AN ABSTRACT OF THE THESIS OF

Addison Wisthoff for the degree of Master of Science in Mechanical Engineering presented on May 26, 2016.

Title: Using Automation to Understand Sustainable Design Trade-Offs and to Promote Environmental Sustainability in the Early Design Phase

Abstract approved:

Dr. Bryony L. DuPont

Sustainable product design is becoming an important component of the development of consumer products. Currently there are limited design resources to aid in the creation of environmentally sustainable products. The purpose of this research is to theorize a new method for integrating sustainable design knowledge into the early design phase of new products and processes. A novel organized search tree—consisting of sustainable product design guidelines, empirical design knowledge, international design regulations and preliminary consumer preference information—is constructed to enable 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). The quiz provides users with weighted questions pertaining to the design or redesign of a product concept, with a list of possible pre-

generated responses to choose from. As a designer progresses through the quiz, user responses are compiled and weighted, and a final report that displays the top ten design attributes contributing to the eventual environmental impact of the product are provided to the user. Accompanied by the top ten list, is a list of design decisions that can be used to better help inform the designer to make improvements that can make the product more sustainable. To further assist designers in understanding the impact of their design decisions, a preliminary investigation into life cycle estimation is conducted by training an artificial neural network on 37 different consumer products. The results of this work found that the design method facilitates designers of varied experience to increase the number of environmentally conscience design decisions made in the concept generation process. It was also found that a neural network can be used to learn valuable correlations between product attributes and life cycle data (which is promising for life cycle impact estimation), but further work into increasing the capability of the neural network approach is required before this data can be used to inform the weights used in the GREEn Quiz. Without new environmentally conscious methods similar to the current method, it will continue to be challenging to design eco-friendly products, and the impact of consumable products will continue to be unsustainable.

Using Automation to Understand Sustainable Design Trade-Offs and to Promote Environmental Sustainability in the Early Design Phase

by
Addison Wisthoff

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented May 26, 2016
Commencement June 2016

Master of Science thesis of Addison Wisthoff presented on May 26, 2016

APPROVED:

Major Professor, representing Mechanical Engineering

Head of the School of Mechanical, Industrial, and Manufacturing Engineering

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Addison Wisthoff, Author

ACKNOWLEDGEMENTS

I would like to expresses sincere appreciation to my advisor for providing guidance, advice, and encouragement during the author's attendance at Oregon State University. I would also like to express gratitude for the support that my lab group provided during meetings. Finally, I would like expresses great appreciation to my parents, brother, and grandparents for providing support and encouragement throughout my higher education experience.

This work was funded by the National Science Foundation CMMI - 1350065 and Oregon State University's School of Mechanical, Industrial, and Manufacturing Engineering.

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

EPA	United State Environmental Agency
LCA	Life-cycle assessment
LCIA	Life-cycle Impact Assessment
SLCA	Simplified LCA
ERPA	Environmentally Responsible Product Assessment
LCI	Life-cycle inventory
DfE	Design for Environment
ECQFD	Environmentally - Conscious Quality Function Deployment
The GREEn Quiz	Guidelines and Regulations for Early design for the Environment
EI99	Eco-Indicator 99
mPt	milliPoint
ι, ς, κ	Node locations
I_ι	Input layer value at node ι
H_ς	Hidden layer value at node ς
O_κ	Estimated output layer value at node κ
$x_{\iota\varsigma}$	Weight linking input layer node ι to hidden layer node ς
$y_{\varsigma\kappa}$	Weight linking hidden layer node ς to output layer node κ
β	Tunable neural network parameter in the activation function
a_ς	Activation value at hidden layer node ς
b_κ	Activation value at output layer node κ
t_κ	Known output layer value at node κ
E	Sum-of-squares error
δ_{Out}	Symbolic variable representing $\frac{\partial E}{\partial O_\kappa}$
η	Tunable neural network parameter in adjusting magnitude of $x_{\iota\varsigma}$ and $y_{\varsigma\kappa}$ error adjustments

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. In a 2009 report by the United States Environmental Protection Agency (EPA), it was found that "in the past 50 years, humans have consumed more resources than in all previous history" [1]. Additionally, the use of renewable resources such as wood or other biomass products in the United States has decreased from 41% to 6% in the last century, with the percentage continuing to decrease in the subsequent years [1]. As nonrenewable resources (including fossil-fuel-based materials, metals, and minerals) are not commonly compostable or biodegradable, most of the materials used in modern production end up in landfills [2]. This large influx of waste can be traced to the beginning of US consumerism in the late 1940's, which brought forth a more materialistic society that led to the sale and purchase of large a quantity and variety of consumer products, most of which eventually end up landfills [3]. In 2013, residential waste generation from products totaled 178.92 million tons [2]. This averages to approximately half a ton of waste per person per year in the United States. While there has been significant effort to encourage recycling of materials in order to reduce this considerable waste, nonrenewable materials such as metals and plastics have a recovery rate of just 34.1% and 9.2% respectively [2]. The majority of waste—made of recyclable materials or otherwise—generated by the US population is from products or is product-related (including product consumables and packaging).

This increase in consumer products has begun to create a push from society to start producing new products with a reduced environmental impact [4]. 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 [5].

The goal of this work is to provide design decisions to designers developing new and redesigned consumer products, such that designers will reduce the environmental impact of products throughout the conceptual design phase. The objective is to inform designers about the impact of their decisions by linking quantitative values based on vetted LCA metrics to design decisions as the designer is making them.

1.1 Literature Review of Sustainable Design Knowledge

To achieve this research goal, a great deal of information must be collected and synthesized. The collection of sustainable design knowledge will consist of information in current literature related to (A) Sustainable Design Guidelines, including Design for End of Life and Use Phase impacts [6]–[11], (B) Design Heuristics, including Design for the Environment and Design for Manufacturing [12]–[18], (C) International Design Standards [8], [19]–[21], (D) Customer Preference for Sustainable Products [22]–[28], (E) Product Cost [29], and (F) Existing Sustainable Design Methods [30]–[42]. While the listed references are exploratory in nature and are not considered exhaustive, they represent the availability of information relating to sustainable design. A detailed description of the acquisition of this design knowledge can be found in subsection 2.1.1.

1.2 Literature Review of Sustainable Design Decisions

Along with the sustainable design knowledge, related design decisions are needed to help inform designs on how to improve their designs. The objective is to provide designers with series of product design decisions that imply how to apply the collection of sustainable design knowledge to any consumer product. Such design decisions are pulled from design textbooks [5], [43], design software [44], and other sources such as design patents [45]. An example of a design decision is organizing subassemblies and parts into modules to improve the process of repair, which is related to the sustainable design knowledge of “products organized into modules allow for easier maintenance and repair, as well as providing a means of separating incompatible materials at a products end of life” [5], [6]. Implementation of the design decisions are discussed in section 2.1.5.

1.3 Literature Review of Life-cycle estimation

Currently there is a series of robust methods that can assist designers in determining 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" [46]. LCA is an *a posteriori* method, and is not designed to be applicable during the early design (product ideation) phase. Considering this, there exist few methods with the depth of LCA that are specifically designed to inform product developers of the environmental impact of design decisions as those decisions are being made. Due to this, LCA is extremely useful when used as a retrospective resource.

Life-cycle impact assessment (LCIA) is a subset of LCA, and focuses specifically on measurable environmental impacts throughout the life cycle. Current LCIA methods include, but are not limited to CML, Eco-indicator 99, simplified LCA (SLCA), environmentally responsible product assessment (ERPA), ReCiPe, and TRACI [35], [36], [47]–[50]. In-depth LCIA methods are generally embodied in commercial software, with each method having their own strengths and weaknesses, as well as the optimum place at which it can be used in the design process. For some LCIA methods, mid-point and end-point metrics are the primary means of measuring environmental impact. Mid-points and end-points are both components of a cause-effect chain that takes life cycle inventory (LCI) data as an input and performs calculations to quantify an assortment of categories [51]. Various LCI data are formulated to generate a single mid-point value. Mid-point values offer insight into the environmental impacts of specific common chemical outputs in a product's life cycle. End-point values are calculated from mid-point values, as well as LCI data to reflect changes in higher-level impact categories, such as effects on human health and loss of species per year.

A visualization of different sustainable design tools can be seen in Figure 1, with a two-dimensional coordinate plane indicating the placement of sustainable design tools by which phase in the design process they are relevant (x-axis) and the quality/type of information the analysis provides (y-axis). Some design methods, such as applying sustainable design guidelines [9]–[11], [52], [53] and Environmentally-Conscious Quality Function Deployment (ECQFD) [39]–[42] are employable during early conceptual design. However, these methods are not designed to yield a quantitative assessment; rather they help to integrate sustainability considerations into the early design process. Environmentally Responsible Product Assessment (ERPA) is a quantitative matrix method that explores the environmental impact of the individual life-cycle phases of a product [30]. Simplified LCA (SLCA) methods are tailored, streamlined methods—essentially skeletonized LCA—that are much less costly to perform and require less input information. While both the ERPA and SLCA methods are designed to be less costly and time-consuming than traditional LCA, they have distinct shortcomings; both require many design decisions to be fully clarified in order to be useful, precluding their use as part of a new conceptual design method. Furthermore, SLCA methods are not widely applicable to many different types of products, and must be tailored for use [31], [32]. There is a clear research gap in sustainable design methods that is both in-depth and accurate (and readily available for the design of varied consumer goods), yet are applicable before and during the concept generation phase of design.

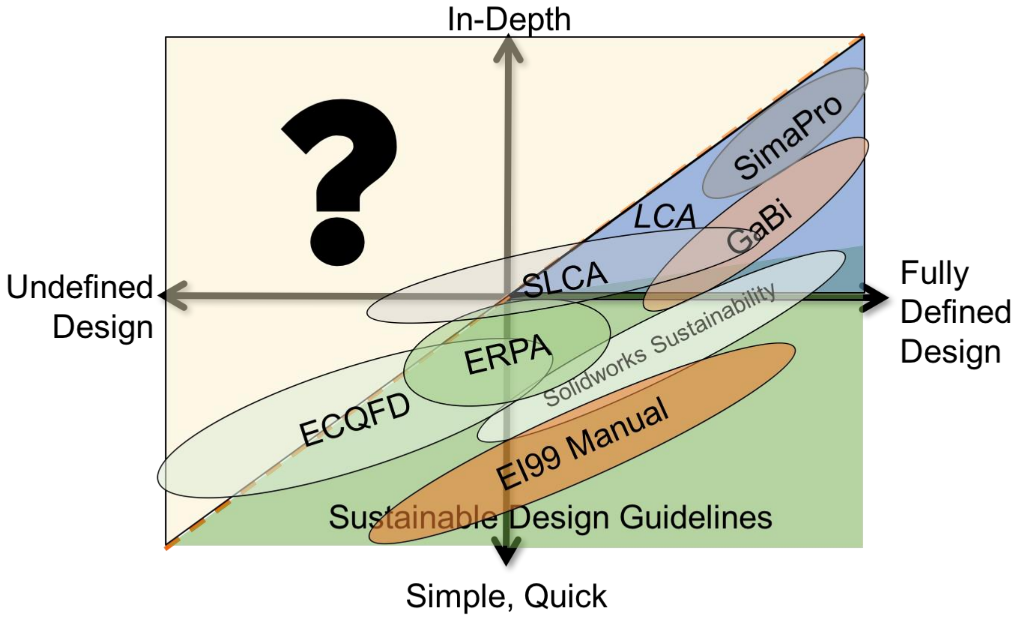


Figure 1: Visualization of a selection of Sustainable Design Tools (x-axis: Phase in the design process y-axis: Quality/type of analysis generated information)

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 [54] [55]. 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.

Previous research has begun to explore LCA estimation to bring LCA data into the early design phase. This is done by take product information available earlier on in the design process and sending it through an estimation algorithm to determine environmental impact of a product earlier in the design process. In LCA estimation methods, product attributes are correlated with known LCA data to estimate the impact of similar products. Estimations can be linked manually by grouping similar products together and making assumptions based on their LCA data. These assumptions can then be used to estimate how a particular product impacts the environment in a given life-cycle phase [56].

An effective method that can be used for performing LCA estimation is machine learning techniques. Machine learning can take product-specific data generated from currently available products and learn from their environmental impact. An informed machine learning algorithm can make estimations of a product's environmental impact during conceptual design. In this work, the machine learning technique employed is a traditional multi-layer perceptron network, commonly known as an artificial neural network [57]. In related research, artificial neural networks are applied to families of similar products, learning the correlation between product attributes and LCA data [55], [58], [59]. However, this previous research does not look at a wide variety of products, and the resulting method is only applicable to selection of product families. The current work seeks to understand this relationship to inform a design method that can be applied to the development of widely varying consumer products.

It is important to consider that LCA has associated uncertainty. LCA estimation methods, and any method that requires estimating any parameters necessary to complete the LCA (such as component weights, distance to transport products, etc.)

introduce uncertainty that can impact the accuracy of the analysis. While uncertainty in LCA is not explicitly treated in this work (but is reserved for more advanced, future research), it is the relative changes in LCA metrics across products and product attributes—not the absolutely metric values themselves—that are important to the conducted analysis.

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 effect it has on reducing the environmental impact of a product [5], [6], [60]. 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 [53].

This thesis intends to provide a new method that designers can use to reduce the environmental impact of a consumer product in and around the conceptual design phase. To accomplish 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 sections include the methodology for development of the decision engine, sustainable design repository, and the artificial neural network used in the life-cycle estimation. The results section includes two case studies used to test the validity of the decision engine and data from a preliminary investigation into life-cycle estimation. Following the results section, the thesis concludes with a discussion and concluding remarks.

2. Methodology

2.1 Decision Engine

2.1.1 Design Knowledge Acquisition

As mentioned in section 1.1, the collection of sustainable design knowledge employed in this research consists of information in current literature. The objective of the design knowledge literature search is to find, sort, and formulate this knowledge into a form that can be used by designers. The design knowledge found relates to six different categories: (A) Sustainable Design Guidelines, including Design for End-of-Life and Use Phase impacts, (B) Design Heuristics, including Design for the Environment and Design for Manufacturing, (C) International Design Standards, (D) Customer Preference for Sustainable Products, (E) Product Cost, and (F) Existing Sustainable Design Methods. Some examples from this set of sustainable design knowledge include "products should have similar or better performance to competing products" [26] and "the product should allow for informative wear to be detected" [6].

2.1.2 Question Formulation

Upon collecting sustainable design knowledge, the information needs to be formatted into a medium that can be used by designers. To accomplish this, design knowledge is written into the form of questions. The core meaning of the sustainable design knowledge was identified and then used to formulate a question by asking a potential user if their design incorporates the given knowledge in the question. These questions are matched with potential user responses in the form of a Likert scale; meaning that each question has responses associated with it that is intended to gauge a user's agreement to a particular question [61]. User responses are prepopulated to facilitate quantifying the results of the process; additionally, users are not reliant on previous understanding or mastery of sustainable product design in order to provide an informed response. This question/answer-generation process is performed on the complete set of obtained design knowledge, resulting in 60 questions and between two and five responses for each. Responses are generated from the formulated question, with the quantity of the responses dependent on the given question. Some questions, such as the example shown in Table 1, have five possible responses, but others, such as the example in Table 2, have only two possible responses.

Table 1: Example Question with Five Likert-Style Responses

Question	Will recyclable materials be used in the design?
Response 1	Recyclable materials will not be used
Response 2	Very few recyclable materials will be used
Response 3	Some recyclable materials will be used
Response 4	Recyclable materials will be used to make most of the product
Response 5	Recyclable material will be used to make the entire product

Table 2: Example Question with Two Likert-Style Responses

Question	Will product consumables be reusable?
Response 1	Consumables are not reusable
Response 2	Consumables are reusable

2.1.3 Search Tree

The questions are arranged in a data tree structure [62], which will facilitate the application of sustainable design knowledge that is directly relevant to the product at hand. This filtering process is possible due to the nature of data trees. As one progresses through the tree, the path they choose determines the future questions they see. To further improve the filtering process, a series of filtering questions are employed that further remove irrelevant questions from the search space, 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 small branch of the tree is seen in Figure 2. The tree consists of preliminary filtering questions and foundational questions; the filtering questions determine which branches of the foundational questions will be included.

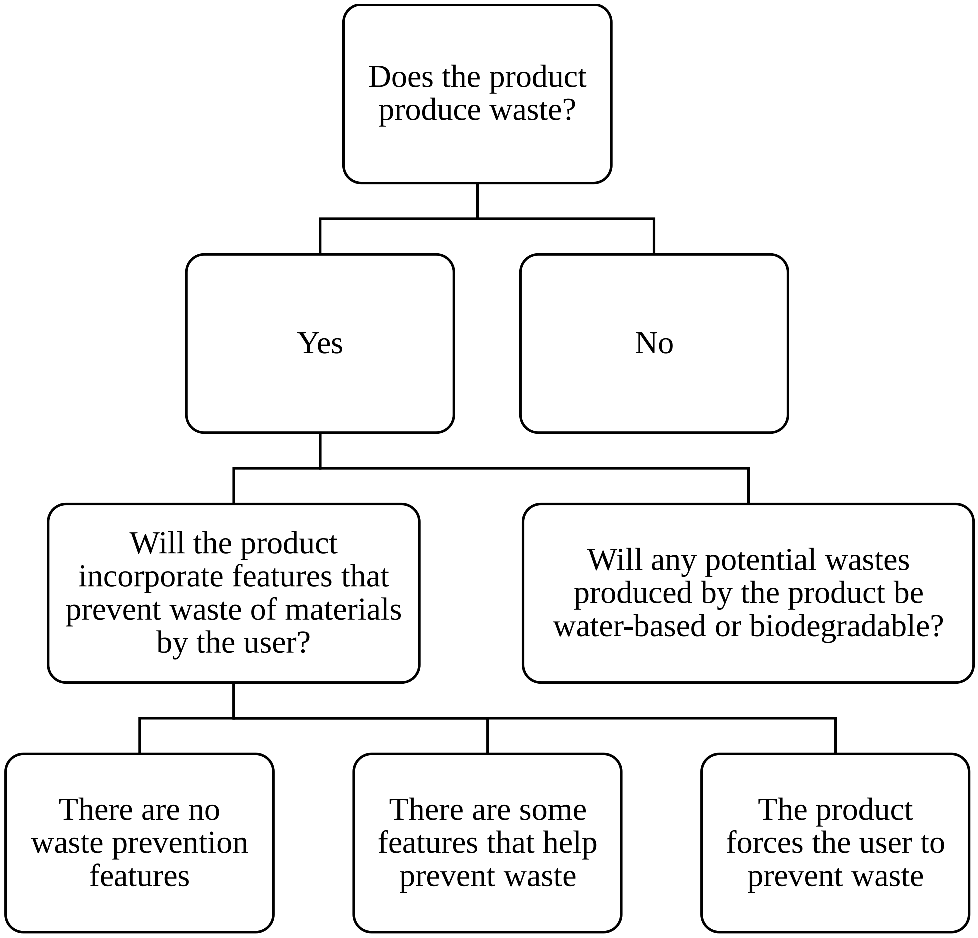


Figure 2: Example of one branch of the search tree

2.1.4 Web-based implementation

In order to make this 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 [63], 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 the user a series of pre-quiz filtering questions, 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 Figure 3.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 Figure 4. The process starts with questions that compare the current design that is being tested with other competing products. The next two consecutive groups deal with questions 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. A complete list of both filtering and sustainable design questions are presented in Table 10 in Appendix 3.

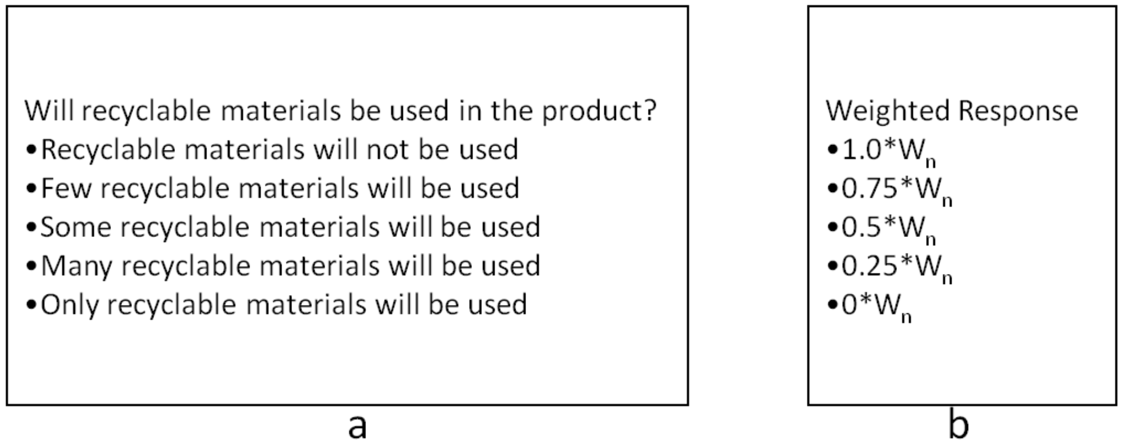


Figure 3: (a) An example question, and (b) Calculating a value for a chosen response

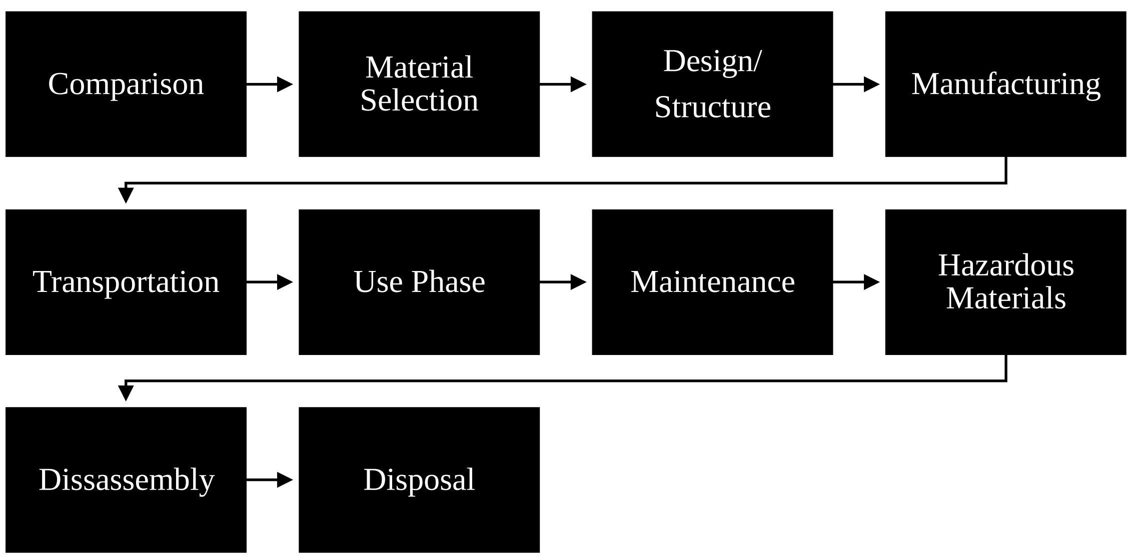


Figure 4: Flow of categories in the GREEn Quiz

2.1.5 Report Development

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 Figure 3.b, where each response in Figure 3.a has a value correlated to the strength or weakness of that response, multiplied by a weight for each question. Currently the weights for each question is uninformed and is set to a value of one; however, the first steps in informing these weights are discussed in section 2.3. 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. It is here where the acquired design decisions (described in section 1.2) are then presented to the designer. 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.

