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Exploring the Effectiveness of Providing Structured Design-for-the-Environment Strategies During Conceptual Design

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). This paper presents two experiments exploring the efficacy of a structured Design for the Environment (DfE) design method called the Guidelines and Regulations for Early design for the Environment (GREEn) Quiz 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 will enable novice designers to better integrate DfE. In this study, we created these DfE strategies, integrated these into the GREEn Quiz, and studied the efficacy of these strategies when presented to designers at both the expert and novice levels. Results suggest that respondents with access to the strategy-based GREEn Quiz produced concepts with evidence of a broader range of sustainable design decisions and higher solution quality scores. This work shows the promise of supplemental DfE methods for concept generation to enable the design of more environmentally sustainable products.
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Introduction

Since the turn of the century, sustainability has risen to the forefront of research in engineering design [1]. There are a growing number of *eco-design* tools to help designers meet the challenge of designing for environmental sustainability [2,3]. Despite this growth, there is interest in eco-design tools that are applicable during the early design phase, as it is estimated that 80% of the environmental impact of a product is determined after only 20% of the design process is complete [4]. The first 20% of the design process generally consists of problem identification, research, and brainstorming that leads to conceptual design [5]. Developing *DfE* tools to inform designers early on about the environmental effects of a potential product will help promote the paradigm shift toward sustainable product design [6].

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), computer-aided design (*CAD*)-*integrated tools*, *Checklists and Guidelines*, and *General Methodologies* [7]. The most extensive tools currently available to analyze the environmental impacts of products are LCAs [8]. 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" [9]. 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 information such as product functions, materials, and manufacturing plans has been solidified. Using traditional LCA during conceptual design—while this information is unclarified—leads to substantial uncertainty in the assessment [10]. 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 the 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 *G*uidelines and *R*egulation for *E*arly design for the *En*vironment (GREEn) Quiz leads to a more effective integration of eco-design principles during concept generation. The GREEn Quiz is a web-based design tool that encourages designers to make design decisions with environmental sustainability in mind [11]. In this work, we have improved the GREEn Quiz to provide users with clear design strategies that can be integrated during concept generation through an end-of-quiz report. We compare different types of information given as part of this end-of-quiz report to ascertain what type is most effective at enabling designers to design concepts with improved environmental sustainability. Two case studies are explored: the first is designed to explore the efficacy of the GREEn Quiz for novice designers when compared against the use of a list of sustainable design guidelines. The second case study explores any potential benefit over existing DfE knowledge by having graduate-level, more experienced eco-designers redesign existing concepts using the GREEn Quiz. 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.

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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 [12]. Some examples of DfX categories are Design for Manufacturing (DfM), Design for Assembly (DfA), Design for Function (DfF), and Design for Safety (DfS); Fig. 1 lists many examples of DfX [13].

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 [14]. 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" [15]. While DfE tools are gaining popularity, few research studies have explored the development and implementation of these tools as applied in the early design phase [16].

LCAs operate as a framework quantifying the impact of a product through its life-cycle phases [17]. 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 [7]. This software is comprehensive enough to be used in sector-specific applications, meaning they can aid in improving the entire design of a product, but one shortcoming is the requirement of practitioner skill and experience. Along with the fact that LCAs can only be implemented with accuracy 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. These tools utilize CAD models to calculate environmental impact through reciprocal data transfers [18], geometries and features [19], and plugins embedded in CAD software [20]. 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 [7]. 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 with component materials identified) needs to be present for analysis, rendering it impossible to use these approaches during early conceptual design.

Fig. 1 Design for X categories [8]

Checklists and Guidelines are approaches that are more useful during the early design phases. Unlike LCAs or CAD-integrated tools, these approaches offer designers direct guidelines and 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 [7]. 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 [21–23]. More recently, guidelines centered around design for the *circular economy* (a design that focuses on product end-of-life, specifically remanufacturing and reuse) have become more prominent [24,25], alongside improved means of measuring product *circularity* [26]. The abstract nature of the Checklist and Guidelines approaches allows easier integration into the early design phases. Telenko's sustainable design guidelines consider the entire product life cycle and are a valuable set of DfE guidelines that, if used during a concept generation process, can encourage designers to think about the downstream environmental sustainability of a concept [27].

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 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 [28–31]. These methodologies change the way companies employ the design process with respect to sustainability.

There is an unexplored need to operationalize downstream environmental impact data, such as those developed through a late-design-stage LCA, to inform early design approaches. 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.

