A Method for Understanding Sustainable Design Trade-offs During the Early Design Phase

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Abstract. The purpose of this research is to present a new method for integrating sustainable design knowledge into the early design phase of new products and processes. A novel organized search tree is constructed to enable the application of sustainable design knowledge before and during concept generation. To further facilitate its application, this search tree is embedded in an easy-to-use web-based application called the GREEn Quiz (Guidelines and Regulations for Early design for the Environment). As a designer progresses through the quiz, user responses are compiled and weighted, and a final environmental impact report is provided to the user. Two research studies are explored to validate the proposed method. The results of these studies show that the search-tree format and presentation of the collection of design knowledge presented in this work provide design engineers with a valuable and informative resource for facilitating the design of products with reduced environmental impacts.

Keywords: Sustainable Products · Product Development · Early Design Phase · Design for the Environment · Sustainable Design Theory

1 Introduction

Unprecedented growth in both global population and affluence has led to a substantial and continual increase in the design, manufacturing, and consumption of consumer products. The increase in consumer products has led to the vast amount of materials being sent to landfills - where they become irrecoverable – which has begun to create a push from society to start producing new products with a reduced environmental impact [1]. Design and development of consumer products is challenging in that there exist very few design methods that inform designers of the environmental impact of new products; in particular, there is a lack of resources that are applicable in the early (pre-concept generation) design phase. This lack of suitable design methods poses an issue, as 80% of the environmental impact of a product is determined after only 20% of the design process is complete [2].

Currently there is a series of robust methods that can assist designers to determine the environmental impact of an existing product, after the design has been fully clarified. This method is called a life-cycle analysis/assessment (LCA). As defined by the ISO 14040 standard, a LCA is a "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" [3]. LCA is a useful method for understanding a product's environmental impact, however, the information required to complete a detailed LCA necessitates that the product being analyzed is completely designed and/or in production. Due to this, LCA is extremely useful when used as a retrospective resource.

Recent work has improved the LCA methodology by bringing the detailed results of LCA to an earlier point in the design process, without sacrificing accuracy [4] [5]. These investigations used an artificial neural network to learn from a test set of completed LCA data to infer the environmental impact of potential design concepts during the concept selection phase. Unlike the proposed work (which is intended to be employed as part of the concept generation process) the work by Sousa et al. facilitates the sustainable design of a product *after* preliminary concept generation has been performed, suggesting improvement to a more established design.

Research into improving integration of Design for Environment (DfE) methods has shown that the earlier DfE is incorporated into the design process, the more of an impact it has on reducing the environmental footprint of a product [2] [6] [7]. Other work has found that the more DfE principles are integrated in the process, the greater the chance that the product would become more sustainable as compared to just using a single tool at one stage in the process [8].

There are multiple DfE methods that can be used in the early design phase that this works seeks to improve upon. These methods include environmentally-based Quality Function Deployment (QFD) [9–12]. The environmentally-based QFD-referred to as Eco-QFD, QDFE, QFD-DfE, and ECQFD-allows the designer to include engineering requirements that are specific to possible environmental impacts the product may contribute. Another method is knowing and applying accepted guidelines and principles that have been found to reduce the impact of a product [7] [13–17]. These lists of guidelines are comprehensive, but may be difficult for sustainable design novices to employ. Point based methods, such as Eco-Indicator and ReCiPe focus on quantifying the environmental impact of a product using a point system that is mapped to specific processes and materials. [18–21]. Other methods include software applications that use CAD models [22] [23]. CAD-based LCA methods take advantage of user-generated CAD models and are able to calculate an impact based on the exact dimensions of a design and user-selected materials and processes. There are some limitations to these methods, as the accuracy of the results are based on the availability of processes and materials within the program's database, and require enough design information to be clarified such that a CAD model can be generated.