2.2 Sustainable Design Repository

As indicated in section 1.3, this work intends explore how an artificial neural network can be used to learn from LCA metrics in order to better inform early-design-phase product design. To do this, a sufficient amount of product and LCA data must be collected, and as such, a preliminary repository of this data was created.

2.2.1 Product Selection

Thirty-seven consumer products were selected to constitute the initial sustainable design repository. The selected consumer products are intended to represent a wide variety of consumer products. They were chosen based on the complexity of the product (quantified by the number of parts), and the number of related questions in the GREEn Quiz. Figure 5 shows a scatter plot of all 37 products with respect to number of parts and related questions, with Table 3 listing the 37 selected products.

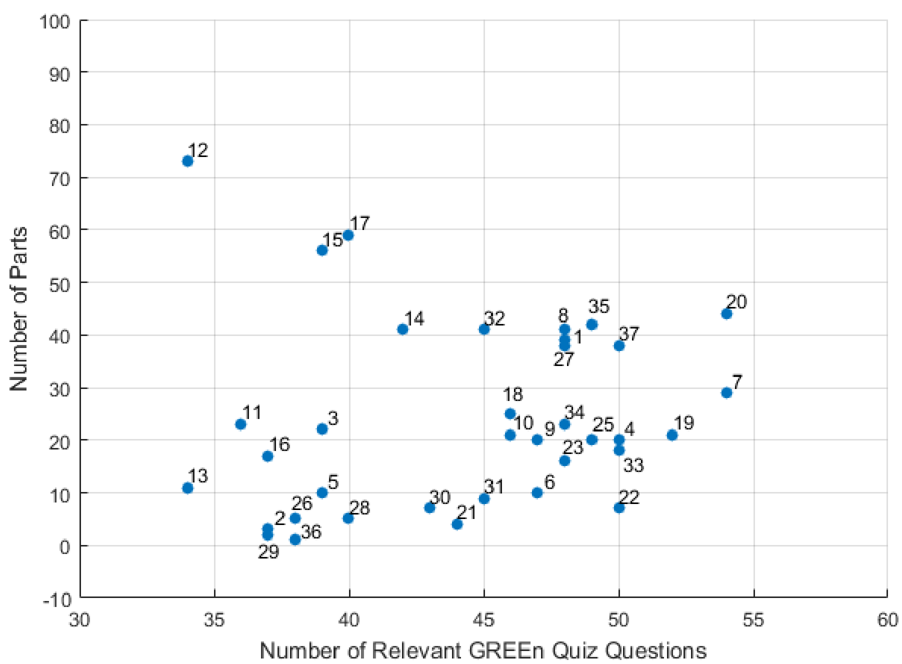


Figure 5: Scatter Plot of 37 Selected Consumer Products (Product 24 is located outside the axes at [53, 239])

Table 3: Sustainable Design Repository Product List

#	Product	#	Product
1	Vacuum	19	Hand Dryer
2	Plastic Water Bottle	20	Single Serve Coffee Maker
3	Office Chair	21	Oil Lamp
4	Coffer Maker	22	Disposable Battery Toothbrush
5	Stapler	23	Tattoo Gun
6	Lamp	24	3D Printer
7	Game Boy	25	Toaster
8	Electric Chainsaw	26	Scissors
9	Drill- Battery pack	27	Blender
10	Drill- Corded	28	Motorcycle Helmet
11	Kayak	29	Soda Can
12	Wooden Bookshelf	30	Mechanical Pencil
13	“Big Wheel” Toy	31	Electric Tea Kettle
14	Bicycle	32	Razor Scooter
15	Spring Drive	33	R/C Car
16	Apple Peeler Corer	34	Electric Shaver
17	Mechanical Calculator	35	Lawn Mower
18	Hand Gun	36	Cast Iron Skillet
-		37	Electric Guitar

2.2.2 Life Cycle Impact Assessment Methods

Three different LCIA methods were specifically selected for the development of the product metrics in this work, based on variation in method fidelity, applicability, and availability. The selected methods, Eco-Indicator 99, ReCiPe (embedded in GaBi software), and Solidworks Sustainability, are prominent methods that represent the breadth of current LCIAs. A description of each of these methods are given as follows:

2.2.2.1 Eco-Indicator 99

Of the three methods employed, Eco-Indicator 99 (EI99) provides the simplest way to observe product impact without the need for software. EI99 looks at the impact a product can have on the environment, which is comprised of three components: Ecosystem Quality, Human Health, and Resources [35]. EI99 provides milliPoint (mPt) indicator values for products based on their environmental impact; a higher indicator value correlates to a greater environmental impact. Three categories of environmental impact were created for the sustainable design repository: production/processes, use phase, and end-of-life. The indicator values for production/processes describe the impact of creating a product, the use-phase values describe the impact of using a product on a yearly basis, and the end-of-life values show the impact of disposing of a product, often times with assumption that the product will end up in a landfill [64].

As some indicator values for materials and processes are not available in the EI99 manual, these must be estimated or determined using another source, such as Matbase [65]. For materials where no information could be retrieved from the EI99 manual or Matbase, the mPt value was estimated based on similarities to other materials and processes.

2.2.2.2 GaBi (ReCiPe)

ReCiPe is the most in-depth LCA method used in this work. ReCiPe employs 21 impact indicators that are used to describe the environmental impact of each of the products. Of the 21 indicators, three of them are end-point indicators and 18 are mid-point indicators [36].

As described in section 1.3, mid-point indicators are measures of impact (such as CO_2) of each product, while end-point indicators are calculated from the 18 mid-point indicators to convey higher level impacts. In order to implement the ReCiPe method, software called GaBi is used [66]. GaBi provides a graphical platform that allows the user to input various product attributes, such as parts, weight, manufacturing processes, and disposal methods. Using these attributes, GaBi is able to apply the ReCiPe method and output the 21 related indicator values.

In GaBi, each product was entered using the information from the products in the preliminary sustainable design repository; this information includes material type, manufacturing methods, weight, number of parts, and disposal method. GaBi works by connecting the materials to their manufacturing methods, then finally to their disposal methods. From there, the user inputs secondary resources, defined by GaBi, for the manufacturing processes. For example, injection molding requires tap water and electricity to complete the molding process. GaBi includes an extensive database that provides the appropriate inputs and outputs specific to each manufacturing process. However, reasonable assumptions were made if GaBi did not have the identical material or process information for a product. In addition to providing material and process data, GaBi has ample information on a variety of resources. These resources, such as electricity, allow the user to identify where production is taking place, and what emissions are tied to that resource. After the user connects all the processes and secondary resources, weights for each material can be defined for each process. When all of the weights for each manufacturing process are defined, GaBi can implement the ReCiPe LCA method to determine the environmental impact.

GaBi displays 13 of the 18 ReCiPe mid-point indicators. The GaBi software combines some of the mid-point metrics into a single indicator. The 13 mid-point indicators displayed by GaBi are shown in Table 4.

GaBi also displays the three end-point ReCiPe indicators. These indicators are not combined and are normalized from all 18 of the ReCiPe mid-point indicators; not just the 13 displayed by GaBi. These end-point indicators are Damage to Human Health (Disability Adjusted Life Year), Damage to Ecosystem Diversity (Species/yr.), and Damage to Resource Availability ($). For purposes of this research, global land occupation potential will not be included, because upon completing the LCA for each of the 37 products the value obtained for global land occupation potential was negligible.

Table 4: ReCiPe Mid -Point Indicators

#	Indicator	Units
1	Global Warming Potential	CO_2
2	Ozone Depletion Potential	CFC-11
3	Terrestrial Acidification Potential	SO_2
4	Freshwater Eutrophication Potential	P
5	Marine Eutrophication Potential	N
6	Global Eco-toxicity Potential[1]	14-DBC

Continued

#	Metric	Units
7	Photochemical Oxidant Formation Potential	NMVOC
8	Particulate Matter Formation Potential	PM_{10}
9	Ionizing Radiation Potential	U^{235}
10	Global Land Occupation Potential[2]	m^2
11	Mineral Depletion	kg of Fe
12	Water Depletion	m^3
13	Fossil Depletion	kg of Oil

1. Four combined indicators. 2. Three combined indicators

2.2.2.3 Solidworks Sustainability

The Solidworks Sustainability is a CAD-based LCA method. Solidworks Sustainability uses a modified CML LCA method to analysis the environmental impact of a product based on the mass of a product calculated from volumetric data, material types, and available manufacturing processes [38], [47]. This method provides an output of four indicators: Carbon Footprint (CO_2), Energy Consumption (MJ), Air Acidification (SO_2), and Water Eutrophication (PO_4). The Solidworks Sustainability method is more of a comparative LCA method than a standalone LCA method; it allows the user to compare the relative change in the four indicators based on changes to material, manufacturing methods, and manufacturing locations.

In order to implement this method, product models were generated using the Solidworks CAD program. These Solidworks models provided the part weights that were used in the previous LCA methods. Each of the part models were assigned a material, life expectancy, manufacturing method, and manufacturing location. The parts of the models were assembled into the full product, use phases were added, and Solidworks Sustainability software generated the four indicators.

2.3 Artificial Neural Network

2.3.1 Development

The artificial neural network used in this work follows the common structure of a three-layer perceptron network, which uses a back-propagated supervised learning method. A three layer perceptron network consists of an input layer, a hidden layer, and an output layer with each node being connected to the neighboring layer by means of a weight, as seen in Figure 6. The motivation for using a neural net is that machine-learning methods, such as this one, are capable of correlating a set of inputs to a set of outputs, which are not a linear function of each other. This feature allows the neural net to estimate unknown non-linear functions. In the case of this work, product attributes are being mapped to LCA metrics.

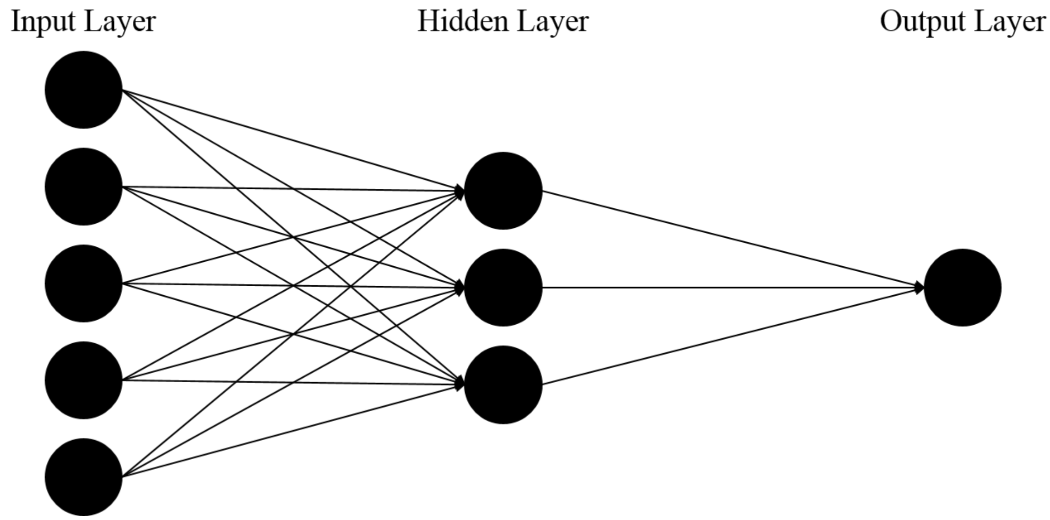


Figure 6: Three-Layer Perceptron Network

Before a neural network is of use, it must go through a training process. Since this work uses supervised learning, the training process starts by initializing all the weights in the network using generated random weights. To assist in the performance of the neural net, the weight is randomly assigned a value in the range of $-\frac{1}{\sqrt{n}}$ to $\frac{1}{\sqrt{n}}$, where n is the number of input nodes in the network [57]. With the weights initialized, the network is ready to begin the first portion of training. This consists of forward propagation through the network. Forward propagation is accomplished by calculating the values of the hidden layer nodes and the output layer nodes. To calculate the value of the hidden layer nodes, the value of the input nodes are multiplied by the weights that are associated to the hidden layer node that is being calculated. This is shown in Eq. 1.

$$H_{\varsigma} = \sum_{i=1}^{N} I_i x_{i\varsigma} \quad (1)$$

where H_ς is a given hidden layer node, N is the total number of nodes in the input layer, I_i is the value at the input layer node i, and $x_{i\varsigma}$ is the weight that links a given input node I_i to the hidden layer node being calculated. The number of hidden layer nodes used is generated from the general rule of thumb of the number of hidden layer nodes is roughly equal to two thirds times the number of input nodes. Upon calculating all of the hidden layer nodes, the activations of each hidden layer node need to be determined. An activation function is used in neural networks to control whether a given node is active, by making its value either zero or one. There are a variety of activation functions that can produce those values given a range of inputs. The activation function selected for this work is the sigmoid function, which is seen in Eq. 2 and Figure 7.

$$a_\varsigma = \frac{1}{1+e^{-\beta H_\varsigma}} \quad (2)$$

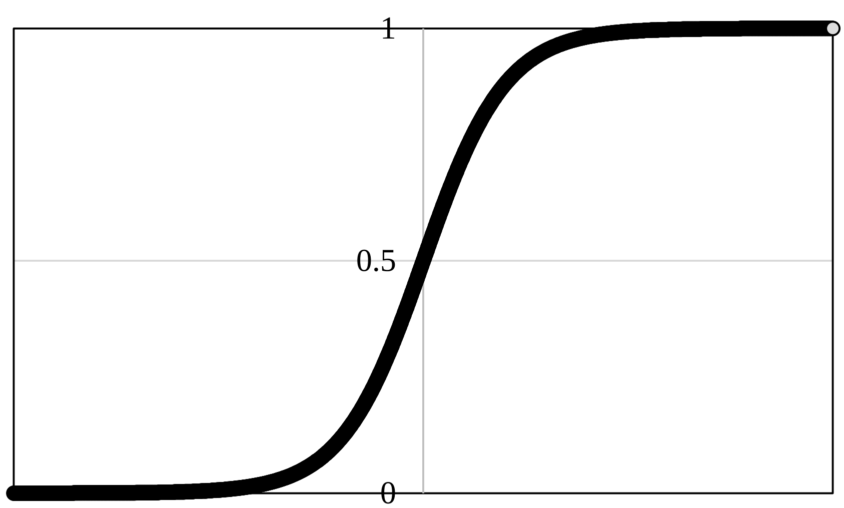


Figure 7: Sigmoid Function

The activation function specific to the hidden layer is represented by a_ς, with β being a tunable parameter, and H_ς a given hidden layer node.

Now the output layer nodes can be calculated. To accomplish this, a similar equation to Eq. 1 is used (Eq. 3). In this case, the values obtained from the activation function in the hidden layer nodes are used to calculate the output layer.

$$O_\kappa = \sum_{j=1}^{N} a_j y_{j\kappa} \tag{3}$$

This results in the output estimation of O_κ being equal to the sum of the product of the activation values, a_ς, of the hidden layer, and the weights $y_{\varsigma\kappa}$, that link a given hidden layer node j to the output node κ. Similar to the hidden layer, the output layer activation values also need to be found, as seen in Eq. 4.

$$b_\kappa = \frac{1}{1+e^{-\beta O_\kappa}} \tag{4}$$

At this point, the output nodes have their first estimated values, but as they are being partially calculated with random weights, these are poor estimations. This is where the second portion of training begins. Now it is necessary to adjust the weights to improve the calculated output estimates that were just found. In general, the most common training method for supervised back propagation is gradient descent [57]. To apply gradient descent to this algorithm, an objective function needs to be selected. The commonly used sum-of-squares method is selected for use and is shown in Eq. 5 [57]:

$$E = \frac{1}{2}\sum_{k=1}^{N}(O_k - t_k)^2 \tag{5}$$

where the error is calculated as half of the difference between the estimated output value and the known output value squared, and then summed for each output layer node k, with O_k being the estimated output and t_k being the normalized known true value.

Now that the objective function and optimization method is selected, it is now possible to adjust the weights in the network. This is achieved by calculating the negative gradient of the error function with respect to the weights. The negative gradient is calculated by taking the partial derivative of the error with respect to the estimated output, as seen in Eq. 6.

$$\frac{\partial E}{\partial y_{\varsigma\kappa}} = \frac{\partial E}{\partial O_\kappa}\frac{\partial O_\kappa}{\partial y_{\varsigma\kappa}} \tag{6}$$

Eq. 6 can be more easily evaluated by calculating $\frac{\partial E}{\partial O_\kappa}$ and $\frac{\partial O_\kappa}{\partial y_{\varsigma\kappa}}$ individually. Eq. 7 through Eq. 15 shows the progression for calculating the gradient with respect to the $y_{\varsigma\kappa}$ weights.

$$\frac{\partial O_\kappa}{\partial y_{\varsigma\kappa}} = \frac{\partial\left(\sum_{j=1}^{N} a_j y_{j\kappa}\right)}{\partial y_{\varsigma\kappa}} \tag{7}$$

Eq. 7 can be simplified to Eq. 8, due to the partial derivative always equals zeros except for when $j = \varsigma$.

$$\frac{\partial O_\kappa}{\partial y_{\varsigma\kappa}} = a_\varsigma \tag{8}$$

The partial derivative of $\frac{\partial E}{\partial O_\kappa}$, from Eq. 6, can be solved by performing the product rule.

$$\frac{\partial E}{\partial O_\kappa} = \frac{\partial E}{\partial b_\kappa}\frac{\partial b_\kappa}{\partial O_\kappa} \tag{9}$$

Similar to before, $\frac{\partial E}{\partial b_\kappa}$ and $\frac{\partial b_\kappa}{\partial O_\kappa}$ can be derived individually.

$$\frac{\partial b_\kappa}{\partial O_\kappa} = \frac{\partial\left(\frac{1}{1+e^{-\beta O_\kappa}}\right)}{\partial O_\kappa} \tag{10}$$

Eq. 10 can be simplified to Eq. 11.

$$\frac{\partial b_\kappa}{\partial O_\kappa} = \beta b_\kappa(1 - b_\kappa) \tag{11}$$

The partial derivative $\frac{\partial E}{\partial b_\kappa}$ can be expanded and then simplified, as seen in Eq. 12 and Eq. 13.

$$\frac{\partial E}{\partial b_\kappa} = \frac{\partial\left(\frac{1}{2}\sum_{k=1}^{N}(O_k - t_k)^2\right)}{\partial b_\kappa} \tag{12}$$

$$\frac{\partial E}{\partial b_\kappa} = (O_k - t_k) \tag{13}$$

Now that both $\frac{\partial E}{\partial b_\kappa}$ and $\frac{\partial b_\kappa}{\partial O_\kappa}$ have been solved, $\frac{\partial E}{\partial O_\kappa}$ can be assigned a placeholder variable.

$$\delta_{Out} = \frac{\partial E}{\partial O_\kappa} = (O_k - t_k)\,\beta b_\kappa(1 - b_\kappa) \tag{14}$$

The formula for $\frac{\partial E}{\partial O_\kappa}$ will be written for now on as δ_{Out}. This results in Eq. 6 simplifying down to Eq. 15.

$$\frac{\partial E}{\partial y_{\varsigma\kappa}} = \delta_{Out} a_\varsigma \tag{15}$$

Up until this point, $\frac{\partial E}{\partial y_{\varsigma\kappa}}$ has been derived. So far, this only adjusts the weights between the hidden layer and output layer. To adjust the weights between the input layer and hidden layer, $\frac{\partial E}{\partial x_{\iota\varsigma}}$, a similar approach is necessary:

$$\frac{\partial E}{\partial x_{\iota\varsigma}} = \frac{\partial E}{\partial H_\varsigma}\frac{\partial H_\varsigma}{\partial x_{\iota\varsigma}} \tag{16}$$

Using the product rule, $\frac{\partial \mathrm{E}}{\partial \mathrm{H}_\varsigma}$ and $\frac{\partial \mathrm{H}_\varsigma}{\partial \mathrm{x}_{\iota\varsigma}}$ in Eq. 16 can be solved individually.

$$\frac{\partial H_\varsigma}{\partial x_{\iota\varsigma}} = \frac{\partial\left(\sum_{i=1}^{N} I_i x_{i\varsigma}\right)}{\partial x_{\iota\varsigma}} \tag{17}$$

Eq. 17 simplifies to Eq. 18, due to the partial derivative always equaling zero except for when $i = \iota$.

$$\frac{\partial H_\varsigma}{\partial x_{\iota\varsigma}} = I_\iota \tag{18}$$

The partial $\frac{\partial E}{\partial H_\varsigma}$ can be derived by the use of another product rule.

$$\frac{\partial E}{\partial H_\varsigma} = \sum_{k=1}^{N}\frac{\partial E}{\partial O_\kappa}\frac{\partial O_\kappa}{\partial H_\varsigma} \tag{19}$$

As recalled from Eq. 14 $\frac{\partial E}{\partial O_\kappa}$ was substituted to be δ_{Out}.

$$\frac{\partial O_\kappa}{\partial H_\varsigma} = \frac{\partial\left(\sum_{j=1}^{N} a_j y_{j\kappa}\right)}{\partial H_\varsigma} \tag{20}$$

The partial of $\frac{\partial O_\kappa}{\partial H_\varsigma}$ simplifies down further, due to the partial derivative always equals zeros except for when $j = \varsigma$.

$$\frac{\partial O_\kappa}{\partial H_\varsigma} = \beta a_\varsigma(1 - a_\varsigma)\, y_{\varsigma\kappa} \tag{21}$$

The partial $\frac{\partial E}{\partial O_\kappa}$ has been derived in Eq. 14, resulting in the substitution shown in Eq. 22.

$$\frac{\partial E}{\partial H_\varsigma} = \delta_{Out}\beta a_\varsigma(1 - a_\varsigma)\, y_{\varsigma\kappa} \tag{22}$$

Taking Eq. 17 and Eq. 22 gives the value $\frac{\partial E}{\partial x_{\iota\varsigma}}$, to adjust the weights between the input layer and hidden layer,

$$\frac{\partial E}{\partial x_{\iota\varsigma}} = \delta_{Out}\beta a_\varsigma(1 - a_\varsigma)\, y_{\varsigma\kappa} I_\iota \tag{23}$$

With Eq. 15 and Eq. 23 the weights of the neural network can be calculated, by evaluating Eq. 24 and Eq. 25, where η is a tunable scaling training parameter.

$$y_{\varsigma\kappa} = y_{\varsigma\kappa} - \eta\delta_{Out} a_\varsigma \tag{24}$$

$$x_{\iota\varsigma} = x_{\iota\varsigma} - \eta\delta_{Out} a_\varsigma(1 - a_\varsigma)\, y_{\varsigma\kappa} I_\iota \tag{25}$$

Up until this point, inputs are fed forward through the neural net, where output estimations are calculated. From there, back propagation and gradient descent is used to adjust the weights in the neural net to improve the overall estimation of the neural network. All of these steps constitute a single iteration of training. In order to properly train a neural net using supervised learning, the training must occur in an iterative process. The neural net trains off of a set of data that has known inputs that correlate to a set of known outputs. This process should be repeated for a predefined number of iterations before the network is validated using a separate set of data. During this training process, the sum-of-squares error formula from Eq. 5 should be used to keep track of the error in the network. By keeping track of the error in the system, the tracked difference in error can be used as a stopping criterion. This is possible because as the neural net trains, the error in the system should continually decease; however, the network will reach a point where it starts to learn to the noise in the training data, rather than the general function the data follows, as seen in Figure 8. It is at this point where the validation data begins to have its error value increase; once this occurs, the neural net can be halted.