Concept Generation. This work focuses on a supplementing approach that is to be applied concurrently with brainstorming and ideation methods in the early design phase. There have been other DfE tools that are designed to be used in this way or ideation tools that have been catered specifically for eco-design.

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 [32] but the "fuzzy front end" (the discovery and initial ideation phases) 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 [5]. 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 [33]. These charts are created by listing functional characteristics and accompanying them with respective engineering solutions [34]. 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 [33]. 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 [35].

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" [36]. The impact of design by analogy shows that it plays an important role in increasing idea stimulation [37]. However, it is understood that introducing analogies beyond the scope of the problem at hand can be harmful in the design process [38]. In current DfE practice, designers are often reliant on their prior experience and knowledge in conducting sustainable design.

"The Theory of Inventive Problem Solving" or TRIZ (the original Russian acronym) 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 [5]. Research on the use of TRIZ has shown success with the integration of DfE methods during product development [39,40].

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 [41]. 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" [42]. 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—one in which we explore the use of the GREEn. Quiz against another early-design-phase DfE approach, and one in which we have established DfE practitioners redesign concepts using the GREEn Quiz to determine if certain categories of sustainable design knowledge are more or less applicable in concept generation. 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 the early design phase.

The GREEn Quiz is a web-based DfE tool that provides designers with abstract environmental sustainability knowledge to influence early design concepts to be more sustainable [43]. The quiz has a total of 60 questions and uses an organized search tree to remove questions that do not pertain to the new design. It does this by asking filtering questions 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.

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 Fig. 3. Once all relevant 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 [44]. Accompanying these strategies is an impact score of each of the ten design areas in Table 1. 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. Two experiments were performed to analyze the effectiveness of providing designers with these DfE strategies after using the GREEn Quiz.

Two case studies are explored in this work, both designed to test the efficacy of the GREEn Quiz during the concept generation phase. The first case study explores the use of the GREEn Quiz by novice DfE designers and compares its use against another early-design-phase eco-design approach. The second case study explores the potential benefits of the GREEn Quiz when used by more experienced DfE designers, with a particular focus on the