The work presented in this paper is intended to provide design engineers with a method suitable for use in the early design phase for designing sustainable products. The resulting method is an easy-to-use, informative design resource that will enable designers to understand the eventual environmental impact of products throughout the early conceptual design phase.

To do this, a novel search tree will be developed that combines sustainable design guidelines, international design regulations and standards, empirical design knowledge, and attributes of product cost and preference. The search tree, created in the form of a series of questions and possible user responses, is preliminarily embedded in a web-based survey; the results of the survey are presented to the user as a final report. The goal of this work is to help inform designers of the environmental impact of design decisions as they are being made, and will contribute to the development of more sustainable products.

The following section discusses the new method and the two studies that were conducted to prove the efficacy of the method. Following the methodology section, results of both studies are presented, and the paper concludes with a discussion and concluding remarks.

2 Methodology

Throughout the design of a product, certain design decisions are made that lock in the environmental impact of a product. Such decisions include material choice, where the product is being manufactured and sold, clarifying the intended use and any consumables (such as electricity or consumed parts), and resulting method(s) of disposal. With a considerable portion of the environmental impact of a product being determined in the early design phase, there is a need for a resource that is accurate, informative, easy to use, and applicable throughout the entire design process. To do this, sustainable design knowledge is collected and organized to provide a foundation for the proposed design resource. In the context of this work, sustainable design knowledge consists of sustainable design guidelines, international design regulations, empirical design knowledge, customer preference, and reference LCA data for existing products.

One goal of the proposed work is to create a method that is widely applicable and easy to use regardless of the previous sustainable design experience of the user. To ensure that the proposed collection of sustainable design knowledge will be easily accessible, this information is rewritten into question form. By converting sustainable design knowledge into relevant questions and presenting them one at a time, this facilitates user understanding and application of the sustainability-related principles. Every question is paired with a set of potential user responses, which are presented as a Likert scale set representing neutrality, agreement, and disagreement with the question. The responses vary in number for each question from two (yes/no) to five, with the wording of each response developed specifically for each question. Along with each question and its corresponding potential responses, there is a “More Information” section that provides the designer with clarification for each question. The clarification provides either examples or alternative phrasing to assist in making responses easier to select for a given question. The use and development of the questions, creation of potential user responses, and the additional information presented with each question are specifically designed to increase user comprehension and ability to apply the knowledge presented.

The questions are arranged in a search tree structure, which will facilitate the application of sustainable design knowledge that is directly relevant to the product at hand. In addition, as series of filtering questions are employed that further remove irrelevant questions, such that the designer’s question set is selected specifically for the type of product being designed. These features are key to making this design resource easy to use. An example of one branch of the search tree is seen in Fig. 1.

The tree consists of preliminary filtering questions and foundational questions; the filtering questions determine which branches of the foundational questions will be included.

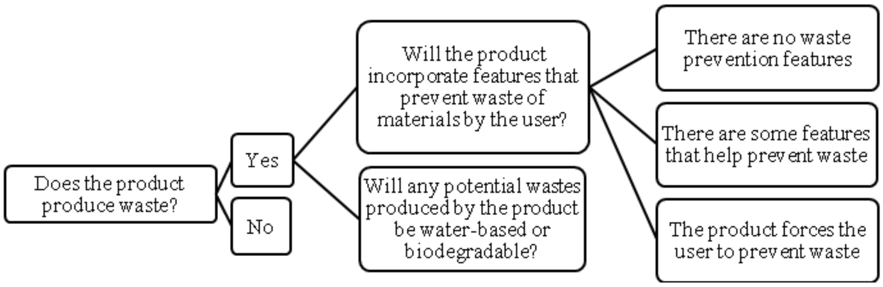

Fig. 1. Example of one branch of the search tree

In order to make this easy-to-use design resource accessible, the physical implementation is web-based. The programming language Python is used for the development of the quiz's backend, while Django, a web application framework [24], is used to provide a means of placing the quiz on a server, such that the quiz may be accessed by multiple users from any location with internet access. The design resource embedded in the web-based application is herein referred to as The GREEn Quiz (Guidelines and Regulations for Early design for the Environment).

