.0058. The average number of concepts produced from each group was 2.2 for Control, 1.7 for Guidelines, and 1.3 for GREEn Quiz.

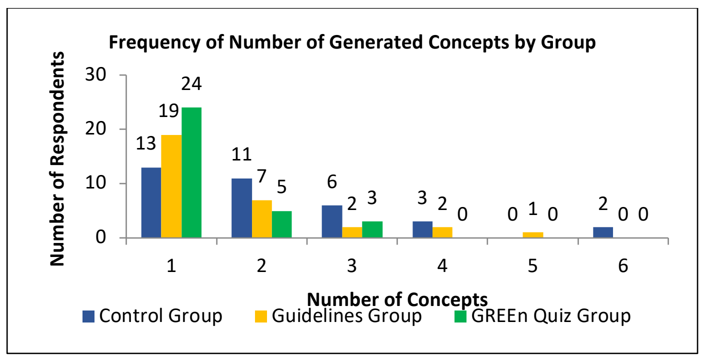


FIGURE 7: FREQUENCY OF THE NUMBER OF CONCEPTS BY GROUP

Number of Design and Sustainable Design Decisions

We counted the total number of novel design decisions and distinguished the sustainable design decisions found within this number for each concept generated by the respondents in each group. Figure 8 shows the total number of design decisions relative to each group. The Control group produced the highest number of overall decisions, but the fewest number of sustainable design decisions; approximately 30% of this group's design decisions were considered sustainable. The Guidelines group produced the second highest overall number and second highest number of sustainable design decisions, with approximately 52% of their design decisions being sustainable. The GREEn Quiz group produced the lowest number of overall design decisions but had the highest number of sustainable design decisions of the three groups. Approximately 58% of the GREEn Quiz group's design decisions were sustainable design decisions.

Again, assuming a null hypothesis that the mean values of the three groups are equal, a single factor ANOVA test showed statistically significant differences in the number of both design and sustainable design decisions between groups. With respect to the number of design decisions, F_{crit}=3.05 at α=0.05, F=3.15 and the p-value is 0.045. With respect to the number of sustainable design decisions, F_{crit}=3.05 at α=0.05, F=15.03 and the p-value is 9.8×10^{-7}. To determine how the means differ, further testing is conducted. Assuming a null hypothesis that the means are equal for the number of design and sustainable design decisions, a comparison of each group is shown in Tables 1 and 2. A *two-sample assuming equal variances* t-test was used comparing the control to both the Guidelines and GREEn Quiz, as well as the Guidelines with the GREEn Quiz group. If $t_{crit} > t_{obs}$, then we accept the null hypothesis. Therefore, we conclude that there are not significant differences in the mean number of design decisions (Table 1), but there are significant differences in the mean number of sustainable design decisions (Table 2).

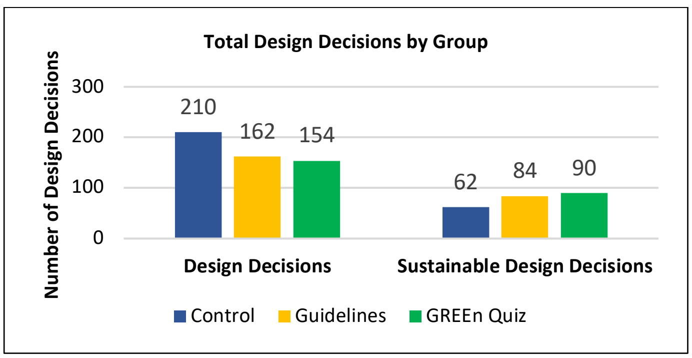


FIGURE 8: TOTAL NUMBER OF DESIGN DECISIONS BY GROUP

TABLE 1: T-TEST COMPARISON OF NUMBER OF DESIGN DECISIONS BY GROUP

	t_{obs}	t_{crit}
Control vs Guideline	0.32	1.98
Control vs GREEn Quiz	1.6	1.99
Guideline vs GREEn Quiz	1.48	2

TABLE 2: T-TEST COMPARISON OF NUMBER OF SUSTAINABLE DESIGN DECISIONS BY GROUP

	t_{obs}	t_{crit}
Control vs Guideline	3.36	1.98
Control vs GREEn Quiz	4.284	1.98
Guideline vs GREEn Quiz	1.45	1.98

Figure 9 shows the frequency of the number of design decisions found in each concept of the Control group and how many of those decisions were sustainable design decisions. Most concepts had five or fewer novel design decisions, and even fewer sustainable design decisions, the distribution skewing towards lower values of both decision type. The most common number of sustainable design decisions made by the Control group was one or zero for most concepts.