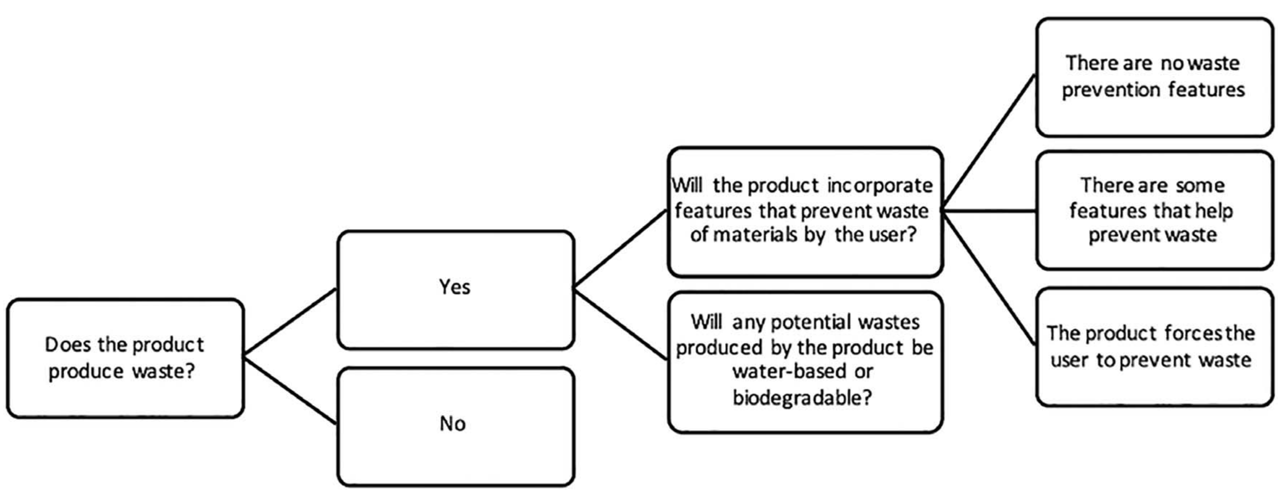
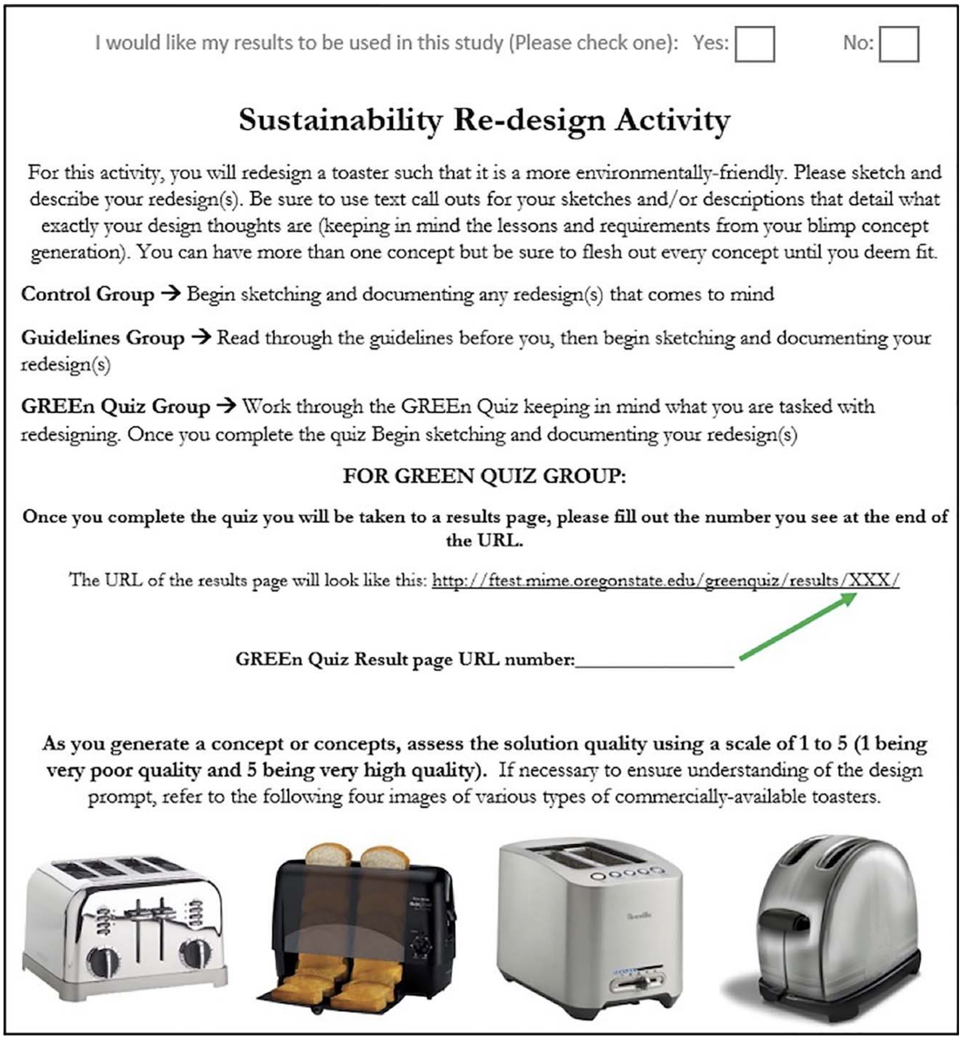


Fig. 2 GREEn Quiz search tree example



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.

Fig. 3 Sustainability redesign activity presented to participants

Table 1 Categories of GREEn Quiz questions and example questions from each

GREEn Quiz category	Example question(s) from category
Comparison	Compared to existing similar products with the same functionality, will the products have a reduced number of parts, and joining elements?
Material selection	Will recyclable materials be used in the design? Will special materials, surface treatments, and structural arrangements be specified to protect a product from dirt, corrosion, and wear?
Design/Structure	Will structural techniques be used to reduce the amount of material in the product?
Manufacturing	Will the number of different materials used to make the product and its components be minimized?
Transportation	Will the design of the product take minimizing the amount of packaging into account? Will folding, nesting, or disassembly be used to transport the products (i.e., from the warehouse to distributors/consumers) in a compact state?
Use phase	Will the product have energy efficient functionality? If the product has multiple operating conditions, will the product be designed as such that it is efficient over a wide range of operating conditions? Will there be default mechanisms to automate the product's efficient use? Are there aspects of the product's design that enable the consumer to easily implement/use the product in an environmentally friendly way?
Maintenance	Will cleaning and maintenance details be indicated on the product?
Hazardous materials	Will any potential wastes produced by the product be water-based or biodegradable? If the product must contain hazardous materials, will it include labels and instructions for safe handling of these materials?
Disassembly	Will the product allow for repetitive disassembly and reassembly?
Disposal	Will destructive disassembly techniques (if required) render components non-reusable? Will the product be organized into modules for repair and end-of-life?

redesign of a concept that had previously been designed with DfE considerations in mind.