The quiz starts by asking pre-quiz filtering questions to the designer, which are selected to help filter out unneeded questions, thus allowing the designer to focus only on what is relevant to their design. After the filtering questions are completed, the questions from the accordant truncated search tree are provided in a depth-first manner. An example question can be seen in Fig. 2.a.

The organization of the quiz is structured such that similar questions – by theme, such as material selection, energy consumption, and transportation - are grouped together. These groups follow the flow seen in Fig. 3. The flow starts with questions that compare the current design that is being tested with other competing products. The next two consecutive groups deal with question regarding the design process, such as material selection and structural design. The questions are then grouped into their respective life-cycle phases: manufacturing, transportation, use, hazardous material, disassembly, and disposal. The motivation for this organization is to present questions in an order that better reflects the timeline of the product being developed from its original concept to the disposal of its final form.

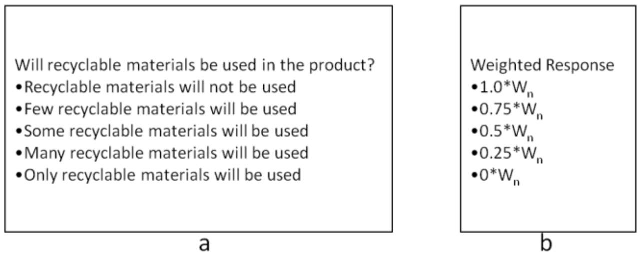

Fig. 2. (a) An example question (b) Calculating a value for a chosen response

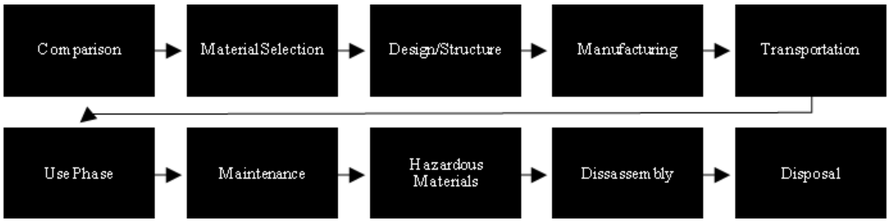

Fig. 3. Flow of categories in the GREEn Quiz

Upon completion of the quiz, a report is presented to the designer. The goal of the report is to provide the user of the quiz with relevant information and potential design decisions that will enable the user to improve their design concept by making it more sustainable. To do this, quantitative values corresponding to each user response provide a score for each answered question. An example of the how the responses are calculated is seen in Fig. 2.b, where each response inherently has a value correlated to the strength of weakness of that response, multiplied by a weight for each question. This score is then presented in the post quiz report, which displays the summed score of each individual group, as well as a list of the top ten contributing questions that have the greatest impact on the environment. After listing the top ten contributors, a follow-up list is provided to give additional motivation and suggestions to improve the environmental impact of the design. The score received for each question and a paragraph discussing the means and/or motivation on how to improve the score is provided. In keeping with the logical attempt to reduce environmental impact, the scoring is structured in such a way that lower scores are better, enabling the designer to try to reduce both the GREEn Quiz score and the environmental impact of the product concept.

While the version of the quiz presented in this work is exploratory and improvements are already underway, it is pertinent to examine the validity of the current instantiation of the proposed methodology. To do this, we will explore whether this methodology is more useful than the current standard. The current standard – assuming that empirical sustainable design knowledge is not applied – is to employ a list of current sustainable design guidelines found in academic literature. To test this, two validation studies were conducted [25].