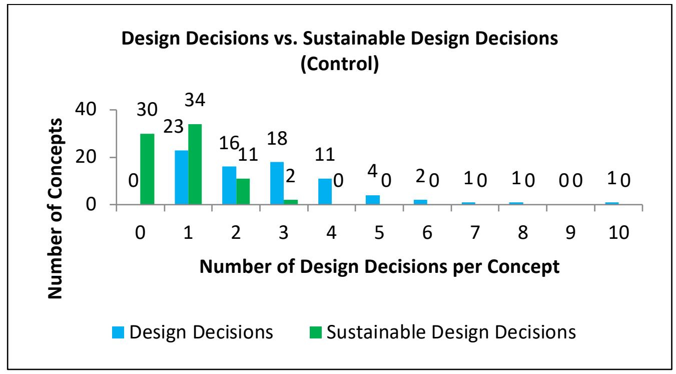


FIGURE 9: FREQUENCY OF DESIGN AND SUSTAINABLE DESIGN DECISIONS IN CONTROL GROUP

Figure 10 shows a similar graph of the frequency of the number of design decisions found in each concept of the Guidelines group. Most of these concepts again had five or fewer novel design decisions but had a noticeable increase in the number of sustainable design decisions made per concept. The distribution of decisions made by this group skews towards higher values compared to the Control group. The most common number of sustainable design decisions was still one or zero, but this group included concepts with up to six sustainable design decisions.

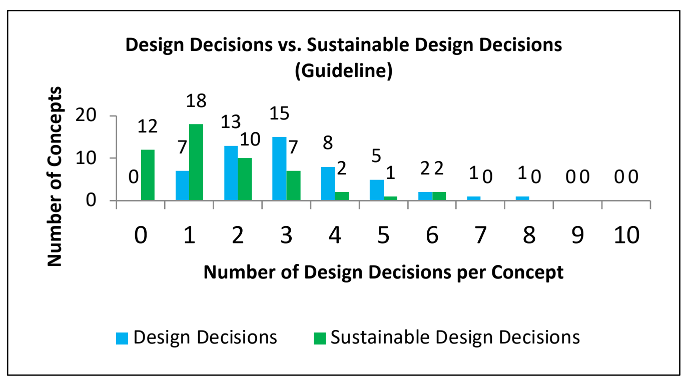


FIGURE 10: FREQUENCY OF DESIGN AND SUSTAINABLE DESIGN DECISIONS IN GUIDELINES GROUP

Figure 11 shows a graph of the frequency of the number of design decisions found in each concept of the GREEn Quiz group. Here there was a noticeable shift towards higher numbers of both decision types per concept. The GREEn Quiz group made up to six design decisions per concept, and the most common number of sustainable design decisions increased to either one or two.