Experiment 1: Redesigning a Toaster (Novice Design for the Environment). The design problem for this experiment involved redesigning an existing consumer product to be more sustainable. The toaster redesign problem is consistent with a previous study, which enables a direct comparison of the results. This design problem was chosen due to familiarity with 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 3 shows the redesign activity presented to the 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 who were 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 have presented the redesign activity shown in Fig. 4 during their Introduction to Design course laboratory 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 redesign without the use of any DfE methods to act as a baseline measurement. The group generating concepts using the sustainable design guidelines was given a printout of sustainable design guidelines developed by Telenko et al. [23]. The group using 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 min of concept generation time to complete the study. Students were not given prescribed ideation or brainstorming approaches to use, only these supplemental DfE methods. 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-min time limit on product ideation began. Those given the sustainable design guidelines were given 5 min to review the printout and then given the same 30-min time limit. The control group was given just 30 min 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 min concluded, the redesign activity sheet was collected and sorted by group.

Metrics. We analyzed each participant's redesign 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 the number of design decisions.

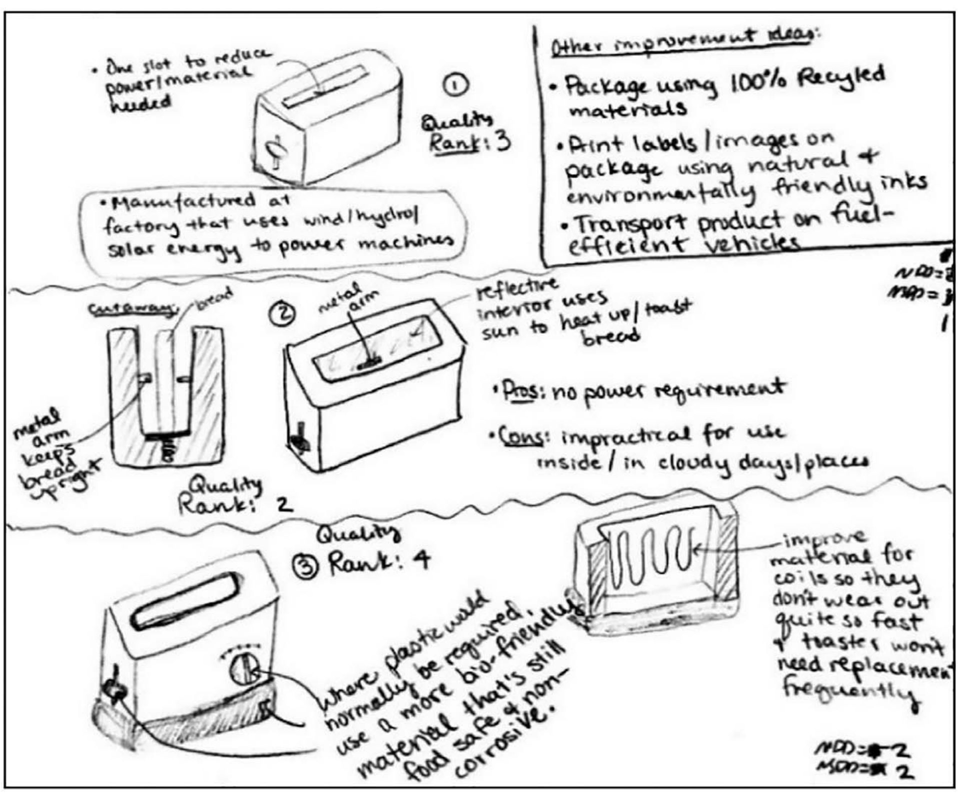


Fig. 4 Example of submitted concepts from Study 1

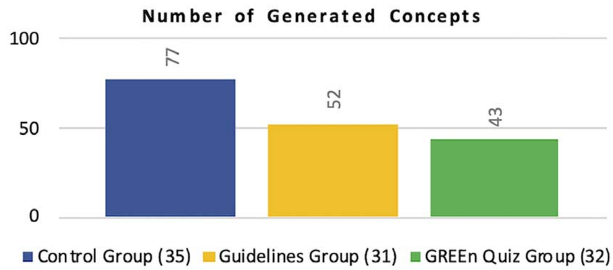


Fig. 5 Total number of generated concepts by Group

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 was 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 *Even Number of Slots, Electrically Powered, Beveled Cube Shape, Spring Pop Up, Plunge Activated, Presence of Heat Settings*, and *Presence of Cancel Button*. These were used to filter out features inherent in current toasters that could influence their redesign, allowing for an analysis of the novel design decisions made as a result of the DfE tools.