The first study was conducted in a junior-level introduction to mechanical design course, where inexperienced students in sustainable design first learn fundamental design principles. Students were divided in to three similarly sized groups, and all three groups were given a sustainable redesign activity to complete. One group (the control group) received only the design activity and no further materials, the second group received a list of sustainable design guidelines from the literature [7], and the final group received access to the GREEn Quiz website. The sustainable re-design activity tasked students with the redesign of a common toaster such that it would have a reduced environmental impact. All students were given 30 minutes to complete the activity to the best of their ability. After completion of the activity, 82 total students participated with 27 students acting as the control, 26 students employing the guidelines, and 29 students using the GREEn Quiz.

The second study was conducted in a graduate-level mechanical design course that specifically focused on sustainable product design, which can be assumed to have more sustainable design knowledge. The course consists of a term-long project, where students learn how to develop a new sustainable product, from an initial broad scope to a patent-ready product, within groups of six students. The purpose of this study was to explore the efficacy of the GREEn Quiz as applied during concept generation. To accomplish this, the study was broken up into two parts: the first was to familiarize students with the guidelines and how the GREEn Quiz worked, and the second was to compare designs that are generated before and after taking the GREEn Quiz. Students were asked to generate concepts individually during this phase of the project, generating at least ten concepts on their own, in the form of sketches and text callouts. After completing the first design concept unassisted, students were then asked to utilize the GREEn Quiz as applied to this first design concept. Upon completing the quiz, the students were asked to redesign or improve upon their concept such that the product concept would be more sustainable. From this study, a direct comparison can be drawn between preliminary expert sustainable design knowledge and the benefits of using and applying the GREEn Quiz.

3 Results

The first study conducted in the undergraduate class focused on how inexperienced designers in sustainable design would perform while using various sustainable design resources to re-design a product. In Fig. 4 and Fig. 5, the average number of design decisions are shown with respect to the three different groups (control, sustainable design guidelines, and GREEn Quiz), with Fig. 4 showing all design decisions, and Fig. 5 showing all stated sustainable design decisions. These design decisions were determined empirically, and are considered to be unique features that are either specifically called out or drawn. Examples of such features include a solar panel embedded in a toaster, as seen in Fig. 6, or a text call-out stating the material for the housing would be made of recycled steel. A sustainable design decision is classified as a feature or aspect of a sketched design which follows one or more ideas captured in sustainable design knowledge within the quiz.

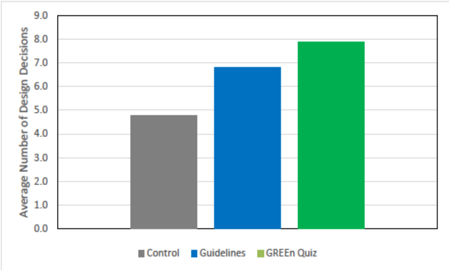

Fig. 4. Average Number of Design Decisions

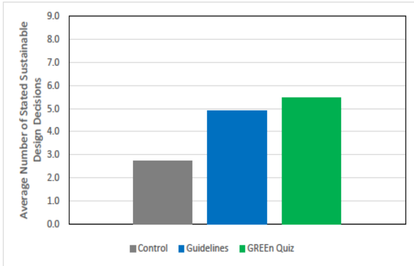

Fig. 5. Average Number of Stated Sustainable Design Decisions

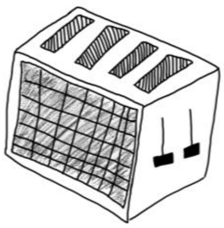

Fig. 6. Example sketch of a Sustainable Design Decision: solar-powered toaster

The second study, conducted in the graduate level class, was focused on designers with previous knowledge in sustainable design. During concept generation, students were instructed to take the GREEn Quiz for a particular product concept. After completion of the GREEn Quiz they were told to redesign their initial concept such that it would be more sustainable. The results of this study are shown in Fig. 7. For both before (blue) and after (orange) employing the GREEn quiz, Fig. 7 shows the number of students who made reference to a question within the GREEn Quiz, by the category in which the referenced question were organized. It is important to note that a given person is only counted once per section even know they may have referenced multiple quiz questions that relate to a single category.