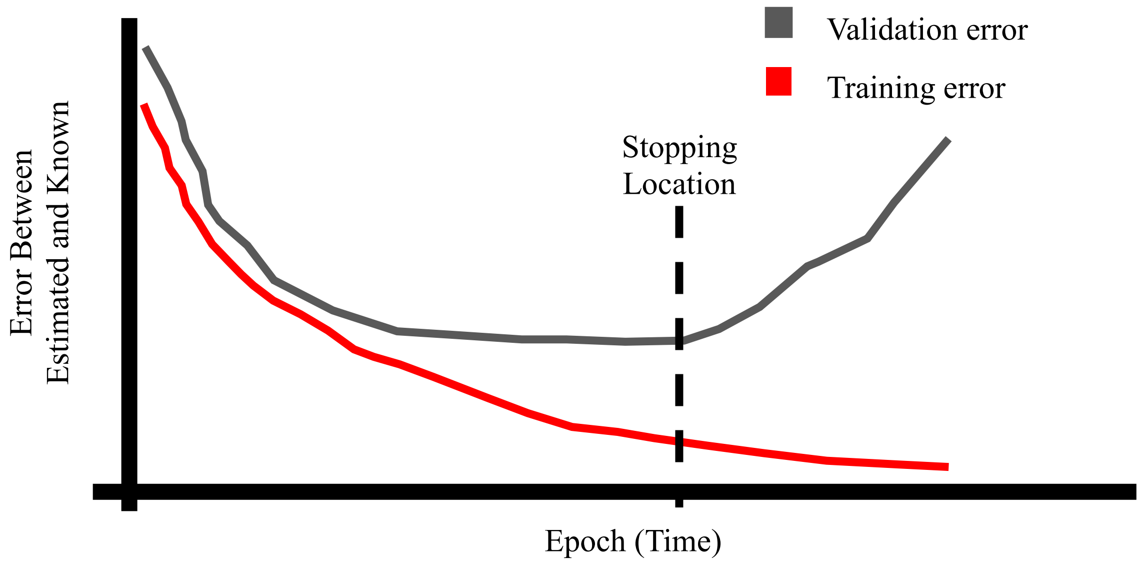


Figure 8: Generalized Neural Network Training and Validation Error Over Time

2.3.2 Development of Product Attributes

In order to use the neural net algorithm as described, a set of inputs needs to be identified. As the first step in the overarching work to relate design decisions to life-cycle impacts, product attributes are mapped to LCA metrics. To accomplish this, a list of 20 quantifiable product attributes relevant to each product in the product repository is used as the input data for the neural net, as seen in Table 5. Product attributes are generated through the systematic application of the GREEn Quiz to each of the 37 products, thereby determining product attributes that were relevant for to the user response to each question.

After generating the product attribute values for each product in the repository, products were then partitioned into similar attribute bins. This resulted in 60 partitioned groups, with a given product having attributes in multiple groups. These bins consisted of products being grouped on a Likert-style scale; generally, one to three groups were made for each of the product attributes. For example, three product groups were generated from the product attribute “Size”: Size_small, Size_medium, and Size_large. Also included in the list of 60 product attribute groups are three new attributes that are logical indicators of whether the product requires electricity, combustion, or human/no energy to operate. Products are partitioned to assist in the performance of the neural network. This allows the network to learn from a set of data, of what is assumed to be products with similar impacts.

Table 5: Product Attributes

Product Attribute	Description
Size	Volume of bounding box (cm^3)
Mass	kg
Number of Parts	Quantity
Number of Types of Material	Quantity
Amount of Energy Required for a Single Operation	Watts/Operation
Lifetime	Years
Number of Consumables per Year	Quantity/Year
Number of Batteries Lifetime	Quantity
Percent Ferrous Metal	Percent total mass
Percent Non-Ferrous Metal	Percent total mass
Percent Plastic	Percent total mass
Percent Glass	Percent total mass
Percent Organic Material	Percent total mass
Percent Hazardous Material	Percent total mass
Percent Electrical Components	Percent total mass
Percent Other Material	Percent total mass
Number of Subassemblies	Quantity
Number of Stock Parts	Quantity
Number of Manufacturing Processes	Quantity
Number of Fasteners	Percent total mass

2.3.3 Applying Product Attributes to the Neural Network

The neural net algorithm discussed in subsection 2.3.1 presents a general methodology of a three-layer perceptron network that uses supervised learning. To relate product attributes to LCA metrics, the neural network structure must take on a slightly altered form. The inputs to the neural network are the normalized values of the 20 product attributes shown in Table 5. Preliminary data found that the performance (the resulting error of the estimated output) of the neural network was greatly improved when estimating one LCA metric at a time, which is why a single metric is used in training and estimating. As commonly practiced, the output layer is normalized to increase performance in the machine learning process. In order to successfully link product attributes to life cycle data, all 60 partitioned product groups are used to estimate a single LCA metric. This is then repeated for the remainder of the 22 LCA metrics.

To further improve the performance of the neural net, a dynamic scaling feature, η, was added to the algorithm to replace a static parameter. The dynamic scaling feature operates by allowing the neural net to have multiple attempts at reducing the error of the network for a given scaling value η. When the maximum number of attempts limit is reached, then η will be scaled by a predetermined value, with the attempts counter then being reset. The new η value then has a similar number of chances to successfully reduce the error of the network. This continues to repeat until either the error is successfully decreased or a number of error reductions are met. If the code is successful in reducing the error, η is reset to its initial value and the attempt counters are reset. If the error does not decrease by the time the maximum number of attempts is made and the number of η reductions reaches a predetermined value, then the algorithm has reached its stopping criterion.

2.3.4 Training the Neural Network

The neural network was trained to the products in the 60 attribute groups along with a network trained to each of the LCA metrics. Due to a limited number of data points, a series of average values for each group was generated to create a validation case. The validation data is generated by taking the average of each input data (product attributes) and output (LCA metric), to create a synthetic product's data set that falls within the intended product attribute group. The resultant data set is used as a stopping mechanism as described at the end of section 2.3.1.

2.3.4.1 Problem Formulation

The tunable parameters used in the training of the neural network are listed in

Table 6.

Table 6: Neural Network Parameters

Parameter	Value
Number of Hidden Layer Nodes	10
Number of Training Iterations	20
β	1
η	0.01

Maximum Number of Tries	500
Number of η reduction	6
η Multiplier	0.1

3. Results

3.1 Case studies

3.1.1 Undergraduate case study

To test the validity of the GREEn Quiz, two separate studies were conducted (Oregon State University Institutional Review Board Study IDs: 6635 and 6816). The first study conducted in an undergraduate class focused on how inexperienced designers in sustainable design would perform while using various sustainable design resources to re-design a product. The class of 96 students were divided into three different groups. These groups differed by the design resource they received. The first group was designated as the control group and did not receive any extra resourced, the second group received a print-out of sustainable design guidelines found in academic literature [6], and the third group received access to the GREEn Quiz. All three groups were then given the following prompt, as seen in Figure 9: “For this activity, please explain how you will redesign a toaster into a more environmentally friendly product. Please write down and/or sketch every design decision that comes to mind.”

Figure 9: Undergraduate Study Activity Prompt

Figure 10 and Figure 11 display the average number of design decisions that are shown with respect to the three different groups (control, sustainable design guidelines, and GREEn Quiz), with Figure 10 showing all design decisions, and Figure 11 showing all stated sustainable design decisions. These design decisions were determined empirically, and are considered to be unique when features are either specifically called out or drawn. Examples of such features include a solar panel embedded in a toaster, as seen in Figure 12, 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.

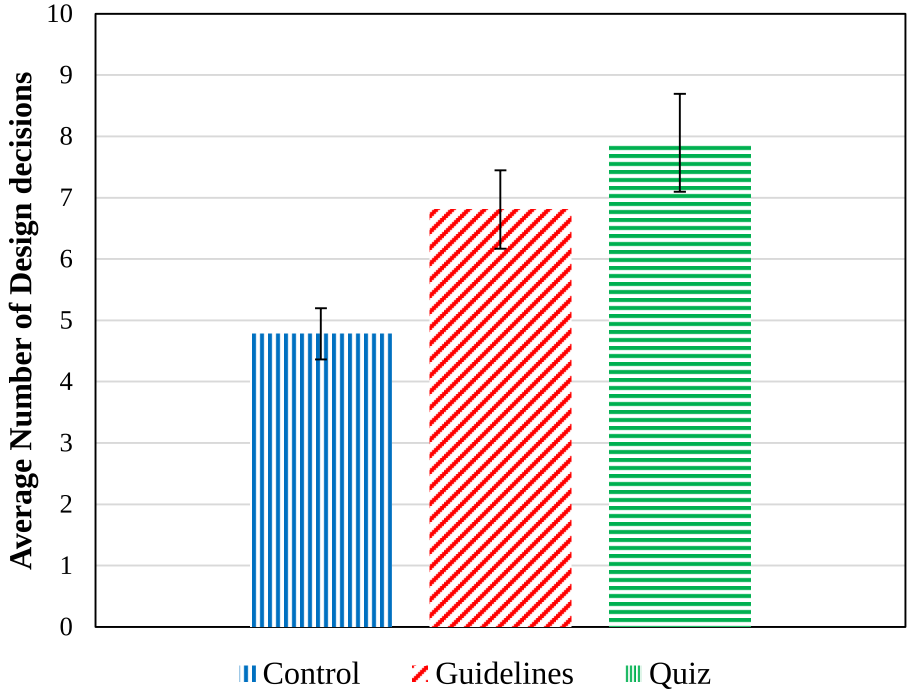


Figure 10: Average Number of Design Decisions

Further results collected from the undergraduate study are shown in Figure 13 and Figure 14. Figure 13 shows the number of average sketches for each group. In Figure 14, the average number of concepts generated per person for each group is shown. Sketches were counted whenever a complete product concept was shown. For example, when a student drew two perspectives of the same concept, as seen in Figure 15, the tally of two sketches were given to that student. For some cases, multiple features were acknowledged, but were not presented in a form where they all existed in the product simultaneously, as seen in Figure 16. For this case a concept was counted for each unique feature that wasn't coexisting with another. Features that were indicated to be part of the same concept were only counted once, as seen in Figure 17.

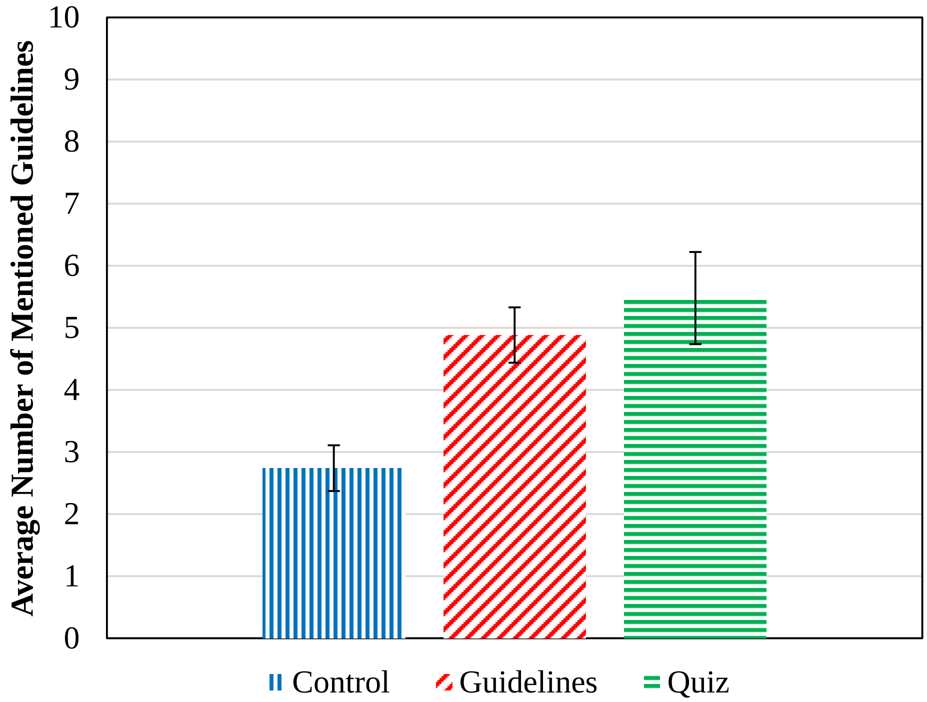


Figure 11: Average Number of Stated Sustainable Design Decisions

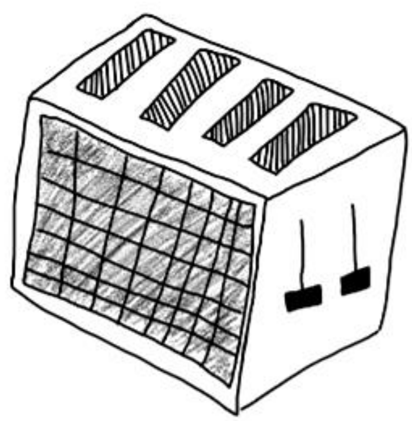


Figure 12: Example sketch of a Sustainable Design Decision: solar-powered toaster

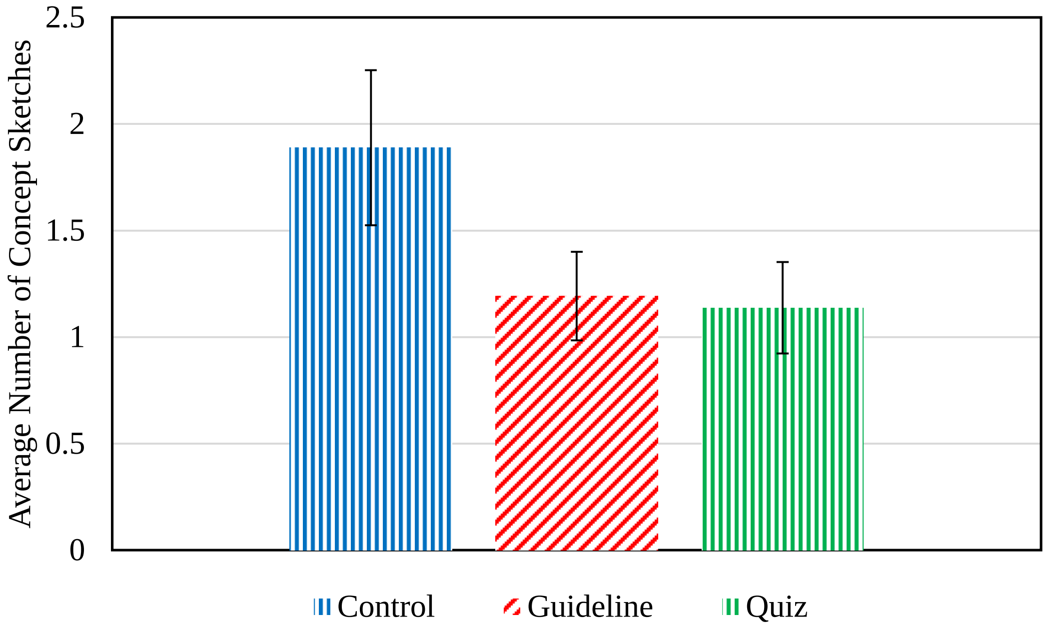


Figure 13: Average Number of Concept Sketches

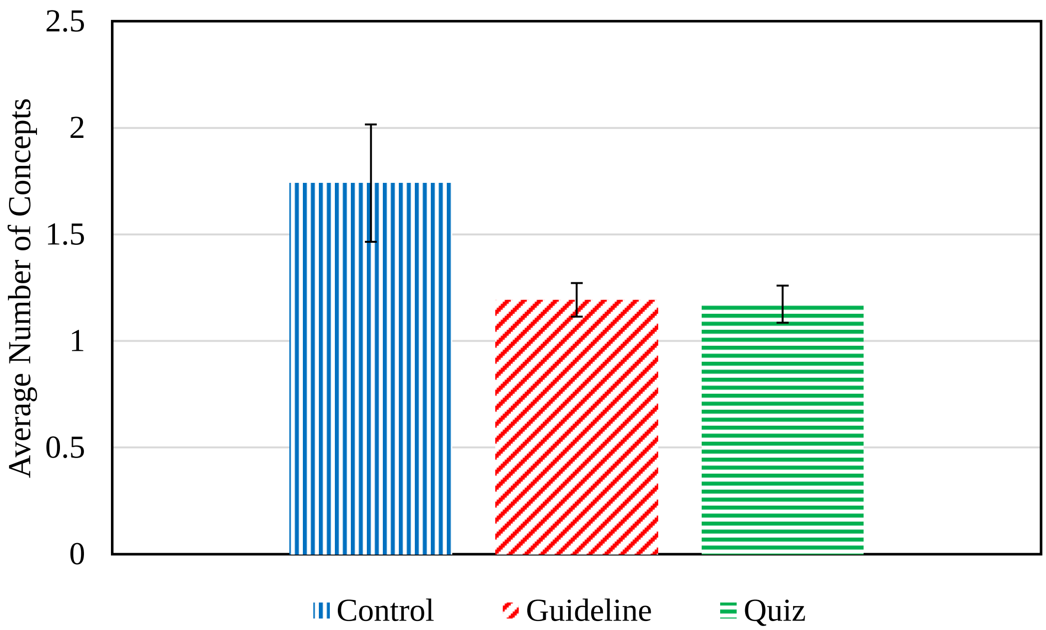


Figure 14: Average Number of Concepts

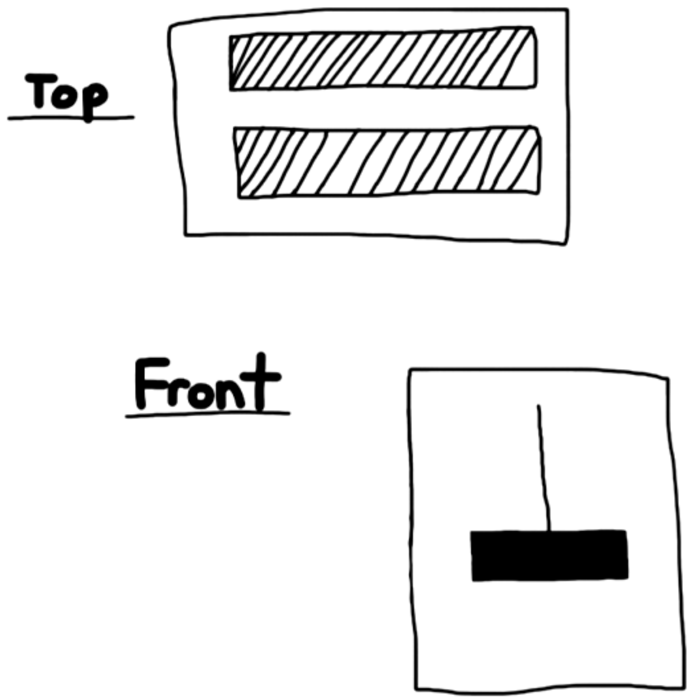


Figure 15: Example of two Sketches of one Concept

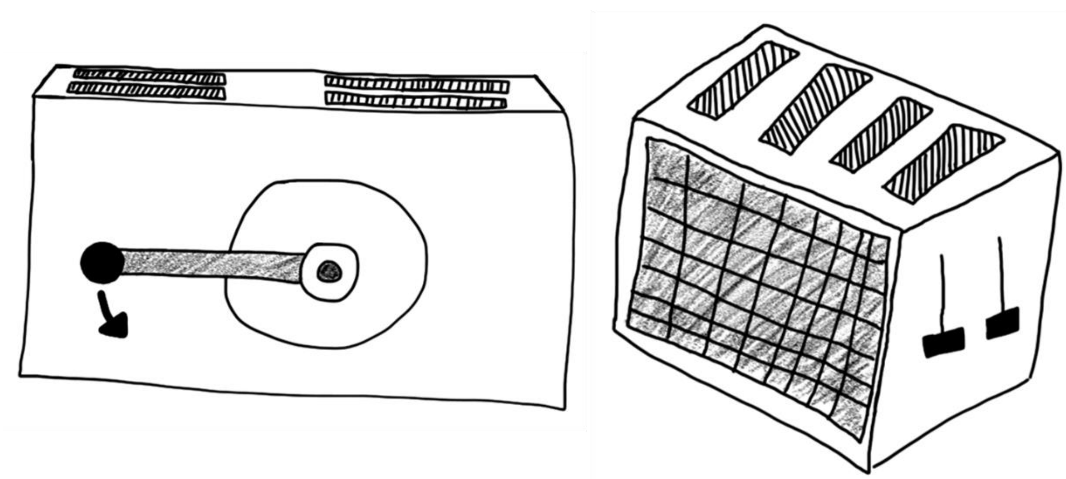


Figure 16: Two sketches of two Unique Designs. Left: Hand Crank Powered Toaster. Right: Solar Powered Toaster

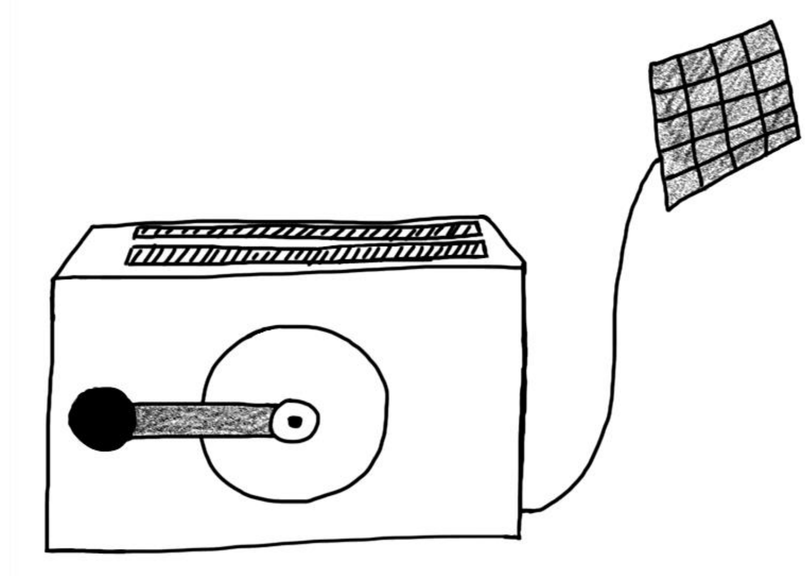


Figure 17: One Concept Sketch of two Features. Sketch of a Human and Solar Powered Toaster

3.1.2 Graduate case study

The second study, conducted in a 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 Figure 18. For both before (blue diagonal) and after (orange horizontal) employing the GREEn quiz, Figure 18 indicates the number of students who referred to a question category within the GREEn Quiz. It is important to note that a given person is only counted once per section even though they may have referenced multiple quiz questions that relate to a single category.