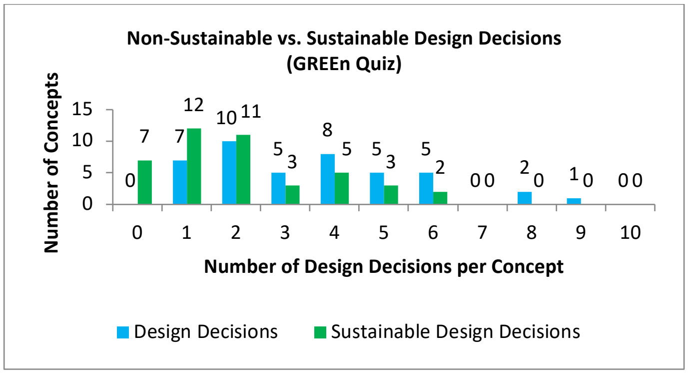


FIGURE 11: FREQUENCY OF DESIGN AND SUSTAINABLE DESIGN DECISIONS IN GREEN QUIZ GROUP

Solution Quality

We analyzed solution quality using two separate assessments: the first being the self-assessed solution quality generated by the respondents, followed by the solution quality assessed from three judges. Overall the GREEn Quiz group had the highest average quality scores via both self-assessed and judged scores, followed by the Guidelines group, with the Control group having the lowest quality scores. Figure 12 shows a graph comparing the average self-assessed scores, followed by Figure 13 showing the average judge scores between the three groups. Assuming a null hypothesis that the mean self-assessed scores of the three groups are equal, a single factor ANOVA test *did not* show statistically significant differences in self-assessed scores between groups. In this case, F_{crit}=3.05 at α=0.05, F=1.88 and the p-value is 0.045.

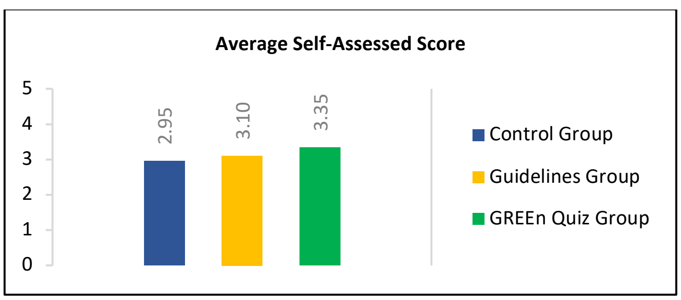


FIGURE 12: AVERAGE SELF-ASSESSED SCORES BY GROUP

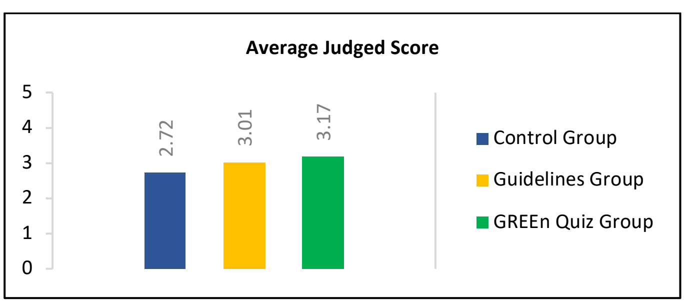


FIGURE 13: AVERAGE JUDGED SCORES BY GROUP

Figures 14, 15, and 16 show plots comparing the judges' scores of each concept from the three groups. These plots show the average score of each concept along with the concept's respective high and low judged score. Concepts across the three groups showed relatively consistent variations between high/low/average judged values (with one notable inconsistency evident in assessing concept 30 of the Guidelines group). This is also consistent with results presented in Figure 13, the GREEn Quiz group concepts have a higher average judge score trend when compared to the other two groups. A single factor ANOVA analysis of the average judge scores for each concept showed that these differences in judged scores are statistically significant between the three groups, F_{crit}=11.08 at α=0.05, F=3.05 and the p-value is 3×10^{-5}. Assuming the null hypothesis that the means are equal for each judge's scores between the three groups, a comparison of each judged score is shown in Table 3. A *two-sample assuming equal variances* t-test was used comparing the control to both the Guidelines and GREEn Quiz, as well as the Guidelines with the GREEn Quiz group. The Guidelines and GREEn Quiz group outperformed the Control Group but did not show statistically significant differences between each other.