While assessing the evidence of sustainable design decision-making is a critical metric for measuring the performance of different eco-design tools, we also wanted to assess whether the concepts were of high quality. This metric is intended to highlight what we assumed would be a trend in the concepts—that respondents who used structured eco-design tools would design higher-quality concepts. The fourth metric was quantifying the *solution quality* of each generated concept. We used two separate metrics for solution quality. The first is a self-assessed solution quality score on a scale of 1–5: 1 being the lowest quality and 5 being the highest quality. The respondents learned about product quality in the course in which this design activity took place. The second quality scored was a judged score. Three judges—selected from a group of sustainable product design experts at Oregon State University—rated 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 judged score for each concept to accompany the self-assessed solution quality generated by the respondents during the study for each of their concepts. In Fig. 4, the designer has ideated three toaster solutions (numbered in small circles), and each of these has provided a self-assessed quality metric of 3, 2, and 4, respectively.

Statistical Analyses. An analysis of variance (ANOVA) statistical test was performed on these metrics to assess whether there is a statistically significant variation between the mean values of the metrics, which would imply that one approach is better than another at achieving higher metric values with sufficient confidence to suggest this improvement is not by chance. As some of the ANOVA tests were very close for some of the metrics in this case study, we also conducted a *two-sample assuming equal variances t*-test to compare each group's metrics, testing a pair of groups at a time (control group compared to GREEn Quiz group, e.g.). The null hypothesis for both of these tests is that there is no substantial difference between the mean values of each of these metrics across the three groups. In ANOVA, the null hypothesis is rejected if the *p*-value is less than the alpha value. In the *t*-test, if $t_{obs} < t_{crit}$, then we reject this null hypothesis. Rejecting the null hypothesis means that there is a statistically significant difference between the mean values of the metric being tested across the three groups of respondents.

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 apply knowledge gained from weeks prior to 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.

At the time of the study, the students had ideated concepts for their final project but had not learned about eco-design tools, like the GREEn Quiz, which are used to supplement concept generation. The students were provided the web address 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 h 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 team's 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 5 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

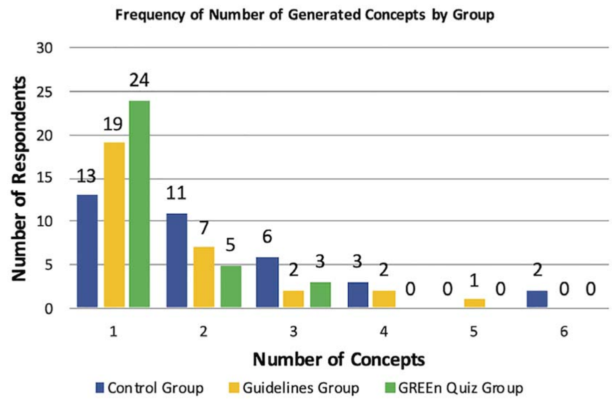


Fig. 6 Number of concepts ideated by each respondent, identified by test group

GREEn Quiz, the control group produced the largest number of concepts, followed by the guideline group and the GREEn Quiz group [45].

Figure 6 shows the frequency of the number of concepts generated by each respondent within each group; most respondents designed only one concept, regardless of 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 three 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 $\alpha = 0.05$, $F = 5.43$ 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.

Number of Design and Sustainable Design Decisions. We assessed the total number of novel design decisions and distinguished the sustainable design decisions (as a subset of a total number of design decisions) for each concept generated by the respondents in each group. Figure 7 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 considered sustainability. 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.

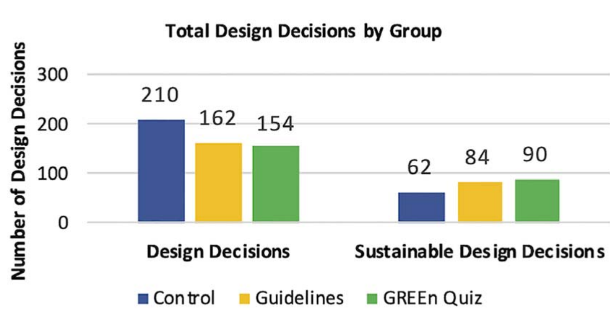


Fig. 7 Total number of design decisions by group

Table 2 *t*-Test comparison of number of design decisions by group

	t_{obs}	t_{crit}	∝	*df*
Control versus Guideline	0.32	1.98	0.05	97
Control versus GREEn Quiz	1.6	1.99	0.05	88
Guideline versus GREEn Quiz	1.48	2	0.05	63