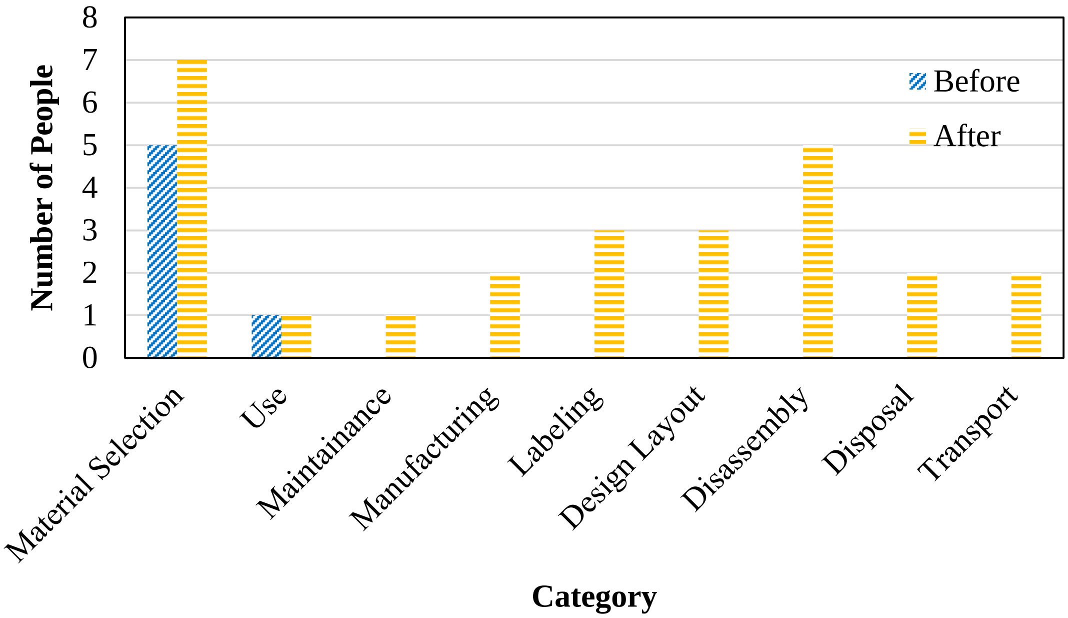


Figure 18: Referenced Sustainable Decisions: Before and After the GREEn Quiz

3.2 Artificial Neural Network

To assist in making a connection between design decisions and life cycle impacts, an intermediate step of linking product attributes to LCA data was performed. The neural net was trained on the set of product attributes detailed in Table 5 and was used to estimate the value of a single LCA metric. Using input data from organized product attribute bins, allowed for 60 groups of products to 22 LCA metrics individually; the full list is available in Appendix 1. The resulting analysis generated a table of percent error for the effectiveness of the neural net. The error was calculated by taking the known output data and comparing it to the estimated value obtained from the neural net. A sample of the results are seen in Table 7 and the entire table of results are in Table 9 of Appendix 2.

Table 7: Selection of Estimated LCA Metric Percent Error Data

Product Attribute Group	ReCiPe: CO2	EI99: Use	SolidWorks: Energy Consumption
Size_Large	1.12E-04	6.83E-06	9.26E-03
Mass_Medium	1.18E-06	1.80E-02	1.81E-02
Number of Parts_Few	5.28E-02	5.93E-02	1.19E-01
Number of types of material_Some	1.51E-05	2.03E-02	2.75E-05
Electrial Energy_Yes	2.93E-07	4.04E-05	5.80E-05
Combustion_No	1.03E-04	3.87E-02	1.00E-06
Energy per use_Some	3.03E-06	1.19E-03	2.54E-02
Lifetime_Medium	9.71E-07	5.39E-06	1.73E-05
Number of Consumables_A lot	8.74E-07	3.85E-02	5.56E-02
Number of Batteries_None	1.33E-05	1.87E-01	5.24E-04
Percent Ferrous Metal_Majority	4.09E-03	1.23E-01	1.15E-01
Percent Non_Ferrous Metal_Some	2.01E-05	1.46E-07	8.15E-08
Percent Plastic_Majority	2.52E-06	6.92E-06	1.31E-06
Hazardous Material_Yes	2.87E-04	6.07E-02	1.12E-03
Electrical Components_Yes	9.60E-03	1.29E-03	8.12E-02

4. Discussion

4.1 Case Studies

Two studies were conducted to test the validity of the GREEn Quiz method. 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 Figure 10 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, who did not receive any additional material. Moreover, the GREEn Quiz group was able to generate the highest 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 Figure 11, the average number of sustainable design decisions for each group is shown. As expected, the trend in Figure 11 is similar as to what is seen in Figure 10, since the sustainable design decisions are a subset of the total number of design decisions referenced in Figure 10. 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.

Other results that were obtained through the undergraduate study include a possible negative correlation between creativity and the design resources applied in the study. As shown in Figure 13 and Figure 14**,** students in the two groups that used a design tool were generally more focused on completing a single toaster redesign. However, the results from the control group indicated that students were creating more sketches of their ideas than the students with a resource. In contrast, the groups that received a design resource tended to write out more information specific to their design, as compared to the control group. This difference in the way students were displaying their ideas could be seen as an indication that sustainable design resources (the list of guidelines and the GREEn Quiz) may indicate a hindrance in creative sketching, but further research is needed to make an informed statement on this matter.

The second study tasked graduate students to evaluate and redesign concepts that were generated for their team-based product design term project. This study allows for the measuring sustainable design improvements in a before-and-after setting. As seen in Figure 18, prior to using the GREEn quiz, the students mentioned only a few potential sustainable design decisions, and in 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-to-interpret format, they are capable of directly applying it in the development of design concepts with a reduced environmental impact.

4.2 Artificial Neural Network

A preliminary investigation into life cycle estimation is conducted to look at predicting life cycle impacts for a given set of product attributes. A three layer artificial neural network is used to train on the product data in the sustainable design repository. The percent error values calculated are low, with the majority of the error values below 1%. The low error values in this data can be attributed to the effectiveness of the product grouping. A low error value indicates that the validation data set was accurately estimated. This is because the error value is the percent difference in the actual LCA metric value versus the estimated LCA metric value the neural network calculated.

The process of creating a working neural network has revealed some interesting aspects of the repository LCA data. For example, during the process of developing the methodology of this work, it was found that neural network could only effectively handle one LCA metric at a time. Based on the results that were obtained, the use of an artificial neural network has shown that LCA estimations through machine learning can provide an effective method for linking product attributes to life-cycle impacts. With future progression of this work and the accumulation of more product data, the results obtained in this work shows a promising preliminary result for estimating products based on their product attributes.

5. Conclusion

This research sets to provide design decisions to designers developing new and redesigned consumer products, such that designers will reduce the environmental impact of products throughout the conceptual design phase. To achieve this goal, sustainable design knowledge was acquired and formatted in the form of a set of questions, and then structured as a search tree. This search tree is meant to provide designers design knowledge in an organized manner, where questions would appear only when relevant. An online web-based application called the GREEn Quiz was developed to be the physical embodiment of the theory. Design decisions were mapped to each question to aid in informing designers about how to improve their concept. To aid in linking quantitative values to design decisions, a preliminary investigation was conducted to map product attributes to vetted LCA metrics from three popular LCA methods by using an artificial neural network to train from a sustainable product design repository.

This work found that upon completion of two separate case studies, the physical embodiment of the theory was able to assist both the undergraduate and graduate students in the design tasks that were presented. It was shown that having a DfE resource, such as the GREEn Quiz when designing during concept generation, allowed the student participants to make informed decisions on how to better improve the sustainability of their product, by providing them with a method that supplies them with developed questions, feasible responses, and a corresponding report that indicates where design improvements can be made and how they can be implemented.

In addition to the findings of the GREEn Quiz, this work found that life cycle estimation by means of an artificial neural network is a feasible approach for eventually linking design decisions to their respective environmental impact. This was performed by training an artificial neural network on the environmental impact and attributes of 37 consumer products from a sustainable design repository.

Future related research should focus on two aspects of this thesis work. One focus should be to improve upon the user interface of the GREEn Quiz. This can lead to a better understanding as to how design resources affect the design process. Improved layouts and the addition of images relating to the presented design knowledge can assist in providing a better user experience, as well as providing a supplemental means of conveying sustainable design information. The second focus of future work is furthering the development of the sustainable product design repository. Furthering this would allow for the progression of linking design decisions to their subsequent environmental impacts. This is due to the amount of data required for using artificial neural network for life cycle estimation.

6. References

[1] U.S. Environmental Protection Agency, “Sustainable Materials Management: The Road Ahead,” 2009.

[2] U.S. Environmental Protection Agency, “Advancing Sustainable Materials Management : 2013 Fact Sheet,” 2015.

[3] PBS, “The Rise of American Consumerism,” 1995. [Online]. Available: http://www.pbs.org/wgbh/americanexperience/features/general-article/tupperware-consumer/. [Accessed: 01-Jul-2015].

[4] M. Gell-Mann, “Visions of a Sustainable World,” *Eng. Sci.*, pp. 5–10, 1992.

[5] K. Otto and K. Wood, *Product Design: Techniques in Reverse Engineering and New Product Development*. Prentice Hall, 2001.

[6] C. Telenko, C. C. Seepersad, and M. E. Webber, “A Compilation of Design for Environment Principles and Guidelines,” *ASME 2008 Int. Des. Eng. Tech. Conf.*, pp. 1–13, 2008.

[7] C. Telenko and C. C. Seepersad, “A Methodology for Identifying Environmentally Conscious Guidelines for Product Design,” *J. Mech. Des.*, vol. 132, no. 9, p. 091009, 2010.

[8] S. Rachuri, P. Sarkar, A. Narayanan, J. H. Lee, and P. Witherell, “Towards a Methodology for Analyzing Sustainability Standards using the Zachman Framework,” 2011.

[9] D. Russo, C. Rizzi, and G. Montelisciani, “Inventive guidelines for a TRIZ-based eco-design matrix,” *J. Clean. Prod.*, vol. 76, pp. 95–105, 2014.

[10] C. Telenko, C. C. Seepersad, and M. E. Webber, “A Method for Developing Design for Environment Guidelines for Future Product Design,” in *ASME International Design Engineering Technical Conference*, 2009, pp. 1–12.

[11] C. Telenko, “Developing Green Design Guidelines : A Formal Method and Case Study,” The University of Texas at Austin, 2009.

[12] L. Y. Ljungberg, “Materials selection and design for development of sustainable products,” *Mater. Des.*, vol. 28, no. 2, pp. 466–479, 2007.

[13] B. DuPont and A. Wisthoff, “Exploring the Retention of Sustainable Design Principles in Engineering Practice through Design Education,” *ASME Int. Des. Eng. Tech. Conf. Comput. Inf. Eng. Conf.*, vol. 8, pp. 1–4, 2015.

[14] V. Goepp, P. Zwolinski, and E. Caillaud, “Design process and data models to support the design of sustainable remanufactured products,” *Comput. Ind.*, vol. 65, no. 3, pp. 480–490, 2014.

[15] M. Paju, J. Heilala, M. Hentula, A. Heikkila, B. Johansson, S. Leong, and K. Lyons, “Framework and Indicators for as Sustainable Manufacturing Mapping Methodology,” in *Proceedings of the 2010 Winter Simulation Conference,* 2010, pp. 1–12.

[16] J. Srivastava and L. H. Shu, “Affordances and Product Design to Support Environmentally Conscious Behavior,” *J. Mech. Des.*, vol. 135, no. 10, p. 101006, 2013.

[17] C. Telenko and C. Seepersad, “Scoping Usage Contexts and Scenarios in Eco-Design,” *Asme 2014 Idetc Dfmlc*, pp. 1–10, 2014.

[18] F. Rubik, “Environmental sound product innovation and Integrated Product Policy ‘ IPP ˆ,” pp. 219–232, 2003.

[19] D. Eddy, S. Krishnamurty, I. Grosse, P. Witherell, J. Wileden, and K. Lewis, “An Integrated Approach to Information Modeling for the Sustainable Design of Products,” *J. Comput. Inf. Sci. Eng.*, vol. 14, no. 2, p. 021011, Apr. 2014.

[20] D. Eddy, S. Krishnamurty, I. Grosse, and J. Wileden, “DETC2014-34280 A Robust Surrogate Modeling Approach for Material Selection in Sustainable Design of Products,” pp. 1–18, 2014.

[21] A. E. D’Alessio, P. Witherell, and S. Rachuri, “Modeling Gaps and Overlaps of Sustainability Standards,” in *CIRP International Conference on Life Cycle Engineering*, 2012.

[22] F. Rasamoelina, C. Bouchard, and A. Aoussat, “Towards a Kansei-Based User Modeling Methodology for Eco-design,” *Int. J. Affect. Eng. - Spec. Issue KEER 2012*, vol. 12, no. 2, pp. 337–348, 2013.

[23] C. Withanage, R. Ashok, K. Holtta-Otto, and K. Otto, “DETC2014-34798 Identifying and Categorizing Opportunities for Design for Sustainable User,” in *ASME 2014 International Design Engineering Technical Conferences*, 2014, pp. 1–12.

[24] PCF Pilot Project Germany, “Product Carbon Footprinting – The Right Way to Promote Low Carbon Products and Consumption Habits?,” http://www.pcf-projekt.de/files/1241103260/lessons-learned_2009.pdf, 2009.

[25] J. She and E. F. Macdonald, “Trigger Features on Prototypes Increase Preference for Sustainability,” in *Proceedings of the ASME 2013 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, 2013, pp. 1–11.

[26] E. MacDonald and J. She, “Seven Cognitive Concepts for Successful Sustainable Design,” *ASME Int. Des. Eng. Tech. Conf. Comput. Inf. Eng. Conf.*, pp. 1–16, 2012.

[27] E. Macdonald, K. Whitefoot, A. Arbor, J. T. Allison, and R. Gonzalez, “An Investigation of Sustainability, Preference, and Profitability in Design Optimization,” in *ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2010, pp. 1–14.

[28] P. Murto, O. Person, and M. Ahola, “Shaping the face of environmentally sustainable products: Image boards and early consumer involvement in ship interior design,” *J. Clean. Prod.*, vol. 75, pp. 86–95, 2014.

[29] D. C. Eddy, S. Krishnamurty, I. R. Grosse, J. C. Wileden, and K. E. Lewis, "A normative decision analysis method for the sustainability-based design of products," *J. Eng. Des.*, vol. 24, no. 5, pp. 342–362, May 2013.

[30] T. E. Graedel and B. R. Allenby, *Industrial Ecology*. Englewood Cliffs, NJ, USA: Prentice Hall, 1995.

[31] A. Bala, M. Raugei, G. Benveniste, C. Gazulla, and P. Fullana-I-Palmer, "Simplified tools for global warming potential evaluation: When 'good enough' is best," *Int. J. Life Cycle Assess.*, vol. 15, no. 5, pp. 489–498, 2010.

[32] T. Hur, J. Lee, J. Ryu, and E. Kwon, "Simplified LCA and matrix methods in identifying the environmental aspects of a product system," *J. Environ. Manage.*, vol. 75, no. 3, pp. 229–237, 2005.

[33] D. C. A. Pigosso, S. R. Souza, A. R. Ometto, and H. Rozenfeld, "Life Cycle Assessment (LCA): discussion on full-scale and simplified assessments to support the product development process," *3rd Int. Work. - Adv. Clean. Prod.*, 2011.

[34] J. Valkama and M. Keskinen, "Comparison of simplified LCA variations for three LCA cases of electronic products from the ecodesign point of view," *IEEE Int. Symp. Electron. Environ.*, 2008.

[35] M. Goedkoop and R. Spriensma, "The Eco-indicator 99 - A damage oriented method for Life Cycle Impact Assessment," *Annex Rep. Eco-Indicator 99*, no. October, p. 144, 2001.

[36] M. Goedkoop, R. Heijungs, M. Huijbregts, A. De Schryver, J. Struijs, and R. Van Zelm, "ReCiPe 2008," 2009.

[37] D. Chang, C. K. M. Lee, and C.-H. Chen, "Review of Life Cycle Assessment towards Sustainable Product Development," *J. Clean. Prod.*, vol. 83, no. July 2015, pp. 48–60, 2014.

[38] Dassault Systems, "SolidWorks Sustainability." [Online]. Available: http://www.solidworks.com/sustainability/. [Accessed: 01-Jul-2015].

[39] S. Vinodh, V. Kamala, and K. Jayakrishna, "Integration of ECQFD, TRIZ, and AHP for innovative and sustainable product development," *Appl. Math. Model.*, vol. 38, no. 11–12, pp. 2758–2770, 2014.

[40] S. Vinodh and G. Rathod, "Integration of ECQFD and LCA for sustainable product design," *J. Clean. Prod.*, vol. 18, no. 8, pp. 833–842, 2010.

[41] A. Romli, P. Prickett, R. Setchi, and S. Soe, "Integrated eco-design decision-making for sustainable product development," *Int. J. Prod. Res.*, no. April 2015, pp. 37–41, 2014.

[42] A. Romli, P. Prickett, R. Setchi, and S. Shoe, "A Conceptual Model for Sustainable Product Design," *Key Eng. Mater.*, vol. 572, pp. 3–6, 2014.

[43] D. G. Ullman, *The Mechanical Design Process*, 4th ed. McGraw-Hill, 2010.

[44] Esko-Graphics bvba, "ArtiosCAD." 2016.

[45] D.-S. Siamak, “Wear Indicator for a Disposable Razor,” 5388331, 1995.

[46] Technical Committee ISO/TC 207, “ISO 14040:2006,” *ISO*, 2006. [Online]. Available: www.iso.org. [Accessed: 01-Jul-2015].

[47] Universiteit Leiden/CML, “LCA resources at CML-IE,” 2008. [Online]. Available: http://www.leidenuniv.nl/interfac/cml/ssp/projects/lca2/. [Accessed: 01-Jan-2016].

[48] J. A. Todd and M. A. Curran, “Streamlined Life-Cycle Assessment: A Final Report from the SETAC North America Streamlined LCA Workgroup,” 1999.

[49] T. E. Graedel, B. R. Allenby, and P. R. Comrie, “Matrix approaches to abridged life cycle assessment,” *Environ. Sci. Technol.*, vol. 29, no. 3, pp. 134–139, 1995.

[50] J. Bare, “Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI).” UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, 2012.

[51] J. C. Bare, P. Hofstetter, D. W. Pennington, and H. A. U. de Haes, “Midpoints versus endpoints: The sacrifices and benefits,” *Int. J. Life Cycle Assess.*, vol. 5, no. 6, pp. 319–326, Nov. 2000.

[52] C. Luttropp and J. Lagerstedt, “EcoDesign and The Ten Golden Rules: generic advice for merging environmental aspects into product development,” *J. Clean. Prod.*, vol. 14, no. 15–16, pp. 1396–1408, 2006.

[53] S. Byggeth, G. Broman, and K. H. Robèrt, “A method for sustainable product development based on a modular system of guiding questions,” *J. Clean. Prod.*, vol. 15, no. 1, pp. 1–11, 2007.

[54] I. Sousa and D. Wallace, “Product classification to support approximate life-cycle assessment of design concepts,” *Technol. Forecast. Soc. Change*, vol. 73, no. 3, pp. 228–249, 2006.

[55] J. Park and K.-K. Seo, “Approximate life cycle assessment of product concepts using multiple regression analysis and artificial neural networks,” *KSME Int. J.*, vol. 17, no. 12, pp. 1969–1976, 2003.

[56] D. Collado-Ruiz and H. Ostad-Ahmad-Ghorabi, “Estimating Environmental Behavior Without Performing a Life Cycle Assessment,” *J. Ind. Ecol.*, vol. 17, no. 1, pp. 31–42, 2013.

[57] S. Marsland, *Machine Learning: An Algorithmic Perspective*, Second. CRC Press, 2015.

[58] I. Sousa, J. L. Eisenhard, and D. Wallace, “Approximate Life-Cycle Assessment of Product Concepts Using Learning Systems,” *J. Ind. Ecol.*, vol. 4, no. 4, pp. 61–81, 2000.

[59] S. Golak, D. Burchart-Korol, K. Czaplicka-Kolarz, and T. Wieczorek, “Application of Neural Network for the Prediction of Eco-efficiency,” *Adv. Neural Networks – ISNN 2011*, vol. 6677, pp. 380–387, 2011.

[60] S. Poole, M. Simon, a Sweatman, T. a Bhamra, S. Evans, T. C. Mcaloone, C. Street, M. M. Sgd, and B. M. K. Oal, "Integrating Environmental Decisions into the Product Development Process : Part 2 The Later Stages," *Concurr. Eng.*, pp. 334–337, 1999.

[61] R. Likert, "A technique for the measurement of attitudes.," *Arch. Psychol.*, 1932.

[62] E. W. Weisstein, "Tree," *MathWorld*, 2016. [Online]. Available: http://mathworld.wolfram.com/Tree.html. [Accessed: 05-Oct-2016].

[63] Django Software Foundation, "Django," 2005. [Online]. Available: https://djangoproject.com. [Accessed: 14-Aug-2015].

[64] U.S. Environmental Protection Agency, "Advancing sustainable materials management: facts and figures 2013," United States Environmental Protection Agency, 2015.

[65] "Matbase." [Online]. Available: www.matbase.com. [Accessed: 01-Jan-2016].

[66] Thinkstep, "GaBi Software," 1999. [Online]. Available: http://www.gabi-software.com. [Accessed: 01-Jul-2015].