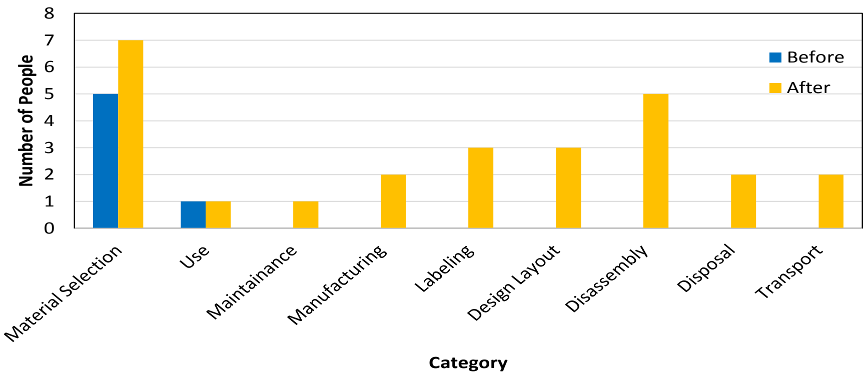

Fig. 7. Referenced Sustainable Decisions: Before and After the GREEn Quiz

4 Discussion

Two studies were conducted to test the validity of the GREEn Quiz. The first study (the undergraduate study) was to verify that the GREEn Quiz would be useful as a design tool and benefit the designer in generating sustainable product designs. As shown in Fig. 4 these results imply that when students are given a resource (be it the list of guidelines or the GREEn quiz), they are able to call out and/or include more design decisions than the control group, which did not receive any additional material. Moreover, the GREEn Quiz group was able to generate the greatest number of average design decisions for that redesign activity. By having directly-applicable and relevant concepts presented in the quiz, the students were able to implement sustainable design knowledge – of which they were previously unaware - and apply it to their redesign.

In Fig. 5, the average number of sustainable design decisions for each group is shown. As expected, the trend in Fig. 5 is similar as to what is seen in Fig. 4, since the sustainable design decisions are a subset of the total number of design decisions referenced in Fig. 4. The GREEn Quiz is intended to assist the designer in making more sustainable design choices, and these results support the statement that by using the proposed method, a designer can design a product that has more sustainable design considerations.

The second study tasked graduate students to evaluate and redesign concepts that they generated for their team-based product design term project affiliated with the class. This study allows for the ability of making sustainable design improvements to be tested in a before-and-after setting. As seen in Fig. 7, prior to using the GREEn quiz, the students mentioned only a few potential sustainable design decisions, in a narrow breadth. After taking the GREEn Quiz and redesigning their initial concept, there were more students making sustainable design decisions and in a wider breadth of categories. The increase in breadth can be attributed to the wide array of sustainable design knowledge encompassed in the quiz. This result shows that when users of the quiz are exposed to knowledge they might not know in an easy-tointerpret format, they are capable of directly applying it in the development of design concepts with a reduced environmental impact.

5 Conclusion

This paper provides a new method to enable designers to determine which design decisions made during the early design of a product will have the highest environmental impact and to encourage the development of sustainable products. The proposed search tree implemented in the GREEn Quiz will provide designers with an easy-to-use method that can assist them in the conceptual design of such products, by supplying them with development questions, feasible responses, and a corresponding report that indicates where design improvements can be made. Two case studies showed a positive relationship between employing the GREEn Quiz and the ability to make more sustainable design decisions during the early design phase, and the ability for GREEn Quiz expert users to explore a wider breadth of feasible sustainable design decisions than when relying on expert knowledge alone.

Future work includes developing an advanced weighting system such that the results of the GREEn Quiz provide relevant quantifiable information to the designer. By allowing the weights to create more meaningful results, it can provide the designer with the ability to make critical design decisions with confidence, knowing that the changes they are making will make the largest impact of reducing the environmental footprint of that product.

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