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 decisions and sustainable design decisions between groups. With respect to the number of design decisions, $F_{crit} = 3.05$ at $\alpha = 0.05$, $F = 3.15$, and the p-value is 0.045. With respect to the number of sustainable design decisions, $F_{crit} = 3.05$ at $\alpha = 0.05$, $F = 15.03$ 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 no significant differences in the mean number of design decisions (Table 2), but there are significant differences in the mean number of sustainable design decisions (Table 3).

Figure 8 shows the frequency of the number of sustainable design decisions found in each concept created by the Control group, the Guidelines group, and the GREEn Quiz group. The Control group concepts had four or fewer sustainable design decisions, where the Guidelines group and GREEn Quiz group concepts had up to six sustainable design decisions per concept, with the distribution skewing toward lower values of both decision types. The most common number of sustainable design decisions made by the Control group was one or zero for most concepts. The distribution of the number of sustainable design decisions for the Guidelines group skews slightly left of the distribution of the number of sustainable design decisions made by the GREEn Quiz group. The most common number of sustainable design decisions per concept for the Guidelines group was zero or 1, and the most common number of sustainable design decisions per concept for the GREEn Quiz group was 1 or 2.

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 9 shows a graph comparing the average self-assessed scores, followed by Fig. 10, 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 showed statistically significant differences in self-assessed scores between groups. In this case, $F_{crit} = 3.05$ at $\alpha = 0.05$, $F = 1.88$ and the p-value is 0.15.

Table 3 *t*-Test comparison of number of sustainable design decisions by group

	t_{obs}	t_{crit}	∝	*df*
Control versus Guideline	3.36	1.98	0.05	112
Control versus GREEn Quiz	4.284	1.98	0.05	103
Guideline versus GREEn Quiz	1.45	1.98	0.05	93

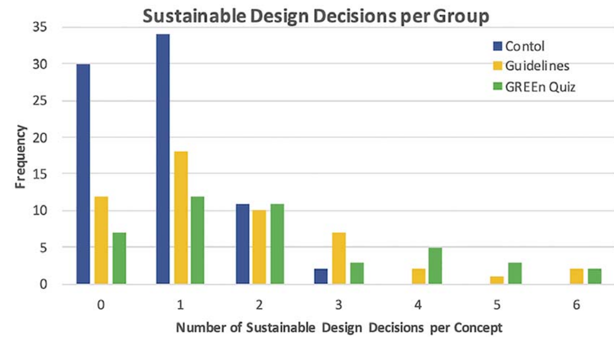


Fig. 8 Frequency of sustainable design decisions in Control, Guidelines, and GREEn Quiz Group concepts

Fig. 9 Average self-assessed scores by group

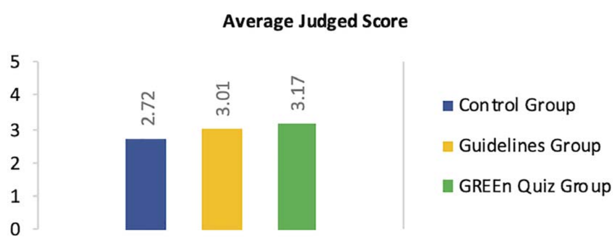


Fig. 10 Average judged scores by group

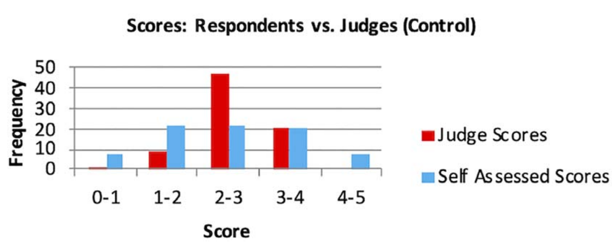


Fig. 11 Respondents and judge score histogram of control group

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 Fig. 13, and the GREEn Quiz group concepts have a higher average judge score 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 $\alpha = 0.05$, $F = 3.05$ 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 4. A *two-sample assuming equal variances t*-test was used comparing the control with 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.

There was noticeable variation in scoring between self-assessed quality scores, and the quality scores determined by the judges. Figures 11–13 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 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 toward higher scores than the other two groups.