APPENDICES

Appendix 1

Table 8: Full Grouping List of Partitioned Products (Pg. 56-57)

Product Attribute Group	Range	Unit
Size_Large	>100000	cm^3
Size_Medium	10000 to 100000	cm^3
Size_Small	<10000	cm^3
Mass_Large	>10	kg
Mass_Medium	1-10	kg
Mass_Small	<1	kg
Number of Parts_A lot	>40	Number
Number of Parts_Medium	20 to 40	Number
Number of Parts_Few	<20	Number
Number of types of material_A lot	>7	Number
Number of types of material_some	4 to 7	Number
Number of types of material_Few	<4	Number
Electrial Energy_Yes	Yes	
Electrical Energy_No	No	
Combustion_Yes	Yes	
Combustion_No	No	
Human_None_Yes	Yes	
Human_None_No	No	
Energy per use_A lot	>100	Watts
Energy per use_Some	10 to 100	Watts
Energy per use_Few	<10	Watts
Lifetime_Long	>5	Years
Lifetime_Medium	1 to 5	Years
Lifetime_Short	<1	Years
Number Consumables_A lot	>100	Number
Number Consumables_Some	1 to 100	Number
Number Consumables_None	0	Number
Number Batteries_A lot	>1	Number
Number Batteries_Some	1	Number
Number Batteries_None	0	Number
Fer Metal_Majority	>60	Percent total Mass
Fer Metal_Some	30 to 60	Percent total Mass
Fer Metal_Minority	<30	Percent total Mass
Non-Fer Metal_A lot	>40	Percent total Mass
Non_Fer Metal_Some	10 to 40	Percent total Mass
Non_Fer Metal_Few	<10	Percent total Mass
Plastic_Majority	>60	Percent total Mass
Plastic_Some	30 to 60	Percent total Mass
Plastic_Minority	<30	Percent total Mass
Glass_None	0	Percent total Mass

Product Attribute Group	Range	Unit
Organic_A lot	>2	Percent total Mass
Organic_Some	<2	Percent total Mass
Organic_None	0	Percent total Mass
Hazardous_Yes	>0	Percent total Mass
Hazardous_None	0	Percent total Mass
Electrical Components_Yes	>0	Percent total Mass
Electrical Components_None	0	Percent total Mass
Other_None	0	Percent total Mass
Number Stock Parts_A lot	>20	Number
Number Stock Parts_Some	5 to 20	Number
Number Stock Parts_None-Few	<5	Number
Number Subassemblies_A lot	>4	Number
Number Subassemblies_Some	3 to 4	Number
Number Subassemblies_Few	<3	Number
Number MFG Proccesses_A lot	>20	Number
Number MFG Processes_Some	10 to 20	Number
Number MFG Processes_Few	<10	Number
Fasteners_A lot	>1	Percent total Mass
Fasteners_Some	<0 to 1	Percent total Mass
Fasteners_None	0	Percent total Mass

Appendix 2

Table 9: Estimation Error from Neural Network of all 60 Attribute Groups for Each Metric (Pg. 58-72)

Product Attribute	ReCiPe Metrics			
	Global Warming Potential	Ozone Depletion Potential	Terrestrial Acidification Potential	Freshwater Eutrophication Potential
Size_Large	1.12E-02	2.07E-02	7.55E-01	2.20E-06
Size_Medium	7.20E-01	3.02E+00	6.53E+00	1.08E-02
Size_Small	3.12E-02	7.78E+00	2.22E-04	1.48E-02
Mass_Large	7.30E+00	4.46E+00	8.83E-01	-1.48E-06
Mass_Medium	1.18E-04	1.78E-03	5.65E-04	1.60E+00
Mass_Small	9.46E-01	7.72E-01	1.58E-01	1.36E-01
Number of Parts_A lot	3.33E-02	1.67E-01	1.70E-01	4.49E+01
Number of Parts_Medium	2.38E-02	3.48E-04	8.38E-04	1.18E-01
Number of Parts_Few	5.28E+00	1.64E-03	1.55E-03	8.61E-01
Num of types of material_A lot	6.33E+00	1.88E-02	6.28E+00	2.06E-05
Num of types of material_some	1.51E-03	6.02E-01	1.91E-03	9.39E+00
Num of types of material_Few	9.05E+00	3.69E-02	7.96E+01	9.24E+00
Electrial Energy_Yes	2.93E-05	9.99E-02	9.39E-02	1.01E+00
Electrical Energy_No	3.19E-01	8.86E-03	1.71E+00	3.57E+00
Combustion_Yes	3.95E-02	1.74E-03	7.79E-01	1.04E-04
Combustion_No	1.03E-02	2.13E-03	1.49E-02	1.86E+00
Human_None_Yes	1.20E+00	1.01E-01	7.80E-01	2.86E-05
Human_None_No	7.12E-01	2.96E+00	1.79E-01	6.09E-01
Energy per use_A lot	1.37E+00	6.14E-02	4.07E-01	4.28E+01

Product Attribute	ReCiPe Metrics			
	Global Warming Potential	Ozone Depletion Potential	Terrestrial Acidification Potential	Freshwater Eutrophication Potential
Energy per use_Some	3.03E-04	3.37E+01	3.94E-02	2.80E-04
Energy per use_Few	3.17E+00	9.97E-01	5.04E-02	2.37E-03
Lifetime_Long	2.19E-03	8.93E-03	5.77E-03	9.69E+00
Lifetime_Medium	9.71E-05	2.02E+00	3.64E-03	3.76E+00
Lifetime_Short	2.95E+03	3.95E+01	7.95E+01	1.45E-02
Num Consumables_A lot	8.74E-05	3.32E-04	2.49E-03	2.05E-01
Num Consumables_Some	2.50E-05	1.24E+00	6.63E+00	6.88E+00
Num Consumables_None	4.87E-01	2.07E-01	5.70E-03	1.10E-01
Num Batteries_A lot	6.76E+01	8.40E-01	1.88E+01	8.00E-02
Num Batteries_Some	1.34E+01	3.99E+00	1.87E-01	7.86E-04
Num Batteries_None	1.33E-03	1.05E-04	4.59E-02	4.23E+00
Fer Metal_Majority	4.09E-01	7.87E-03	5.89E+00	3.61E-01
Fer Metal_Some	1.76E-01	5.92E-01	2.08E-03	3.95E+01
Fer Metal_Minority	4.34E-05	1.89E+01	1.62E-01	3.95E-05
Non-Fer Metal_A lot	2.79E-02	6.23E-01	1.04E-02	2.19E+00
Non_Fer Metal_Some	2.01E-03	2.84E-02	3.09E-05	1.10E-05
Non_Fer Metal_Few	2.63E-04	1.40E-02	1.38E+01	1.20E+00

Product Attribute	ReCiPe Metrics			
	Global Warming Potential	Ozone Depletion Potential	Terrestrial Acidification Potential	Freshwater Eutrophication Potential
Plastic_Majority	2.52E-04	6.75E+00	1.04E-03	5.14E-01
Plastic_Some	4.60E+00	1.89E-01	6.74E+00	5.73E-01
Plastic_Minority	6.01E+00	2.94E-04	5.92E-03	5.80E-01
Glass_None	9.08E-03	1.34E+01	2.42E-02	7.16E-01
Organic_A lot	1.69E-01	2.70E-01	7.82E-02	1.52E-06
Organic_Some	5.41E+00	1.90E+00	1.38E+00	1.07E-03
Organic_None	2.00E-03	7.29E-02	1.97E-03	1.41E+00
Hazardous_Yes	2.87E-02	6.43E-01	1.87E+01	2.24E-02
Hazardous_None	3.63E-02	1.21E+01	1.14E+01	4.68E+00
Electrical Components_Yes	9.60E-01	8.50E-01	1.11E+01	9.56E-01
Electrical Components_None	8.15E-05	2.92E-01	4.12E-04	5.49E-02
Other_None	1.74E+00	1.85E-02	4.04E+00	5.28E+00
Num Stock Parts_A lot	1.27E+00	6.49E-02	9.01E-04	8.56E-03
Num Stock Parts_Some	5.03E-04	2.68E-02	2.45E+00	6.28E+00
Num Stock Parts_None-Few	3.15E-04	9.19E-03	2.06E-02	1.72E-01
Num Subassemblies_A lot	8.55E-03	2.20E+00	5.92E+00	1.76E-01
Num Subassemblies_Some	1.68E-01	4.95E-05	5.64E-01	3.39E+00
Num Subassemblies_Few	2.22E-01	6.62E-01	1.48E-01	9.49E-01
Num MFG Proccesses_A lot	3.00E-02	2.90E-01	9.99E+00	3.23E+00

Product Attribute	ReCiPe Metrics			
	Global Warming Potential	Ozone Depletion Potential	Terrestrial Acidification Potential	Freshwater Eutrophication Potential
Num MFG Processes_Some	1.36E-02	1.16E-01	5.24E-04	5.19E-02
Num MFG Processes_Few	1.20E+01	1.32E+00	6.68E-01	1.10E+01
Num Fasteners_A lot	3.84E-02	1.12E-01	2.33E-02	9.98E-03
Num Fasteners_Some	1.84E-02	1.46E-01	4.86E+00	3.94E+00
Num Fasteners_None	1.29E-02	2.54E-02	9.17E+00	1.65E-01

Product Attribute	ReCiPe Metrics			
	Marine Eutrophication Potential	Global Eco-toxicity Potential[1]	Photochemical Oxidant Formation Potential	Particulate Matter Formation Potential
Size_Large	4.24E-03	3.47E+00	6.20E-03	2.27E-01
Size_Medium	1.26E+01	1.03E-03	1.32E+00	1.29E+00
Size_Small	3.24E-02	8.46E+00	1.12E-03	7.10E-01
Mass_Large	9.00E-04	1.23E-01	4.01E+00	6.06E-04
Mass_Medium	8.81E+00	5.99E-01	1.94E-04	2.93E-02
Mass_Small	3.39E+00	9.92E+00	2.75E-04	7.94E-01
Number of Parts_A lot	1.17E-01	3.35E+00	1.00E-01	2.78E+00
Number of Parts_Medium	4.47E-02	1.37E-02	1.37E-04	6.48E+00
Number of Parts_Few	2.30E+00	1.79E-01	1.02E-03	5.18E-01

Product Attribute	ReCiPe Metrics			
	Marine Eutrophication Potential	Global Eco-toxicity Potential[1]	Photochemical Oxidant Formation Potential	Particulate Matter Formation Potential
Num of types of material_A lot	4.91E-03	7.24E+00	2.02E-02	3.23E+00
Num of types of material_some	2.28E+00	2.84E+00	4.14E-04	1.13E-02
Num of types of material_Few	4.98E-02	9.38E-03	4.39E-02	1.57E-03
Electrial Energy_Yes	3.41E-03	3.71E-01	1.32E-01	5.61E+00
Electrical Energy_No	1.27E-02	1.04E-01	3.15E-04	5.87E-01
Combustion _Yes	1.55E-03	1.43E-02	3.65E-01	1.70E-02
Combustion _No	3.01E-01	1.27E+00	1.06E+01	4.74E-01
Human_None_Yes	7.29E-03	4.34E+01	3.40E+00	8.60E+00
Human_None_No	5.95E-04	3.25E+00	6.60E+00	1.13E-01
Energy per use_A lot	5.74E-02	1.46E-03	1.39E+00	4.12E-05
Energy per use_Some	1.27E-04	6.20E+00	2.84E-02	1.74E-01
Energy per use_Few	3.15E-03	9.97E-03	2.00E+00	1.30E-02
Lifetime_Long	6.87E-05	1.52E-03	6.15E-03	1.58E-01
Lifetime_Medium	2.87E-02	1.36E+01	2.42E-02	2.85E-02
Lifetime_Short	2.19E+03	3.53E+02	2.67E+02	7.03E-01
Num Consumables_A lot	1.76E-01	1.08E+00	2.70E-01	1.21E-01

Product Attribute	ReCiPe Metrics			
	Marine Eutrophication Potential	Global Eco-toxicity Potential[1]	Photochemical Oxidant Formation Potential	Particulate Matter Formation Potential
Num Consumables_Some	5.13E+00	1.17E+00	8.17E-01	1.23E-02
Num Consumables_None	3.57E-02	5.57E+00	1.73E-03	8.13E-01
Num Batteries_A lot	4.57E+01	6.22E+00	4.06E-01	1.09E+01
Num Batteries_Some	3.49E+00	4.62E-02	3.24E+00	1.23E-03
Num Batteries_None	3.04E+01	8.19E-05	3.35E-02	2.51E-02
Fer Metal_Majority	2.45E+00	1.31E-01	4.63E-02	2.79E-02
Fer Metal_Some	6.79E-02	9.25E-04	2.07E-04	7.72E-01
Fer Metal_Minority	2.90E+00	3.38E-02	1.30E+01	2.82E-02
Non-Fer Metal_A lot	2.04E-04	3.33E-03	1.35E+00	1.44E-02
Non_Fer Metal_Some	7.18E+00	8.21E-02	1.03E+01	5.52E-01
Non_Fer Metal_Few	1.82E-03	6.26E-04	7.51E-03	1.53E-01
Plastic_Majority	4.10E-01	2.66E-01	6.19E-04	4.45E-04
Plastic_Some	3.24E+00	1.46E+02	6.51E-01	6.54E+00
Plastic_Minority	1.53E+01	4.21E+00	2.44E-01	2.51E-01
Glass_None	3.94E-01	6.76E-01	3.87E+00	5.13E-02
Organic_A lot	3.09E-06	2.15E-03	1.03E-02	2.06E-04
Organic_Some	1.44E-01	7.61E-01	3.53E+00	5.91E+00

Product Attribute	ReCiPe Metrics			
	Marine Eutrophication Potential	Global Eco-toxicity Potential[1]	Photochemical Oxidant Formation Potential	Particulate Matter Formation Potential
Organic_None	2.29E-03	8.97E-01	7.34E-03	6.27E-02
Hazardous_Yes	3.15E+01	6.68E-04	3.26E-02	1.14E-03
Hazardous_None	1.77E-03	2.13E+01	1.22E-01	2.68E-03
Electrical Components_Yes	6.89E-04	7.32E-01	2.48E-02	6.54E-02
Electrical Components_None	3.86E-02	3.24E-03	9.89E+00	5.40E+00
Other_None	1.47E-01	5.81E-05	1.22E+01	3.05E-02
Num Stock Parts_A lot	7.97E-02	6.79E-01	3.92E-05	1.74E-02
Num Stock Parts_Some	3.29E-01	1.74E+00	7.86E-01	2.40E-02
Num Stock Parts_None-Few	1.32E+01	6.99E-03	1.04E+02	1.71E-01
Num Subassemblies_A lot	1.03E-01	2.17E-01	3.36E-01	6.00E-01
Num Subassemblies_Some	2.98E+00	1.65E+00	3.52E-01	4.45E-03
Num Subassemblies_Few	8.50E-01	4.56E-03	2.53E+00	5.96E-02
Num MFG Proccesses_A lot	2.53E-04	1.77E-02	2.67E+01	6.69E-02
Num MFG Processes_Some	2.08E-01	1.01E-01	4.51E-03	2.48E-02
Num MFG Processes_Few	1.05E+00	3.47E-03	5.93E-01	6.16E+00

Product Attribute	ReCiPe Metrics			
	Marine Eutrophication Potential	Global Eco-toxicity Potential[1]	Photochemical Oxidant Formation Potential	Particulate Matter Formation Potential
Num Fasteners_A lot	5.75E+00	6.16E+00	2.60E-01	1.79E+00
Num Fasteners_Some	5.03E+00	1.81E-02	1.50E+01	4.16E-03
Num Fasteners_None	3.73E+01	4.56E-02	4.60E+01	1.98E-02

Product Attribute	ReCiPe Metrics			
	Ionizing Radiation Potential	Mineral Depletion	Water Depletion	Fossil Depletion
Size_Large	9.35E-05	1.54E-01	3.82E+00	2.56E+00
Size_Medium	9.94E-05	9.73E-03	8.54E-02	8.99E-04
Size_Small	2.86E-03	8.30E-01	5.80E+00	2.89E+00
Mass_Large	2.85E-01	1.02E+00	6.44E-01	2.90E-03
Mass_Medium	1.15E+01	8.43E-03	5.77E-01	4.12E-04
Mass_Small	4.06E-03	1.99E+00	2.83E-03	8.59E-02
Number of Parts_A lot	1.84E+00	1.18E-01	7.80E-01	8.65E-02
Number of Parts_Medium	6.55E-05	6.16E-01	7.97E-04	1.07E-02
Number of Parts_Few	2.45E-03	1.74E-03	8.71E-03	2.95E-03
Num of types of material_A lot	1.58E+00	2.34E-04	4.82E-05	1.64E-01
Num of types of material_some	3.37E-01	2.60E-02	1.74E-01	4.60E-05

Product Attribute	ReCiPe Metrics			
	Ionizing Radiation Potential	Mineral Depletion	Water Depletion	Fossil Depletion
Num of types of material_Few	1.81E+01	4.07E+00	3.32E-03	2.11E-03
Electrial Energy_Yes	6.04E+00	3.40E-03	3.76E-01	3.08E-01
Electrical Energy_No	4.34E-03	1.14E+00	2.53E-02	7.61E-02
Combustion_Yes	2.57E-04	3.82E-02	6.13E-02	6.93E-03
Combustion_No	1.16E-04	2.22E+00	2.17E-03	2.92E-01
Human_None_Yes	5.59E-01	2.98E-02	9.44E+00	4.96E-01
Human_None_No	1.87E-02	2.28E-01	1.52E-01	1.13E+00
Energy per use_A lot	1.45E-04	4.10E+00	3.09E-04	1.79E-03
Energy per use_Some	3.44E-01	5.42E+00	3.26E-02	4.78E-05
Energy per use_Few	6.98E-04	4.06E-03	3.18E-01	7.29E-01
Lifetime_Long	1.71E-03	2.76E-02	3.96E-01	1.62E-03
Lifetime_Medium	1.13E-01	1.37E+00	1.04E-01	1.94E-02
Lifetime_Short	2.79E+01	1.59E+04	6.62E+00	1.14E+00
Num Consumables_A lot	1.35E-01	3.72E-03	8.29E-02	1.49E-01
Num Consumables_Some	5.90E+00	4.72E-04	8.30E+00	5.33E+00
Num Consumables_None	1.71E-03	3.21E-03	8.56E-03	3.76E-02
Num Batteries_A lot	1.49E-02	1.16E+01	4.86E-02	1.73E-01

Product Attribute	ReCiPe Metrics			
	Ionizing Radiation Potential	Mineral Depletion	Water Depletion	Fossil Depletion
Num Batteries_Some	4.48E-04	2.70E-01	2.34E+01	1.01E+01
Num Batteries_None	4.18E+01	2.60E-01	1.03E+00	1.33E-02
Fer Metal_Majority	2.22E+01	5.70E+00	2.10E-03	2.05E-01
Fer Metal_Some	5.64E+00	3.87E-03	1.02E+00	7.54E-01
Fer Metal_Minority	1.83E-03	1.27E+00	2.61E-02	2.02E+00
Non-Fer Metal_A lot	1.16E-01	4.09E-03	6.48E-01	4.05E-02
Non_Fer Metal_Some	4.05E-06	3.21E-02	3.06E-02	2.17E+01
Non_Fer Metal_Few	7.29E-02	1.53E-02	6.08E-02	5.73E-02
Plastic_Majority	9.04E+00	1.29E-02	1.37E-01	2.70E-01
Plastic_Some	1.43E+00	3.82E+01	2.23E-02	1.05E-03
Plastic_Minority	1.08E-01	7.08E-01	1.30E-01	5.11E+00
Glass_None	6.04E+00	2.76E-03	5.59E+00	1.63E-03
Organic_A lot	4.83E-05	6.02E-05	8.95E+00	6.58E-05
Organic_Some	2.97E+00	8.76E-01	1.70E-03	4.07E-02
Organic_None	2.84E+00	6.49E-03	2.29E-02	4.58E-03
Hazardous_Yes	4.74E-01	6.39E-02	2.94E-01	8.19E-02
Hazardous_None	2.11E-04	1.87E-03	1.52E+00	4.59E-05
Electrical Components_Yes	1.05E+00	6.40E-01	5.60E-01	3.84E-02

Product Attribute	ReCiPe Metrics			
	Ionizing Radiation Potential	Mineral Depletion	Water Depletion	Fossil Depletion
Electrical Components _None	8.93E-05	8.59E-03	8.14E-03	1.27E-03
Other_None	4.19E-05	1.80E+01	9.79E+00	9.57E-02
Num Stock Parts_A lot	6.82E+00	1.39E-01	4.05E-01	9.56E+00
Num Stock Parts_Some	1.46E+00	2.31E-01	1.04E+00	9.67E-01
Num Stock Parts_None-Few	5.22E-01	2.62E-03	7.26E+00	1.25E-01
Num Subassemblies_A lot	1.07E-01	6.13E-01	1.68E-03	2.76E-01
Num Subassemblies_Some	1.02E-01	1.75E+01	5.26E-02	4.38E-03
Num Subassemblies_Few	1.93E-01	2.37E-01	3.56E-01	5.56E-03
Num MFG Proccesses_ A lot	2.38E-01	4.02E-02	5.38E-01	9.76E+00
Num MFG Processes_Some	7.78E+00	1.17E-01	2.50E-03	2.61E-03
Num MFG Processes_Few	6.55E-01	6.04E+01	1.76E-01	5.54E-01
Num Fasteners_A lot	9.51E-01	1.00E+01	4.46E+00	4.11E+00
Num Fasteners_Some	1.20E+00	5.92E-01	1.36E-04	2.18E-03
Num Fasteners_None	8.06E-02	3.65E-01	1.67E-01	1.60E+00

Product Attribute	Eco-indicator 99 Metrics		
	Production	Use	Disposal
Size_Large	1.35E+00	6.83E-04	-4.55E-03
Size_Medium	2.20E+00	9.13E+00	-3.42E-04
Size_Small	4.03E-03	9.30E-02	1.18E-05
Mass_Large	1.93E-05	9.69E-02	-2.35E-02
Mass_Medium	7.06E-01	1.80E+00	-1.59E-05
Mass_Small	1.84E-01	2.68E-01	-2.86E+00
Number of Parts_A lot	1.67E+00	1.30E-02	-1.48E-05
Number of Parts_Medium	1.30E+01	2.74E-03	-2.44E-05
Number of Parts_Few	6.13E-02	5.93E+00	-2.53E-05
Num of types of material_A lot	1.17E-01	2.01E-03	-7.84E-04
Num of types of material_some	1.80E-04	2.03E+00	-7.45E-06
Num of types of material_Few	1.58E-01	9.92E-01	-2.09E-05
Electrial Energy_Yes	3.80E+00	4.04E-03	-7.35E-06
Electrical Energy_No	5.39E+00	5.52E+00	-7.59E-05
Combustion_Yes	1.09E+01	7.27E+00	-8.91E-06
Combustion_No	3.72E+00	3.87E+00	2.23E-04
Human_None_Yes	6.41E-03	1.15E+02	7.82E-05
Human_None_No	2.84E-02	7.35E+00	-1.69E-05
Energy per use_A lot	6.92E-01	2.53E-01	-1.07E-05
Energy per use_Some	9.95E-02	1.19E-01	-8.82E-06
Energy per use_Few	1.47E-01	2.02E+01	-5.89E-04
Lifetime_Long	3.31E+01	1.53E+00	-1.32E-04
Lifetime_Medium	7.24E-04	5.39E-04	-9.20E-06
Lifetime_Short	3.71E-02	6.55E+04	-1.37E+02
Num Consumables_A lot	3.69E-02	3.85E+00	2.27E-05
Num Consumables_Some	7.85E-01	3.03E-01	-2.89E-06
Num Consumables_None	2.23E-04	1.38E-04	-1.04E-04
Num Batteries_A lot	7.15E+00	2.72E+01	1.38E-01
Num Batteries_Some	1.99E-01	6.17E-01	-3.32E-05
Num Batteries_None	1.11E+00	1.87E+01	8.53E-05
Fer Metal_Majority	1.52E+00	1.23E+01	-2.15E-05
Fer Metal_Some	6.02E-03	5.44E-04	-2.74E-04
Fer Metal_Minority	4.43E-05	2.46E-03	-3.45E-06
Non-Fer Metal_A lot	1.48E-05	1.44E-01	-6.47E-06
Non_Fer Metal_Some	1.14E-02	1.46E-05	-1.22E-05
Non_Fer Metal_Few	2.06E-01	1.05E+02	-2.14E-04
Plastic_Majority	2.19E-02	6.92E-04	-1.08E-05
Plastic_Some	5.07E+00	1.27E-02	8.06E-03

Product Attribute	Eco-indicator 99 Metrics		
	Production	Use	Disposal
Plastic_Minority	3.18E-01	3.89E-02	1.05E-03
Glass_None	1.36E+01	7.64E+00	7.12E-05
Organic_A lot	4.79E-04	5.51E-01	-2.12E-05
Organic_Some	8.25E-02	2.69E-04	-9.64E-06
Organic_None	5.76E-02	1.42E+00	-7.33E-05
Hazardous_Yes	8.29E-03	6.07E+00	-1.36E-05
Hazardous_None	3.82E-01	2.95E+00	4.45E-05
Electrical Components_Yes	1.61E+00	1.29E-01	-3.81E-06
Electrical Components_None	8.34E+00	8.57E-03	-2.96E-05
Other_None	6.73E-03	4.60E+00	5.12E-05
Num Stock Parts_A lot	1.13E-03	5.03E+00	-7.95E-06
Num Stock Parts_Some	1.19E-03	2.72E+00	-5.44E-06
Num Stock Parts_None-Few	4.88E-03	8.74E-04	-1.54E-05
Num Subassemblies_A lot	2.76E-05	9.41E-04	-6.19E-06
Num Subassemblies_Some	1.76E-04	2.37E-03	-3.86E-05
Num Subassemblies_Few	4.96E-05	2.09E+01	1.99E-05
Num MFG Proccesses_A lot	1.05E-01	6.92E+00	-1.64E-04
Num MFG Processes_Some	9.77E-04	3.49E+00	-3.96E-05
Num MFG Processes_Few	7.04E-03	9.83E-01	-7.01E-05
Num Fasteners_A lot	1.72E-02	4.03E-03	-1.23E-05
Num Fasteners_Some	5.53E-03	4.03E+00	-1.85E-04
Num Fasteners_None	1.36E-02	8.18E-01	-5.35E-05