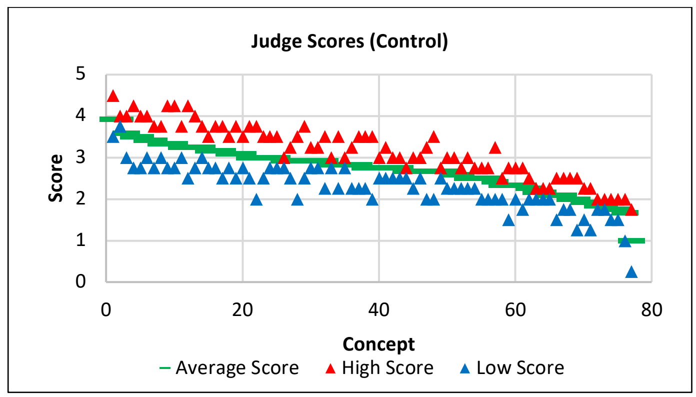


FIGURE 14: AVERAGE, HIGH, AND LOW JUDGE SCORES IN CONTROL GROUP

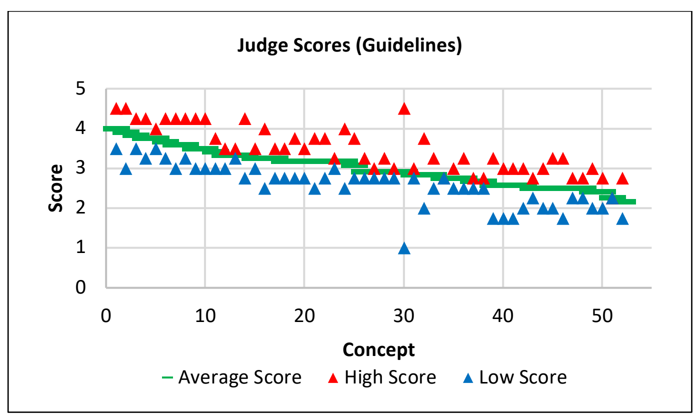


FIGURE 15: AVERAGE, HIGH, AND LOW JUDGE SCORES IN GUIDELINES GROUP

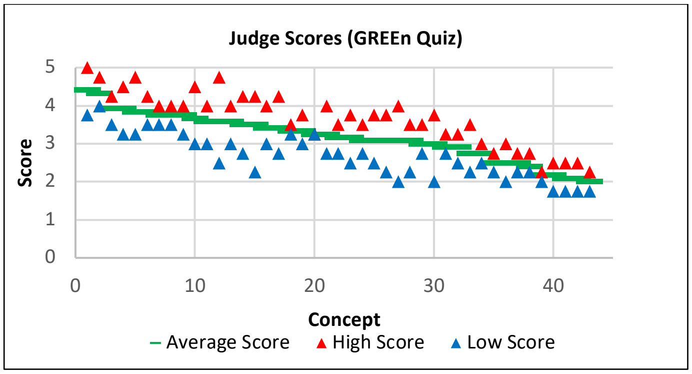


FIGURE 16: AVERAGE, HIGH, AND LOW JUDGE SCORES IN GREEN QUIZ GROUP

Table 3: T-TEST COMPARISON OF JUDGED SCORES BY GROUP

	t_{obs}	t_{crit}
Control vs Guideline	3.25	1.98
Control vs GREEn Quiz	4.23	1.98
Guideline vs GREEn Quiz	1.45	1.98

There was noticeable variation in scoring between self-assessed quality scores, and the quality scores determined by the judges. Figures 17, 18, and 19 show histograms comparing self-assessed scores with the averaged judge scores for each group. The Control group exhibited the largest variation in self-assessment scores, having a much larger variance compared to the averaged judge scores. There was a noticeable lack of variance in averaged judge scores in the Guideline group—the concepts found in this group were never scored lower than two or higher than four. Comparatively, the GREEn Quiz group showed both judged and self-assessed scores varied consistently between respondents, with both respondents and judges trending towards higher scores than the other two groups.