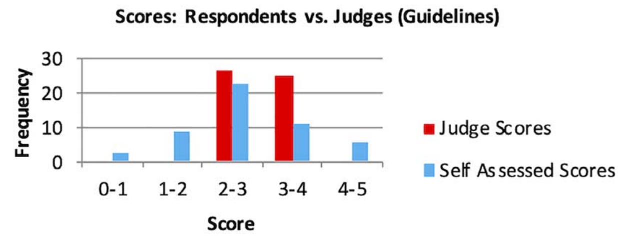


Fig. 12 Respondents and judge score histogram of guideline group

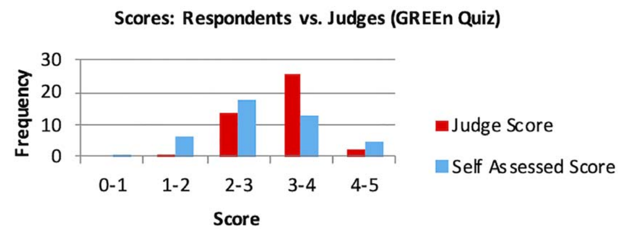


Fig. 13 Respondents and judge score histogram of GREEn Quiz Group

Table 4 *t*-Test comparison of judged scores by group

	t_{obs}	t_{crit}	∝	*df*
Control versus Guideline	3.25	1.98	0.05	127
Control versus GREEn Quiz	4.23	1.98	0.05	118
Guideline versus GREEn Quiz	1.45	1.98	0.05	93

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 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 14 shows the number of design decisions and number of sustainable design decisions present in each concept before and after the groups took the GREEn Quiz. The highest number of sustainable design decisions in all the concepts prior to taking the GREEn Quiz was two. After taking the GREEn Quiz, there was a noticeable difference in the number of both design and sustainable design

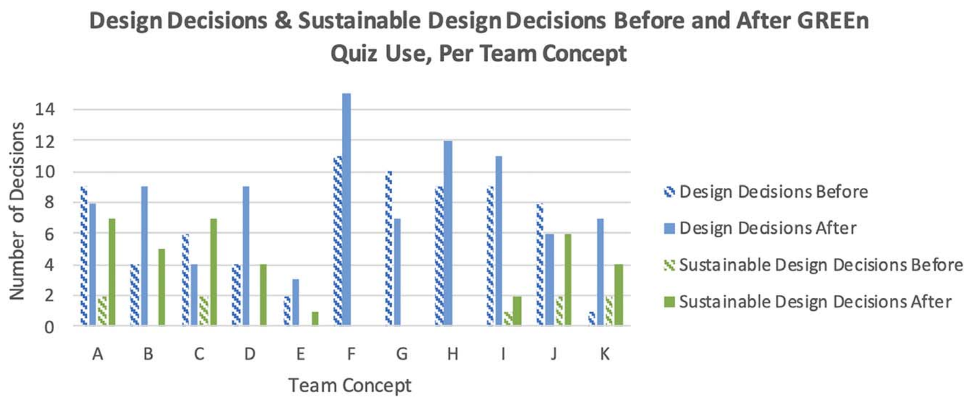


Fig. 14 Number of design and sustainable design decisions before and after taking GREEn Quiz

decisions. However, the number of sustainable design decisions had a much higher increase. 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 ($\alpha = 0.05$) 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 ($\alpha = 0.05$).

Categories of Design Decisions. We categorized design decisions into the following categories: Material Selection, Use, Maintenance, Manufacturing, Labeling, Design Layout, Disposal, and Transport. Figure 15 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.

Discussion

The GREEn Quiz walks engineering designers through a series of questions that are intended to encourage the direct consideration of product environmental sustainability during concept generation. These questions are organized into a search tree, which enables an efficient presentation of questions that are relevant to the design task at hand, a property that improves on list-based eco-design tools. Further, most questions address sustainable design principles, but the GREEn Quiz also includes questions about product economics and customer preference, which expands on the knowledge content of list-based eco-design tools. Additionally, the GREEn Quiz ends by providing the designer with a detailed report that includes further information and design strategies that are intended to be easily integrated into concept generation, not simply guidelines for design. Two studies were undertaken to assess how well the information from the GREEn Quiz was embedded into the generation of concepts: one test considered novice designers redesigning an existing product (a toaster) to be more environmentally sustainable, comparing the GREEn Quiz against a control group and a group that received a list of sustainable design guidelines; and a second test where we had graduate-level designers—with DfE expertise—design a concept, use the GREEn Quiz, and then redesign the concept with information gleaned from the quiz. Both studies indicate the GREEn Quiz shows promise as an eco-design tool that is applicable in the early design phase.