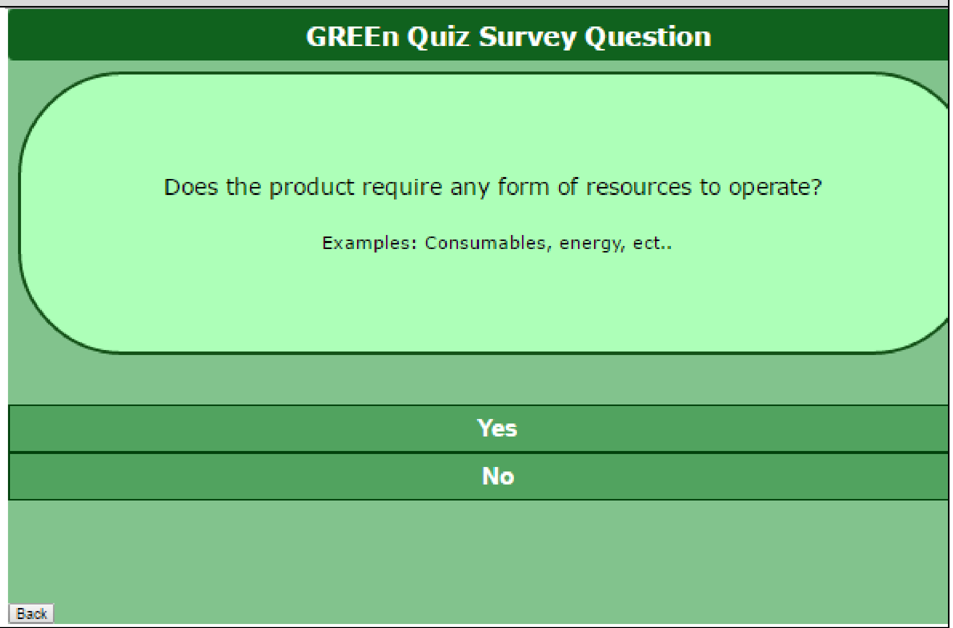
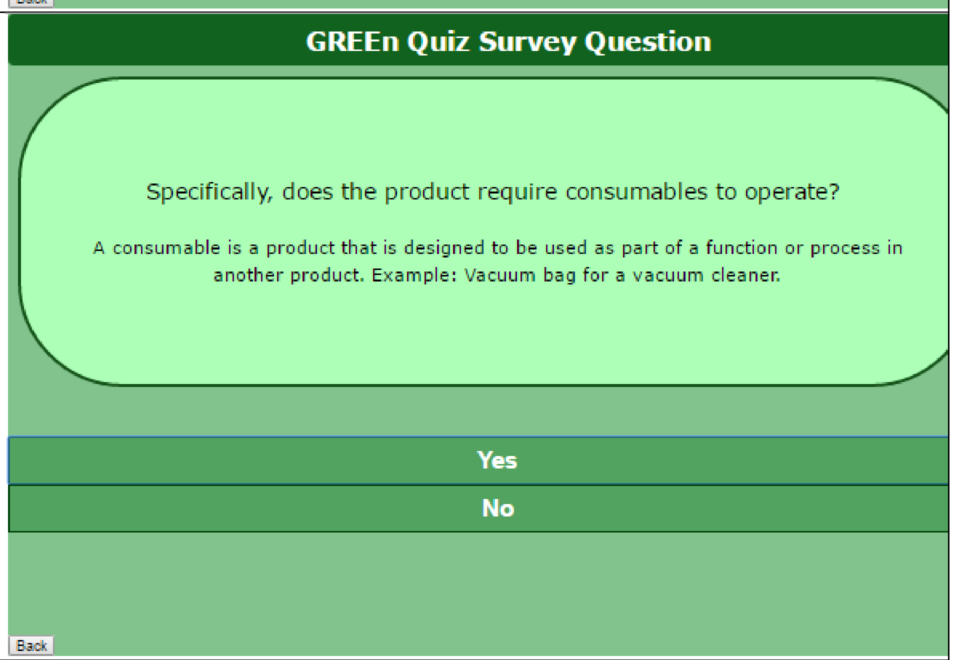
Product Attribute	Solidworks Sustainability			
	Carbon Footprint	Energy consumption	Air Acidification	Water Eutorphication
Size_Large	6.34E-01	9.26E-01	2.48E-03	2.43E-03
Size_Medium	9.81E-03	5.72E-05	2.16E-01	5.63E-03
Size_Small	5.86E-04	3.77E+00	1.44E-02	9.13E-04
Mass_Large	2.17E-01	9.86E+00	3.26E-05	1.75E-01
Mass_Medium	3.04E+00	1.81E+00	1.16E-01	5.68E-01
Mass_Small	2.92E-03	1.57E-01	3.58E-02	2.50E+00
Number of Parts_A lot	1.45E+00	1.55E+01	3.79E-03	1.67E-02
Number of Parts_Medium	1.20E-01	5.41E-01	1.58E-02	9.86E-02

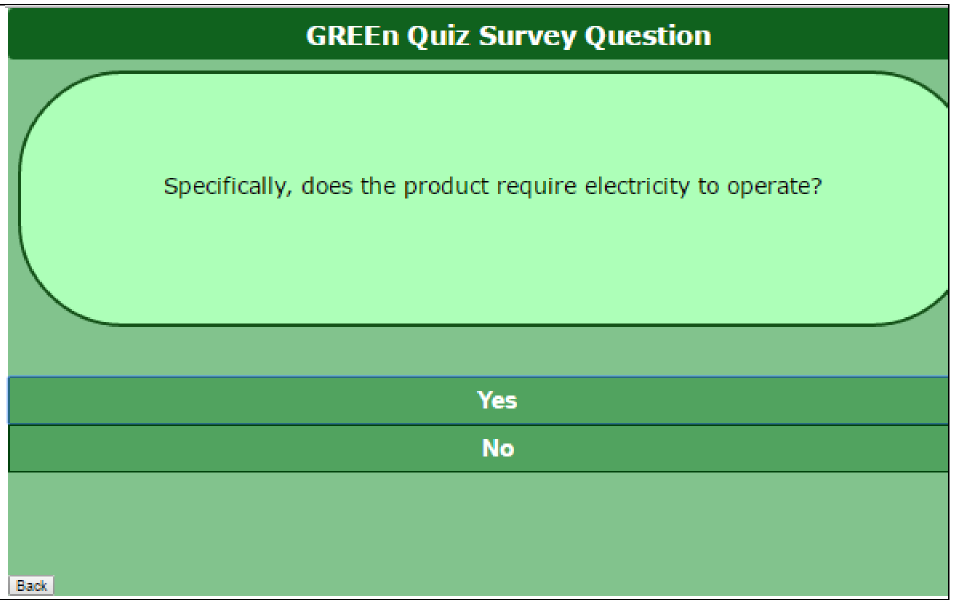
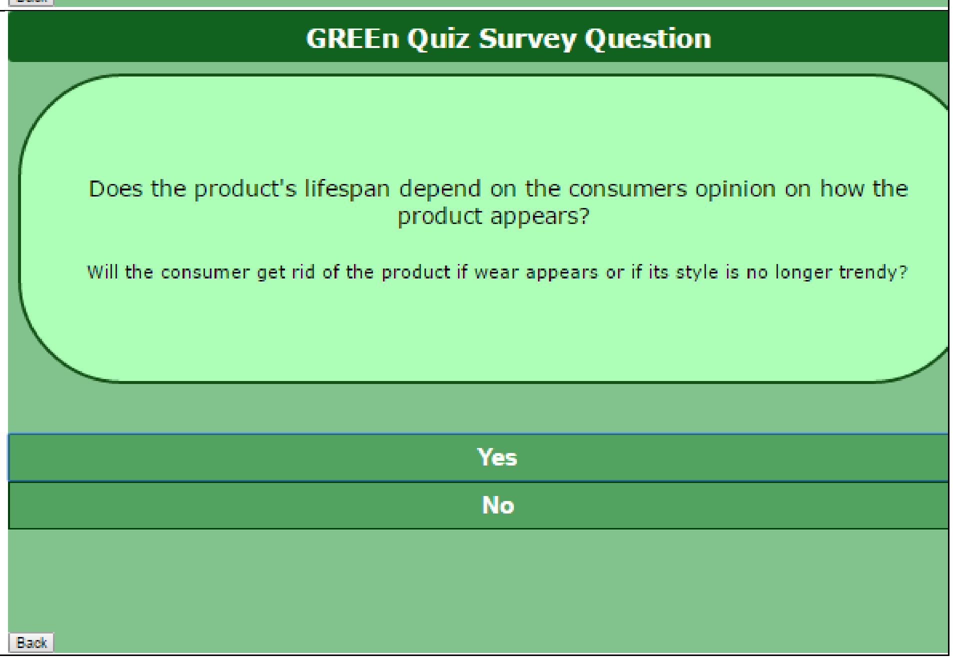
Product Attribute	Solidworks Sustainability			
	Carbon Footprint	Energy consumption	Air Acidification	Water Eutorphication
Number of Parts_Few	1.78E+00	1.19E+01	2.05E+00	9.78E-04
Num of types of material_A lot	4.00E-01	2.24E-05	8.84E-01	1.65E-03
Num of types of material_some	1.35E-04	2.75E-03	2.34E-03	2.61E+00
Num of types of material_Few	6.25E-01	8.46E-03	6.54E+00	3.37E+00
Electrial Energy_Yes	1.61E-05	5.80E-03	8.99E-02	1.24E-03
Electrical Energy_No	2.91E-02	2.04E-01	2.11E-03	1.06E-04
Combustion_Yes	4.30E-02	1.38E-05	2.13E-04	2.21E-01
Combustion_No	6.64E+00	1.00E-04	3.60E-01	1.65E-01
Human_None_Yes	5.33E-04	1.77E-03	9.04E+00	4.48E-02
Human_None_No	6.36E-01	3.82E+00	8.05E+00	6.75E-03
Energy per use_A lot	4.95E+00	2.47E-01	8.51E-03	1.21E+00
Energy per use_Some	8.04E-01	2.54E+00	6.54E-02	1.23E+01
Energy per use_Few	2.64E+00	7.85E-05	2.52E-04	2.11E+00
Lifetime_Long	1.09E-01	1.80E-01	5.31E-02	5.15E+00
Lifetime_Medium	2.75E-03	1.73E-03	2.06E-01	2.08E-01
Lifetime_Short	4.19E-01	1.43E+02	9.37E+01	5.56E-01
Num Consumables_A lot	1.06E+00	5.56E+00	3.87E-01	1.72E+00
Num Consumables_Some	2.76E-05	1.09E-03	1.65E-01	1.30E+00
Num Consumables_None	5.71E-01	9.38E-01	3.04E-04	1.80E-02
Num Batteries_A lot	2.21E+00	1.61E+01	3.64E-01	2.30E-01
Num Batteries_Some	3.38E-02	1.17E-03	1.77E-02	4.06E-04
Num Batteries_None	1.74E-01	5.24E-02	5.22E+00	6.30E-04
Fer Metal_Majority	5.36E+00	1.15E+01	6.03E+00	3.54E+01
Fer Metal_Some	9.57E-01	1.10E-01	4.53E-02	7.02E-02
Fer Metal_Minority	1.15E-01	2.02E-03	3.33E-02	1.16E-02
Non-Fer Metal_A lot	4.63E-05	1.32E-02	1.78E+00	4.84E+00
Non_Fer Metal_Some	1.45E-05	8.15E-06	5.87E-06	5.09E-06
Non_Fer Metal_Few	2.57E-01	7.65E-01	1.41E-04	8.06E-01
Plastic_Majority	2.56E-02	1.31E-04	7.69E-03	1.02E+00

Product Attribute	Solidworks Sustainability			
	Carbon Footprint	Energy consumption	Air Acidification	Water Eutorphication
Plastic_Some	2.37E-01	9.34E+00	4.65E-01	3.03E-03
Plastic_Minority	5.51E-02	3.54E-02	8.32E-05	8.89E-04
Glass_None	5.76E+00	1.52E-01	5.09E+00	3.05E+00
Organic_A lot	3.28E-01	8.88E-02	6.56E+00	2.35E+01
Organic_Some	3.63E+00	1.97E+00	1.34E+00	2.81E+00
Organic_None	9.32E-02	2.93E-01	7.15E+00	5.27E-01
Hazardous_Yes	4.28E-01	1.12E-01	2.25E-02	1.33E-04
Hazardous_None	1.56E+01	1.15E-01	1.81E-01	7.93E-02
Electrical Components_Yes	3.25E-02	8.12E+00	2.29E+00	1.92E-04
Electrical Components_None	2.97E+00	8.30E-02	2.33E-01	1.51E-01
Other_None	8.10E-01	4.49E-02	1.98E-01	8.90E-02
Num Stock Parts_A lot	5.41E-01	1.12E-04	4.10E-01	1.33E+01
Num Stock Parts_Some	1.25E-02	3.81E+00	8.28E+00	6.61E+00
Num Stock Parts_None-Few	1.44E-02	3.39E-02	1.92E+00	6.32E-04
Num Subassemblies_A lot	9.23E-01	2.01E-04	1.35E-01	9.64E-03
Num Subassemblies_Some	1.47E+00	3.31E+00	3.76E+00	2.48E+01
Num Subassemblies_Few	6.91E-03	1.57E+02	2.57E+00	4.94E-03
Num MFG Proccesses_A lot	9.72E-02	1.03E+00	1.45E-03	6.23E-01
Num MFG Processes_Some	2.50E-01	6.26E-03	2.44E+00	3.05E+00
Num MFG Processes_Few	4.95E-01	7.56E-03	2.02E-04	1.14E-01
Num Fasteners_A lot	1.92E-02	1.02E+00	2.67E+00	4.76E+00
Num Fasteners_Some	3.13E+00	2.60E+00	6.03E+00	9.90E-03
Num Fasteners_None	7.99E-04	7.04E-02	7.59E+00	3.52E-03

Appendix 3

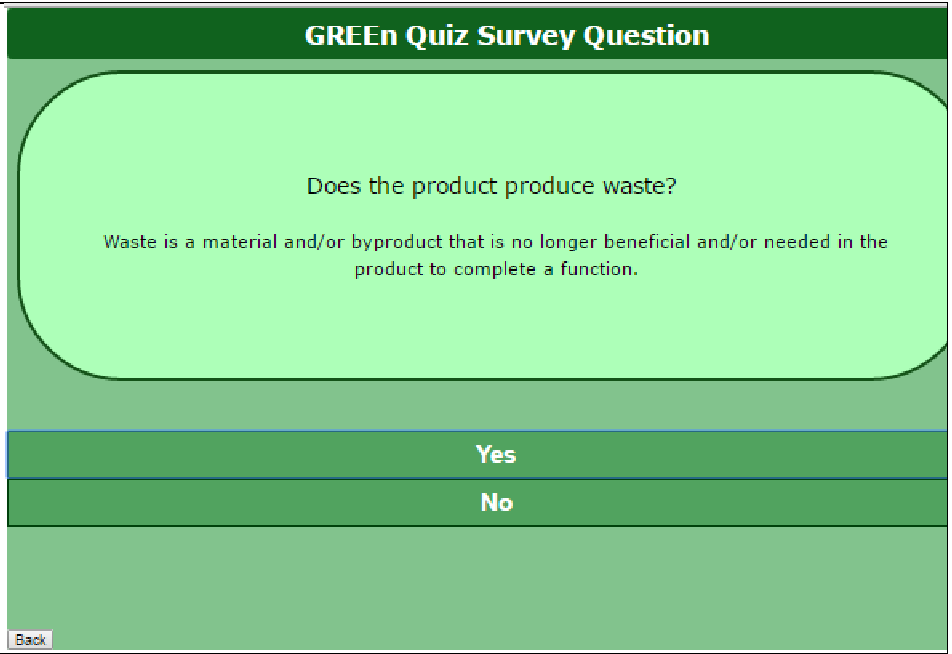
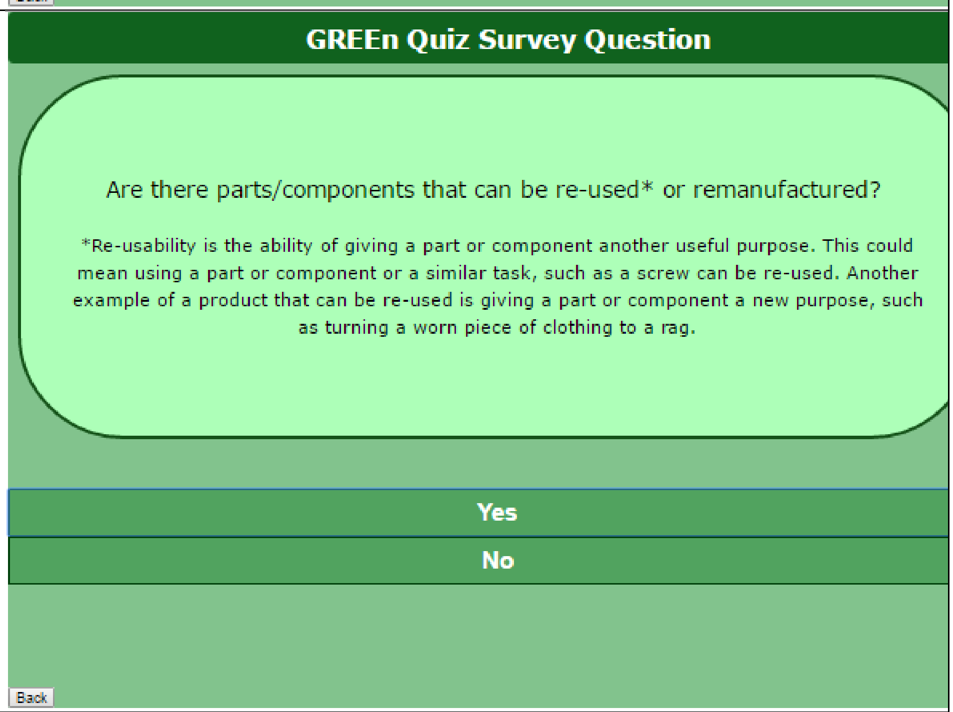
Table 10 : Table of GREEn Quiz Questions (Pg. 73-106)

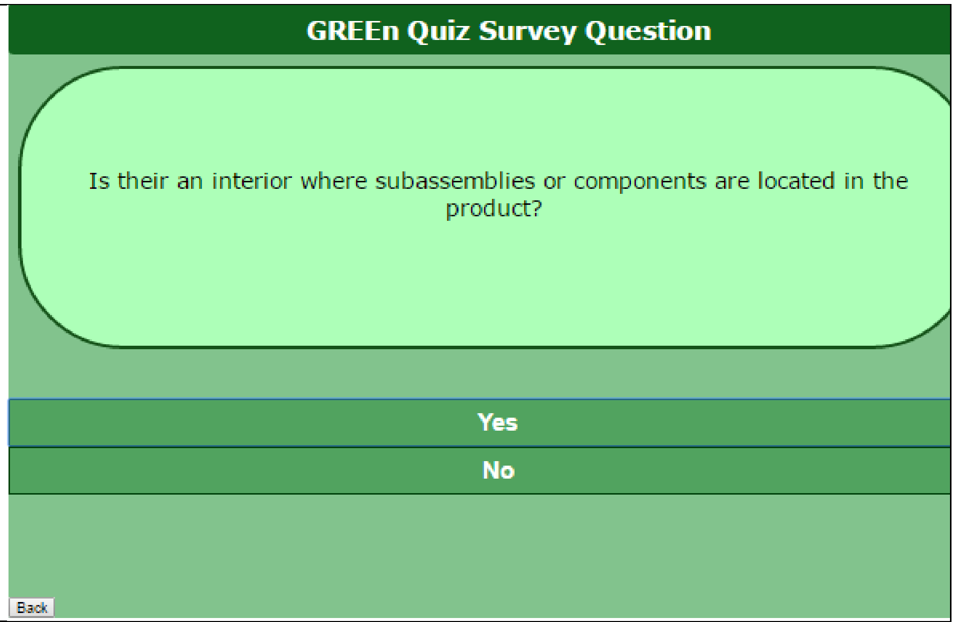
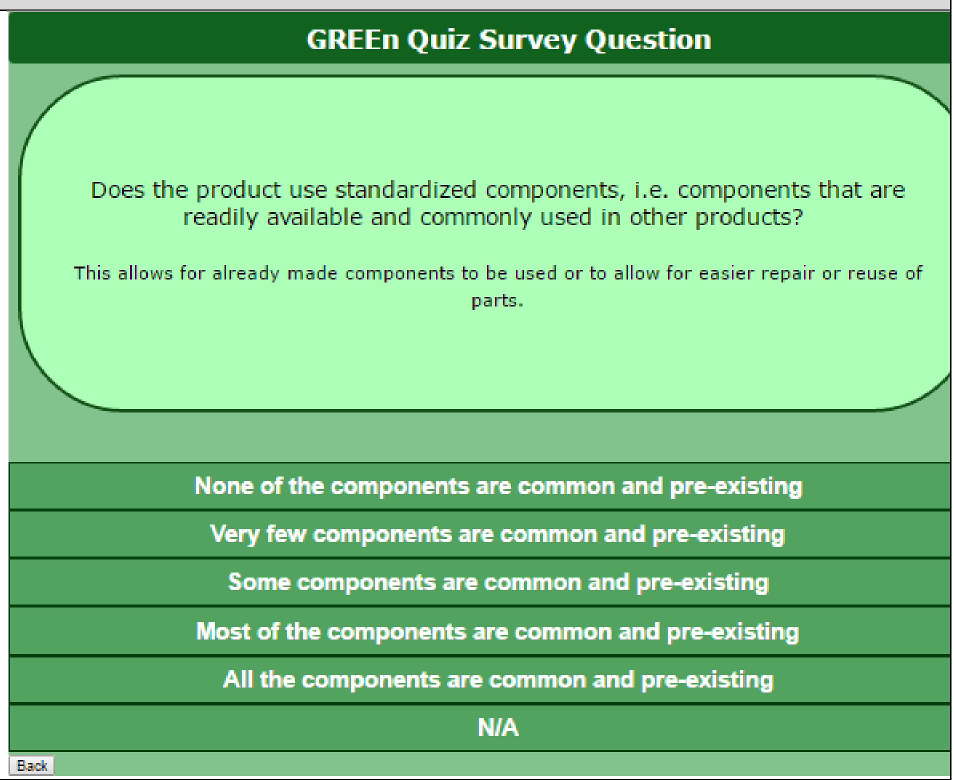
Filtering Questions	GREEn Quiz Question Screen Capture
1	
2	