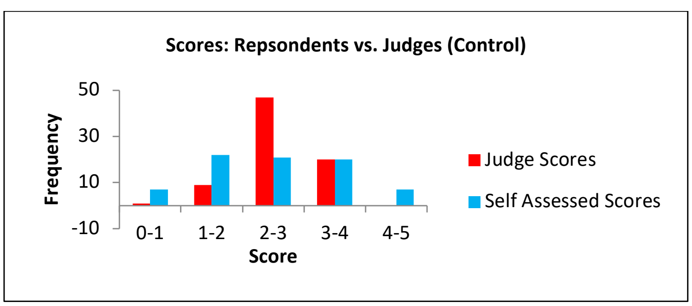


FIGURE 17: RESPONDENTS AND JUDGE SCORE HISTOGRAM OF CONTROL GROUP

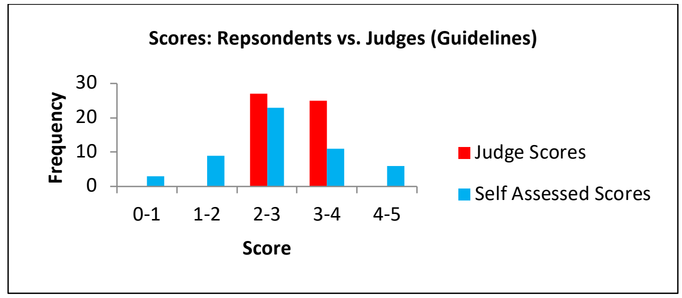


FIGURE 18: RESPONDENTS AND JUDGE SCORE HISTOGRAM OF GUIDELINE GROUP

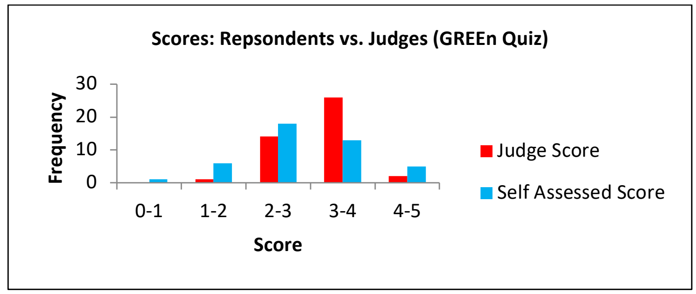


FIGURE 19: RESPONDENTS AND JUDGE SCORE HISTOGRAM OF GUIDELINE GROUP

Experiment 2: Redesigning Established Concepts

In the following section, we present the results of the experiment in which respondents redesigned established concepts generated in the graduate Sustainable Product Design course at Oregon State University.

Number of Design and Sustainable Design Decisions

We totaled the number of design decisions and sustainable design decisions from each team's concept both the before and after using the GREEn Quiz. Of the 12 teams that submitted these study materials, only 11 of these materials were suitable for analysis. Figure 20 shows the number of design decisions and number of sustainable design decisions present in each concept before the groups took the GREEn Quiz. The highest number of sustainable design decisions in all the concepts was found to to be two.

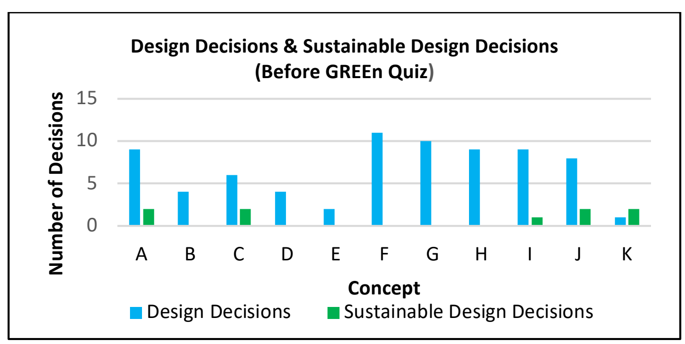


FIGURE 20: FREQUENCY OF DESIGN AND SUSTAINABLE DESIGN DECISIONS BEFORE TAKING GREEN QUIZ

Figure 21 shows the number of design decisions and number of sustainable design decisions present in each concept after the groups took the GREEn Quiz. There was a noticeable difference in the number of both types of design decisions after using the GREEn Quiz. However, the number of sustainable design decisions had a much higher increase and the difference in number of design decisions was negligible. The average number of design decisions before and after using the GREEn Quiz was 6.63 and 8.27 respectively. The average number of sustainable design decisions before and after using the GREEn Quiz was 0.82 and 3.27 respectively. This was also confirmed using a t-test of the data. With respect to the number of design decisions, a two-tailed p-value of 0.124 (α=0.05) was calculated using a *paired two sample for means* test. For the number of sustainable design decisions a *paired two sample for means test* calculated a two-tailed p-value of 0.0036 (α=0.05).