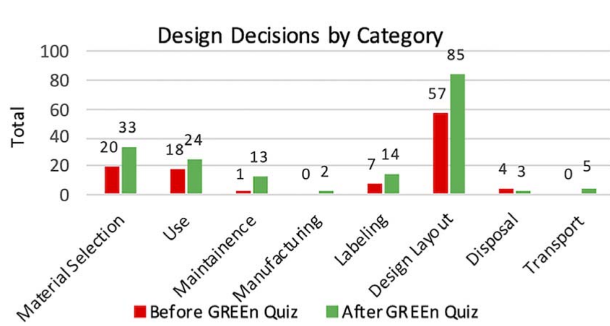


Fig. 15 Frequency of design decisions in product categories before/after the GREEn Quiz

The research question that informed the first experiment in this paper was the hypothesis that the GREEn Quiz and the resulting structured information it provides are an easier pathway to making sustainable design decisions than either a list of guidelines or being provided no information at all. The results showed that both the GREEn Quiz and Guidelines groups were able to integrate more sustainable design decisions into their concepts; the raw data showed that the GREEn Quiz may be better at this integration than the guidelines group, but subsequent statistical analyses suggest these tools actually have similar performance in this regard. 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 the total number of design decisions. The reason for this could be attributed to both the GREEn Quiz group and the Guidelines group using provided information that possibly behave as constraints during concept generation. A study on design fixation corroborated that adherence to a set of guidelines or ideas can limit the potential output of conceptual designs [46]. This theory is also reflected in the experimental results, as both the guidelines 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 performed the conceptual design of a product, used the GREEn Quiz, and then redesigned their concepts with the information gleaned from the GREEn Quiz. These designers had advanced DfE expertise as they were graduate students in the mechanical design program, and at the time of the study, they were taking a sustainable product design course. Most notable were the results that these designers were able to make sustainable design decisions across a much broader spectrum of DfE categories than prior to using the GREEn Quiz. The use of the GREEn Quiz by these teams provided them with abstracted design knowledge that enabled them to produce concepts that are more likely to be environmentally sustainable.

The first experiment also showed that concepts generated after the use 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-apply baseline of sustainable knowledge that both novice and experienced designers interpret 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 group, but similar to one another, indicating that both the GREEn Quiz and a list-based approach help designers to make sustainable design decisions during concept generation.

The GREEn Quiz is meant to be applied in the early design phase (prior to and during conceptual design) and provides abstracted DfE strategies that are relevant to the design of specific products. Currently, sustainable design guidelines are the only approach designed for use during this phase of environmentally sustainable design. We have shown that this type of information—broad knowledge written in accessible language, followed by potential design strategies—is able to be embedded in the concept generation process by both novice and more experienced DfE designers. The GREEn Quiz is differentiated from other eco-design tools that are applicable during the early design phase by providing this information in a digital search tree format, allowing users to focus only on those principles that are relevant to the design of the product at hand. The report provided to users of the GREEn Quiz is also catered to the responses selected by the user, providing design strategies specifically related to the designer's assessment of how well the concept meets each question.

Conclusions

This research study sought to support the hypothesis that providing structured Design for the Environment strategies results in more effective sustainability considerations in the early 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 concepts generated by participants in two experiments performed at Oregon State University.

Research into early design phase integration of DfE methods is crucial in catalyzing the world's transition into a more sustainable future. However, few sustainable design methods are intended to supplement the "fuzzy front end" of engineering design, particularly during concept generation. Building on the knowledge transfer of list-based eco-design tools, the GREEn Quiz experiments provided evidence that sustainable design strategies can be incorporated into the early phases of the engineering design process. These studies indicate that providing DfE information and strategies—using the digital GREEn Quiz presented in this paper and also list-based sustainable design guidelines—enables users to understand and design specifically toward sustainability outcomes earlier during the design process when these considerations are less costly and time-consuming. The GREEn Quiz, specifically, has also helped increase the breadth of sustainable design decisions that users make, even those users with more extensive design for sustainability knowledge.

After further testing and refinement, the GREEn Quiz will be a publicly available web resource from the Oregon State University Design Engineering Laboratory. This design tool is intended for both educational and industrial use, and we will record use metrics and user feedback to ensure that user needs are continuously met.

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Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The data sets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request. The authors attest that all data for this study are included in the paper.

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