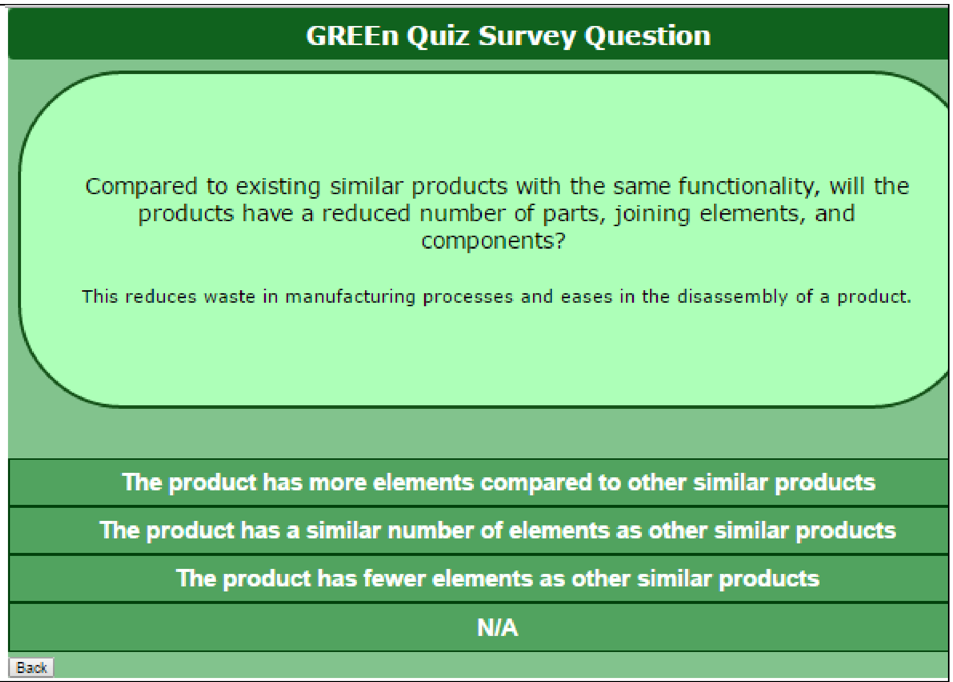
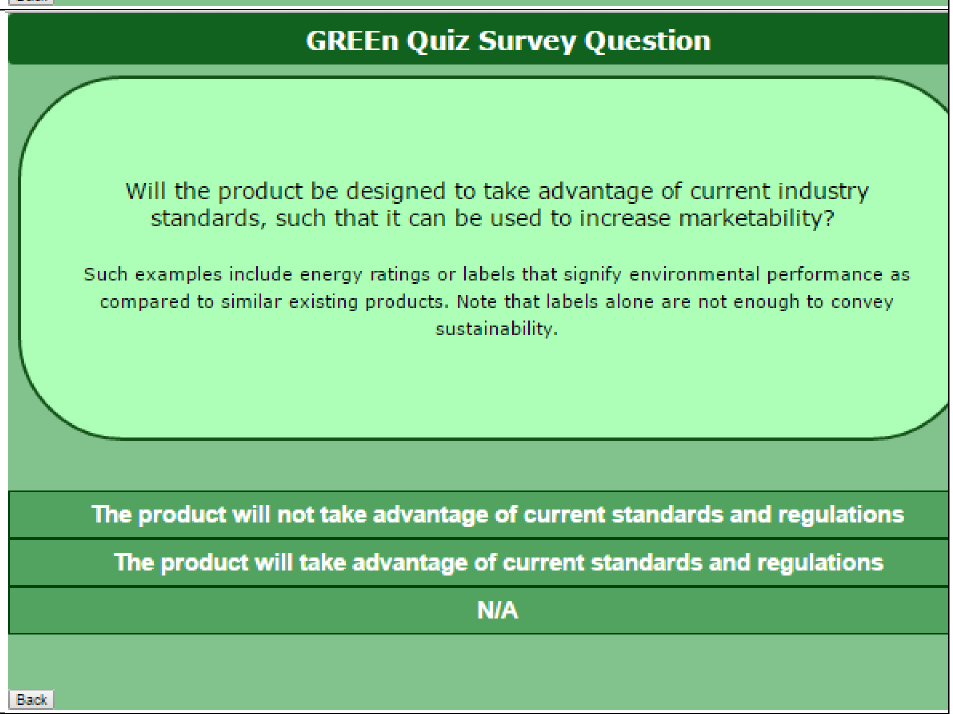
3	
4	

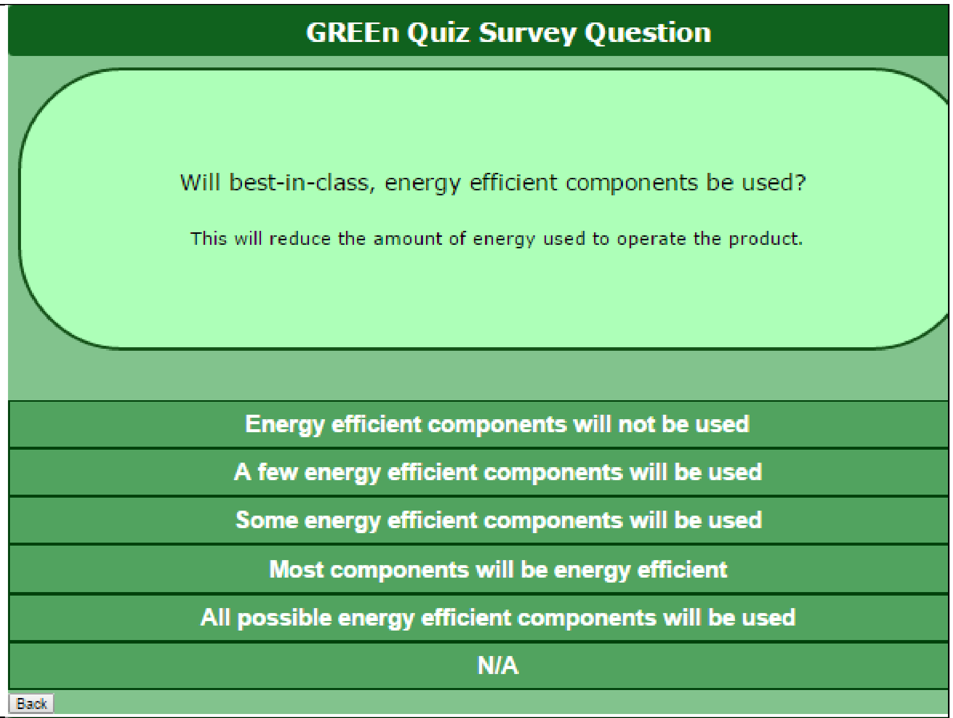
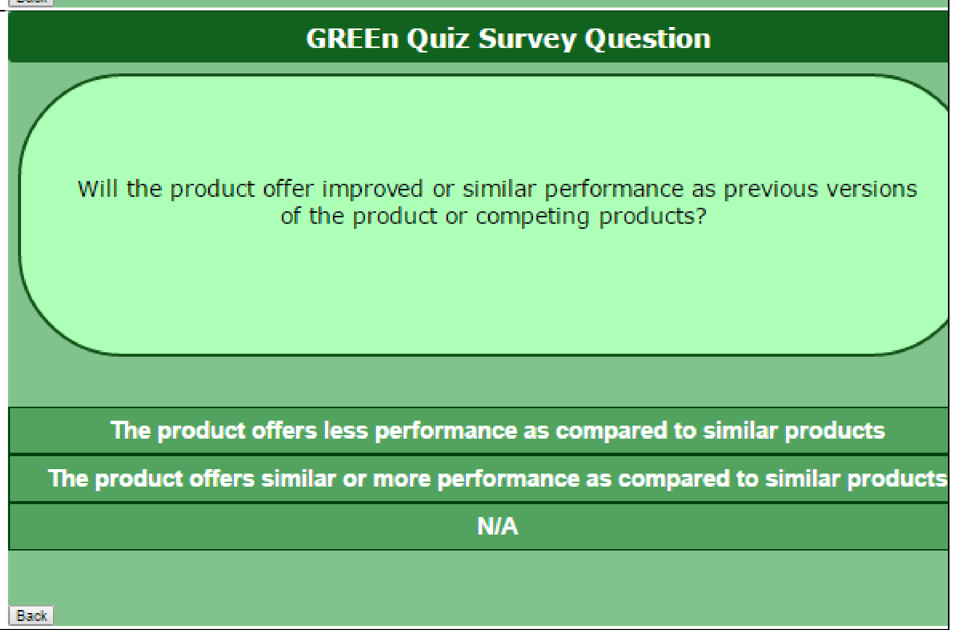
GREEn Quiz Survey Question
Specifically, does the product require electricity to operate?
Yes
No
Back

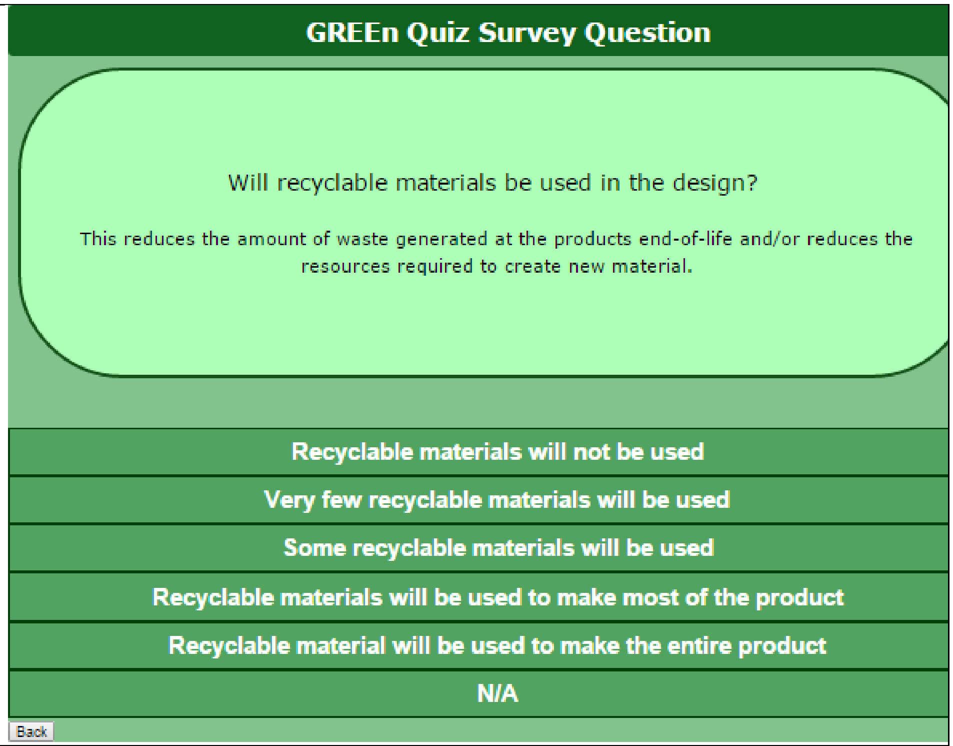
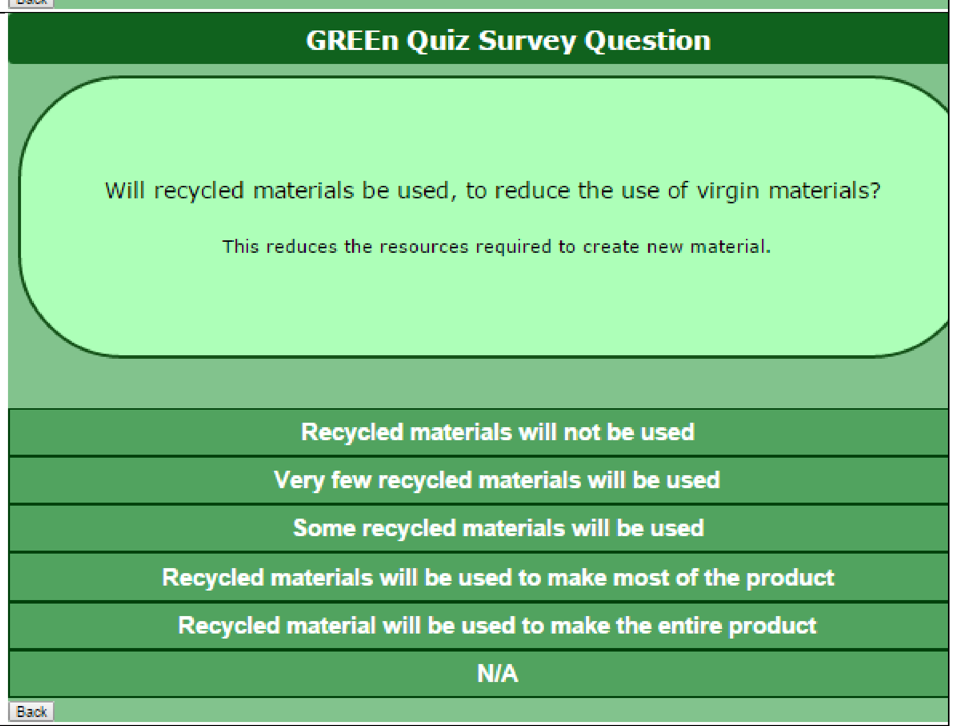
GREEn Quiz Survey Question
Does the product's lifespan depend on the consumers opinion on how the product appears?
Will the consumer get rid of the product if wear appears or if its style is no longer trendy?
Yes
No
Back

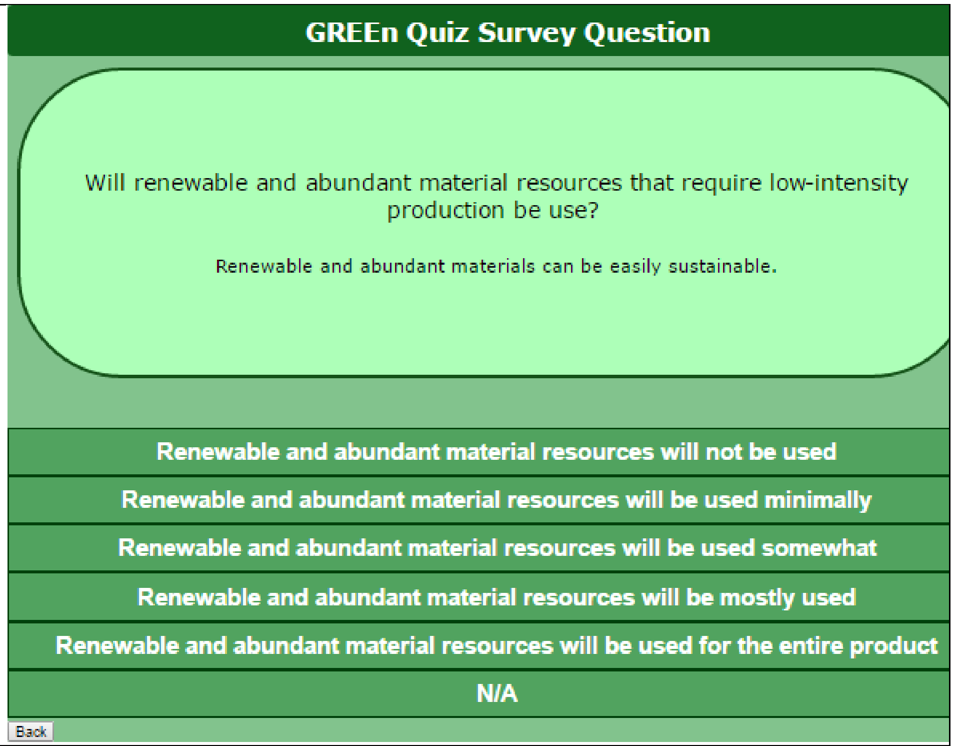
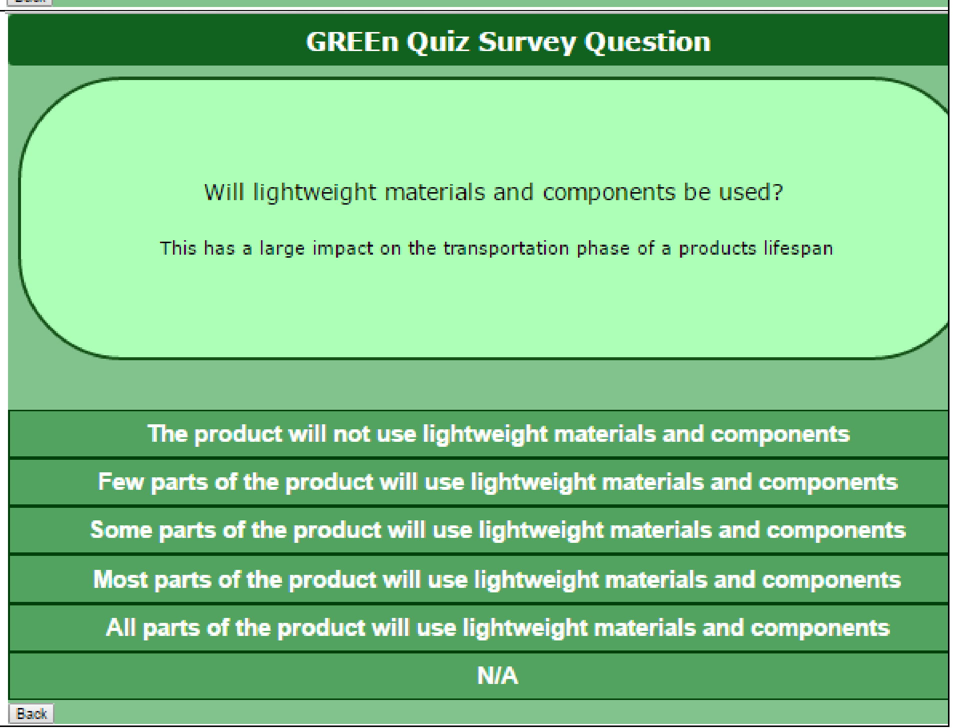
5	 GREEn Quiz Survey Question Does the product produce waste? Waste is a material and/or byproduct that is no longer beneficial and/or needed in the product to complete a function. Yes No Back
6	 GREEn Quiz Survey Question Are there parts/components that can be re-used* or remanufactured? *Re-usability is the ability of giving a part or component another useful purpose. This could mean using a part or component or a similar task, such as a screw can be re-used. Another example of a product that can be re-used is giving a part or component a new purpose, such as turning a worn piece of clothing to a rag. Yes No Back

<table>
<tr><td>7</td><td>
</td></tr>
<tr><td>Sustainable Design Questions</td><td>GREEn Quiz Question Screen Capture</td></tr>
<tr><td>1</td><td>
</td></tr>
</table>

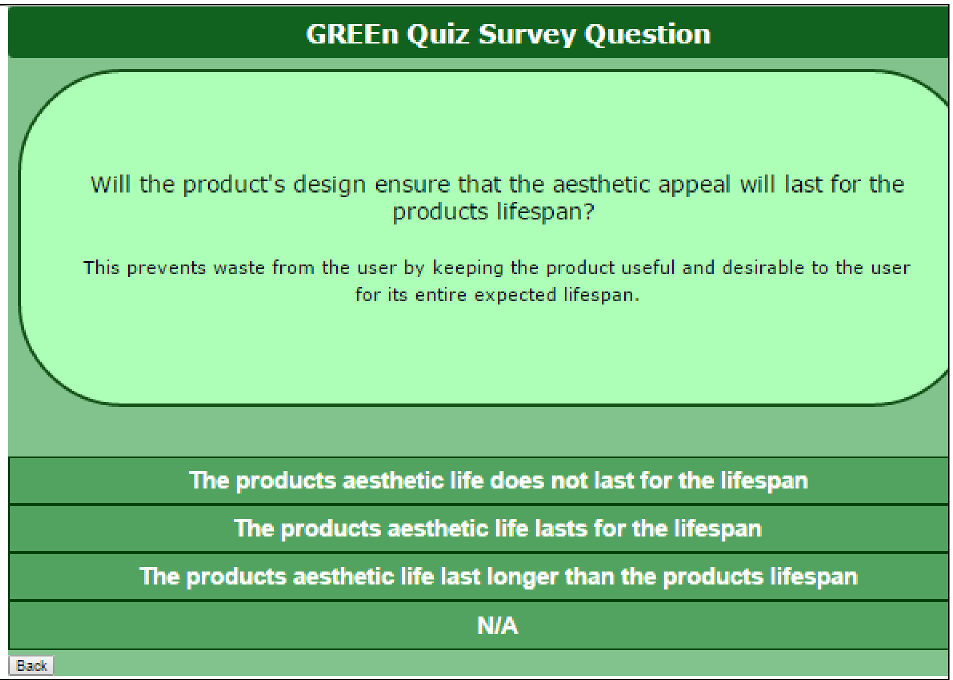
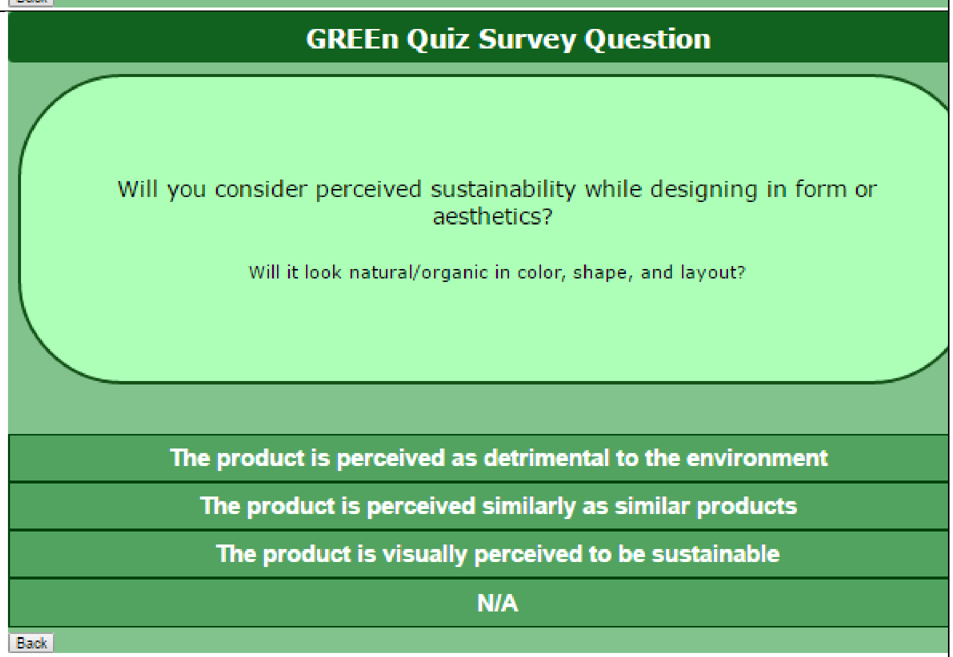
<table>
<tr><td>2</td><td>
</td></tr>
<tr><td>3</td><td>
</td></tr>
</table>