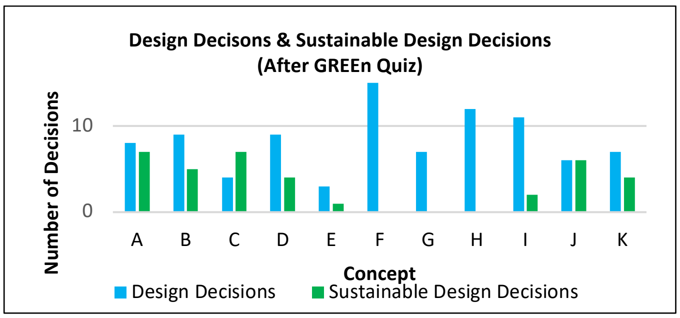


Figure 21: FREQUENCY OF DESIGN AND SUSTAINABLE DESIGN DECISIONS AFTER TAKING GREEN QUIZ

Categories of Design Decisions

We categorized design decisions into the following categories: Material Selection, Use, Maintenance, Manufacturing, Labeling, Design Layout, Disposal, and Transport. Figure 22 shows the total count before and after taking the GREEn Quiz. After taking the GREEn Quiz, designers increased both the number of design decisions and the categorical breadth of these decisions with respect to the outlined product categories.

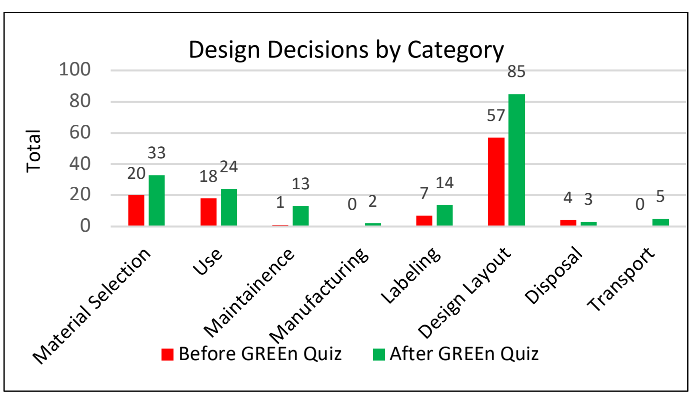


FIGURE 22: FREQUENCY OF DESIGN DECISIONS IN PRODUCT CATEGORIES BEFORE/AFTER THE GREEN QUIZ

DISCUSSION

The first experiment shows that although users of the GREEn Quiz had a lower number of generated concepts, they had an increased number and ratio of sustainable design decisions compared to total number of design decisions. The reason for this could be attributed to the latter two groups using structured directions that possibly behave as constraints during concept generation. A study on design fixation correlated that adherence to a set of guidelines or ideas can limit the potential output of conceptual designs [34]. This theory is also correlated with the experimental results, as both the guideline and GREEn Quiz groups adhered to their respective tools.

The second experiment also showed an increase in the number of sustainable design decisions after using the GREEn Quiz. Teams were able to embed more sustainable design decisions into their existing concepts. It also increased awareness of different areas of product design that can relate to sustainability. Showing that providing these teams with abstracted design knowledge using the GREEn Quiz produced more potentially sustainable concepts.

The first experiment also showed that users of the GREEn Quiz had higher judged solution qualities compared to the control group and similar results to the Guidelines group. The lack of variation between the three groups' self-assessed scores could be attributed to the experience level of the participants. Without more adequate knowledge and experience the participants might be unsure of the actual quality of their proposed solutions. The GREEn Quiz group also produced the lowest variation between judged and self-assessed scores compared to the others. This is possibly a result of the GREEn Quiz providing an easier to utilize baseline of sustainable knowledge that both novice and experienced designers see as being of higher quality. With respect to the number of sustainable design decisions, the Guidelines and GREEn Quiz group produced more than the control but similarly to one another.

CONCLUSIONS

This paper presents evidence to support the hypothesis that providing structured Design for the Environment strategies results in more effective DfE considerations earlier in the design phase. If the environmental effects of design decisions are better understood during the early design phases; incorporation and utilization of DfE methods could lead to more sustainable and environmentally friendly products. The efficacy of incorporating DfE knowledge was measured by analyzing the conceptual designs generated by participants in two experiments performed at Oregon State University.

It can be concluded that these experiments support the hypothesis that providing early DfE design knowledge using the GREEn Quiz results in more effective DfE knowledge consideration earlier in the design phase. Research into early design phase integration of DfE methods is crucial in catalyzing the world's transition into a more sustainable future. However, there are very few sustainable design methods that elucidate the "fuzzy front end" of engineering design. The GREEn Quiz experiments provided evidence that sustainable and more environmentally friendly design decisions can be incorporated into the engineering design process.

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