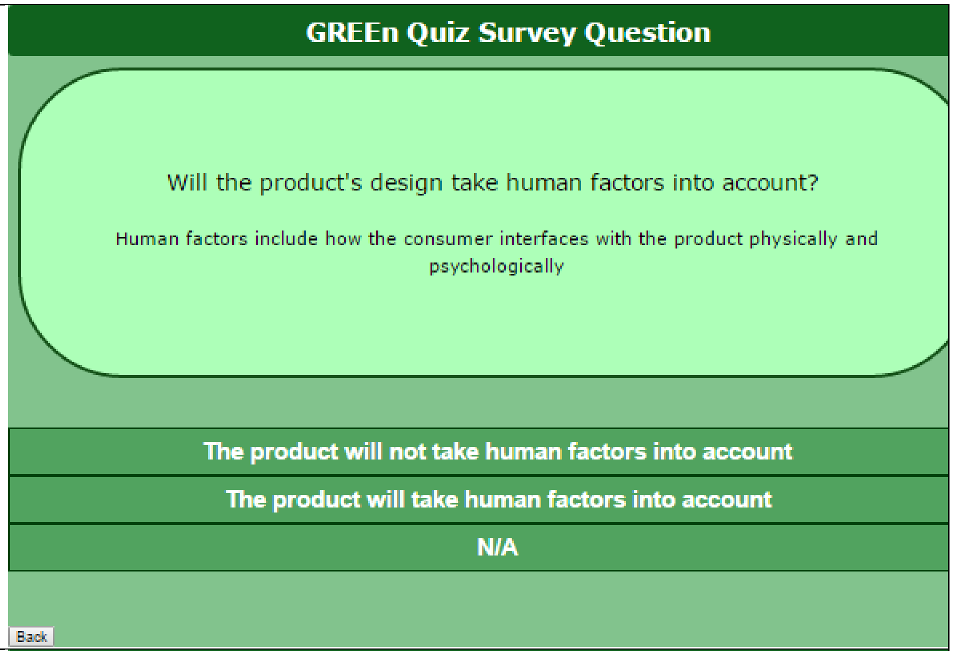
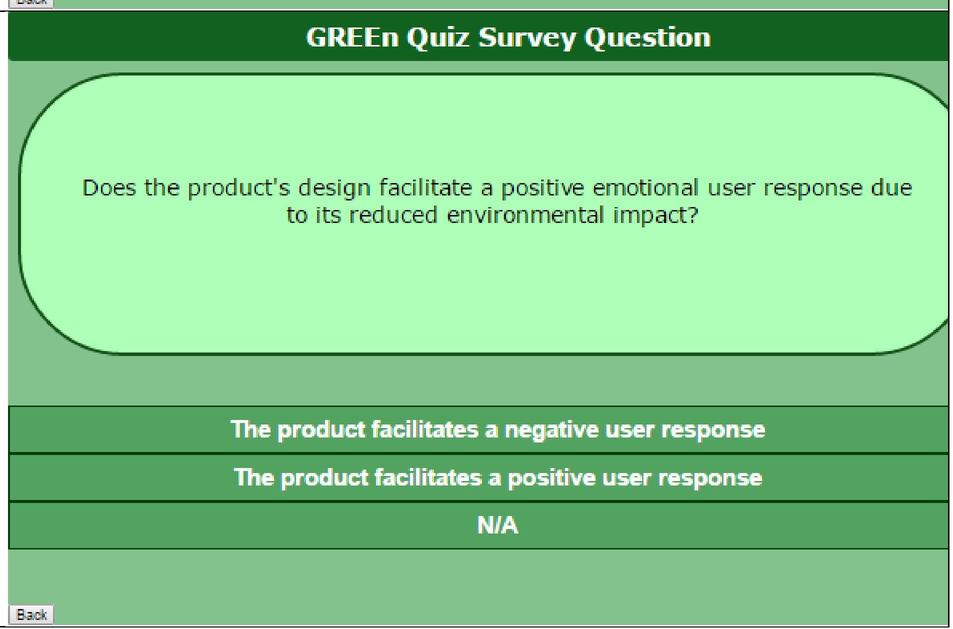
4	 GREEn Quiz Survey Question Will best-in-class, energy efficient components be used? This will reduce the amount of energy used to operate the product. Energy efficient components will not be used A few energy efficient components will be used Some energy efficient components will be used Most components will be energy efficient All possible energy efficient components will be used N/A Back
5	 GREEn Quiz Survey Question Will the product offer improved or similar performance as previous versions of the product or competing products? The product offers less performance as compared to similar products The product offers similar or more performance as compared to similar products N/A Back

6	 GREEn Quiz Survey Question Will recyclable materials be used in the design? This reduces the amount of waste generated at the products end-of-life and/or reduces the resources required to create new material. Recyclable materials will not be used Very few recyclable materials will be used Some recyclable materials will be used Recyclable materials will be used to make most of the product Recyclable material will be used to make the entire product N/A Back
7	 GREEn Quiz Survey Question Will recycled materials be used, to reduce the use of virgin materials? This reduces the resources required to create new material. Recycled materials will not be used Very few recycled materials will be used Some recycled materials will be used Recycled materials will be used to make most of the product Recycled material will be used to make the entire product N/A Back

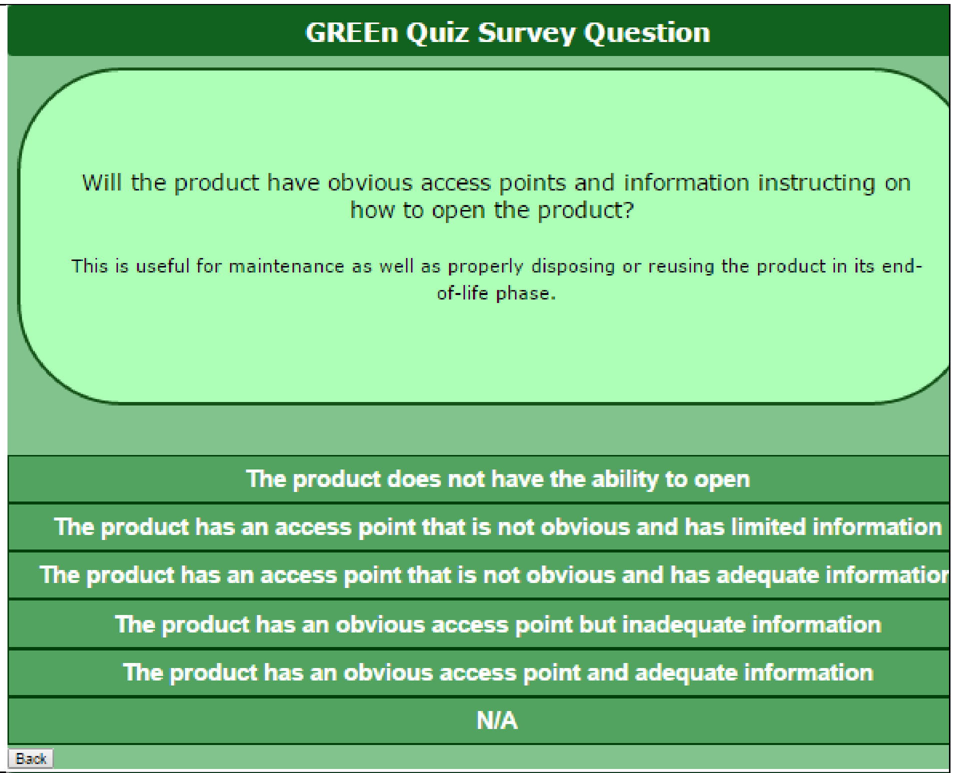
<table>
<tr><td>8</td><td>
</td></tr>
<tr><td>9</td><td>
</td></tr>
</table>

10	**GREEn Quiz Survey Question** Will materials and their respective fasteners be mutually compatible for recycling? Grouping materials so there is less disassembly at the end-of-life phase. Materials and fasteners are not recyclable Limited materials and their fasteners are mutually recyclable Some materials and their fasteners are mutually recyclable Most materials and their fasteners are mutually recyclable All materials and their fasteners are mutually recyclable N/A Back
11	**GREEn Quiz Survey Question** Will the product allow for wear to be detected? This can be useful in pinpointing what parts/components are damaged so they can be replaced instead of the entire product being thrown out. The product will not show wear The product shows wear but this affects the aesthetic appeal The product shows informative wear without affecting the aesthetic appeal N/A Back

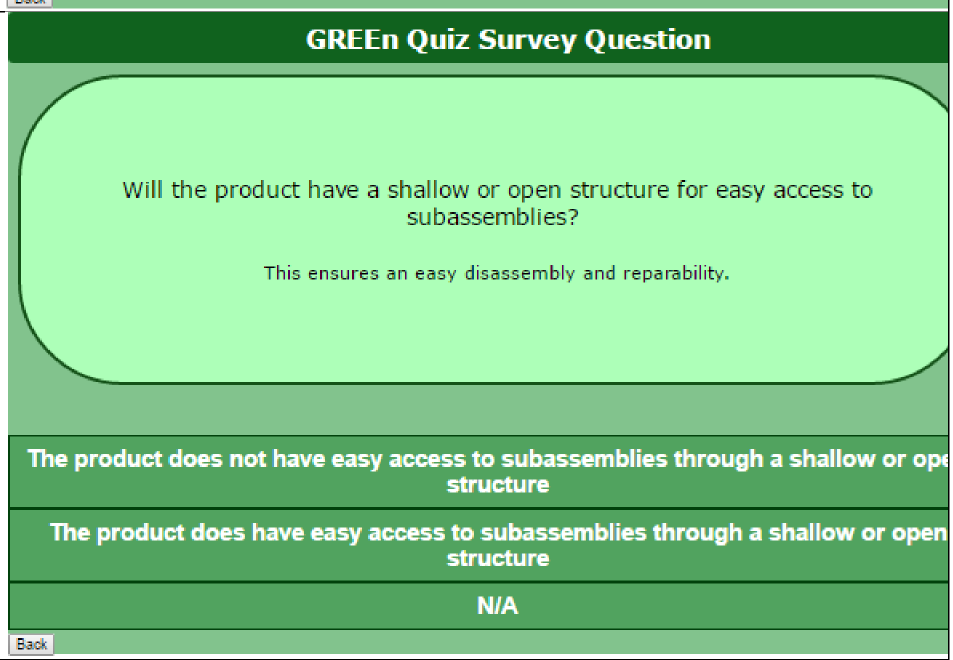
<table>
<tr><td>12</td><td>
</td></tr>
<tr><td>13</td><td>
</td></tr>
</table>

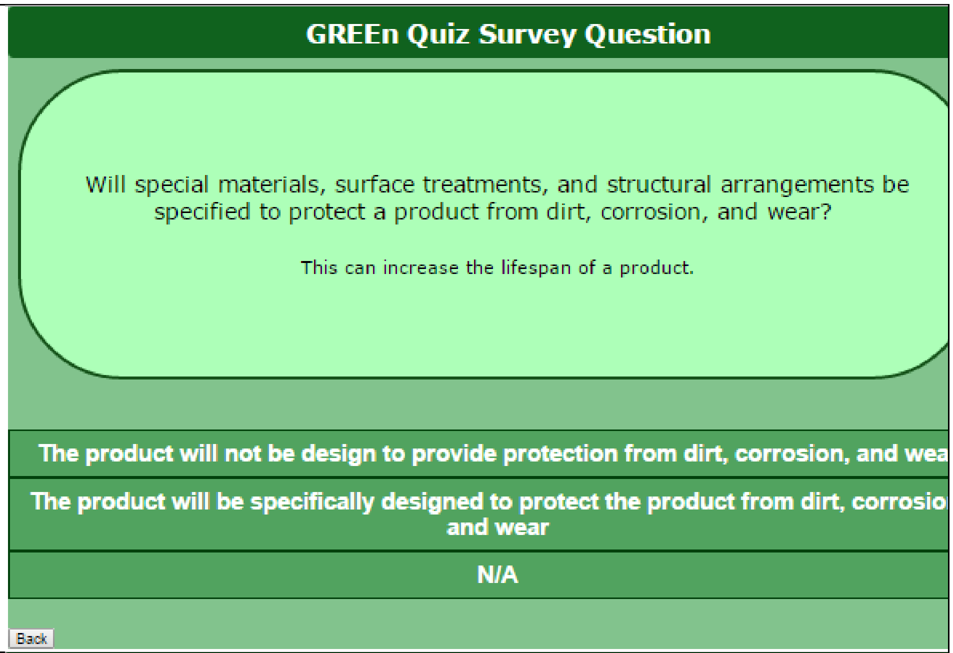
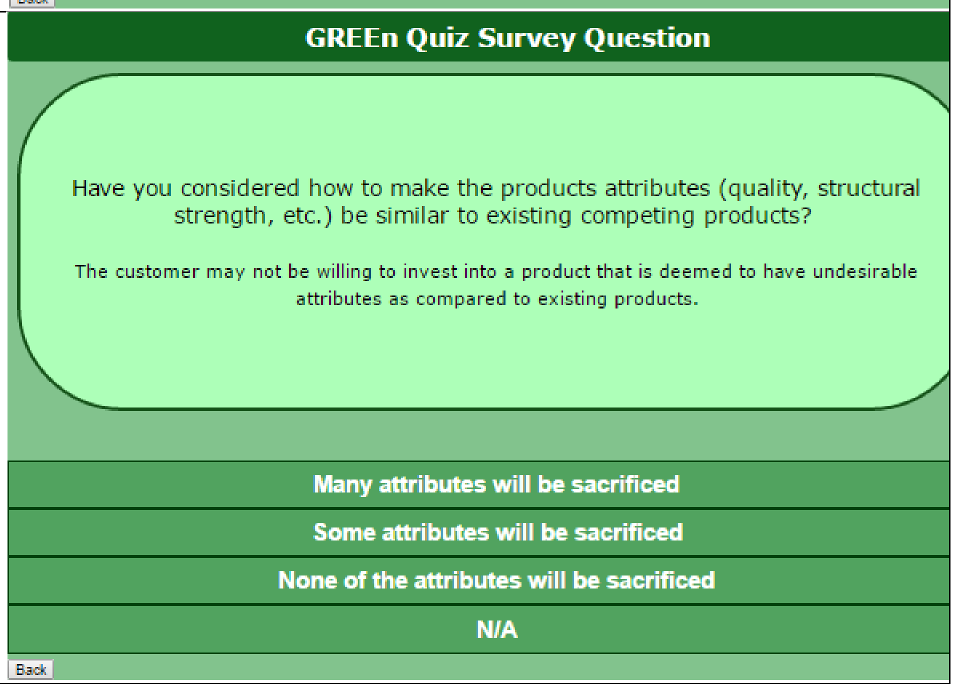
<table>
<tr><td>14</td><td>
</td></tr>
<tr><td>15</td><td>
</td></tr>
</table>

16

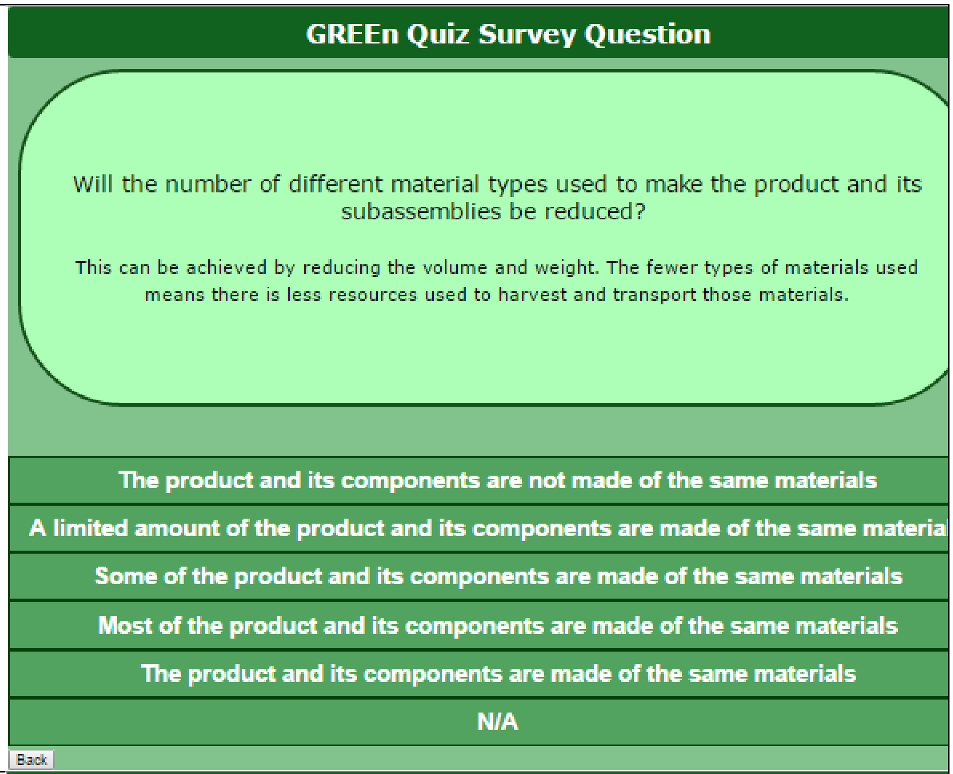

GREEn Quiz Survey Question
Will the product have obvious access points and information instructing on how to open the product?
This is useful for maintenance as well as properly disposing or reusing the product in its end-of-life phase.
The product does not have the ability to open
The product has an access point that is not obvious and has limited information
The product has an access point that is not obvious and has adequate informatior
The product has an obvious access point but inadequate information
The product has an obvious access point and adequate information
N/A
Back

17

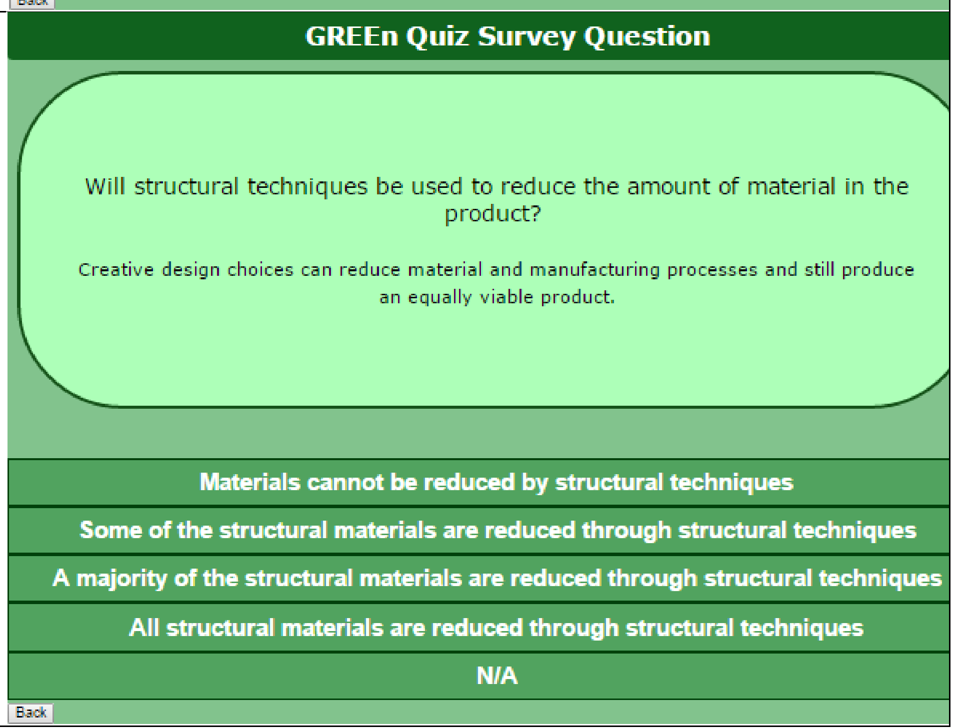

GREEn Quiz Survey Question
Will the product have a shallow or open structure for easy access to subassemblies?
This ensures an easy disassembly and reparability.
The product does not have easy access to subassemblies through a shallow or ope structure
The product does have easy access to subassemblies through a shallow or open structure
N/A
Back

<table>
<tr><td>18</td><td>
</td></tr>
<tr><td>19</td><td>
</td></tr>
</table>

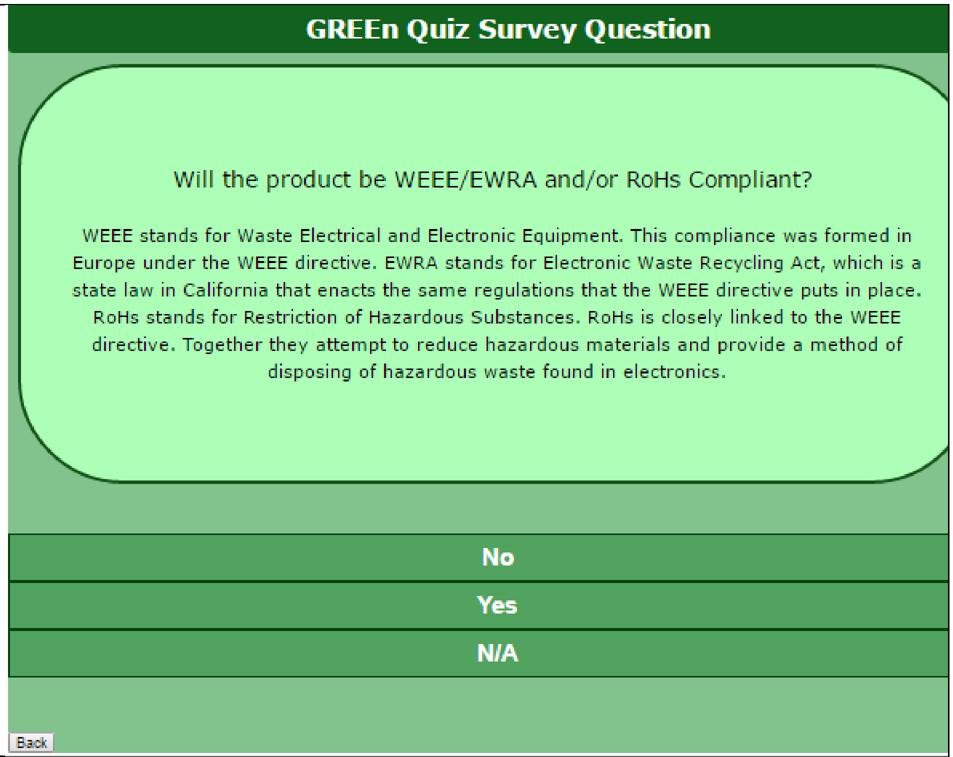
20


GREEn Quiz Survey Question
Will the number of different material types used to make the product and its subassemblies be reduced?
This can be achieved by reducing the volume and weight. The fewer types of materials used means there is less resources used to harvest and transport those materials.
The product and its components are not made of the same materials
A limited amount of the product and its components are made of the same materia
Some of the product and its components are made of the same materials
Most of the product and its components are made of the same materials
The product and its components are made of the same materials
N/A
Back

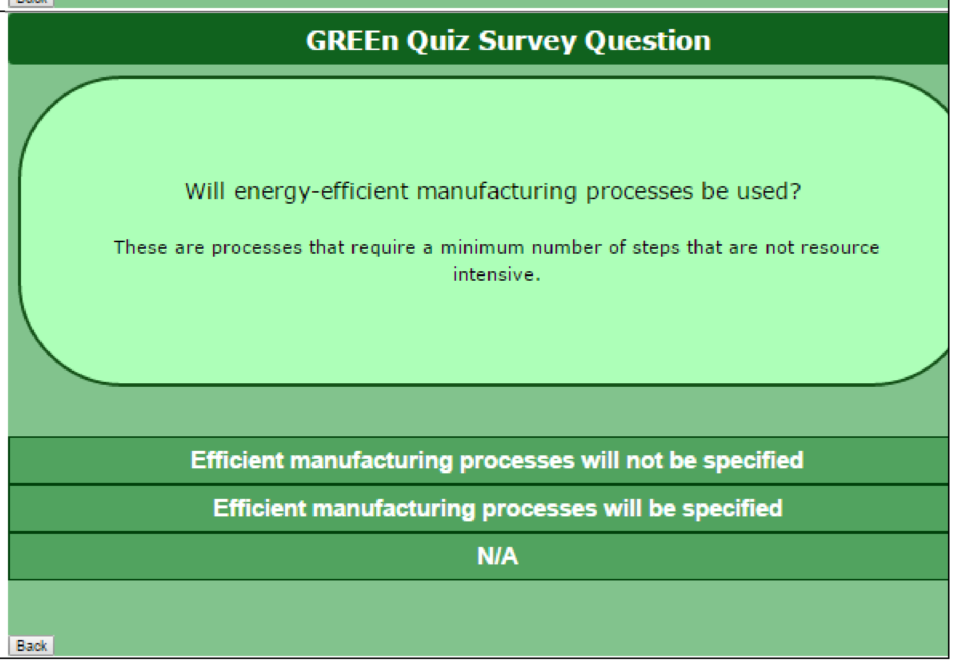
21


GREEn Quiz Survey Question
Will structural techniques be used to reduce the amount of material in the product?
Creative design choices can reduce material and manufacturing processes and still produce an equally viable product.
Materials cannot be reduced by structural techniques
Some of the structural materials are reduced through structural techniques
A majority of the structural materials are reduced through structural techniques
All structural materials are reduced through structural techniques
N/A
Back

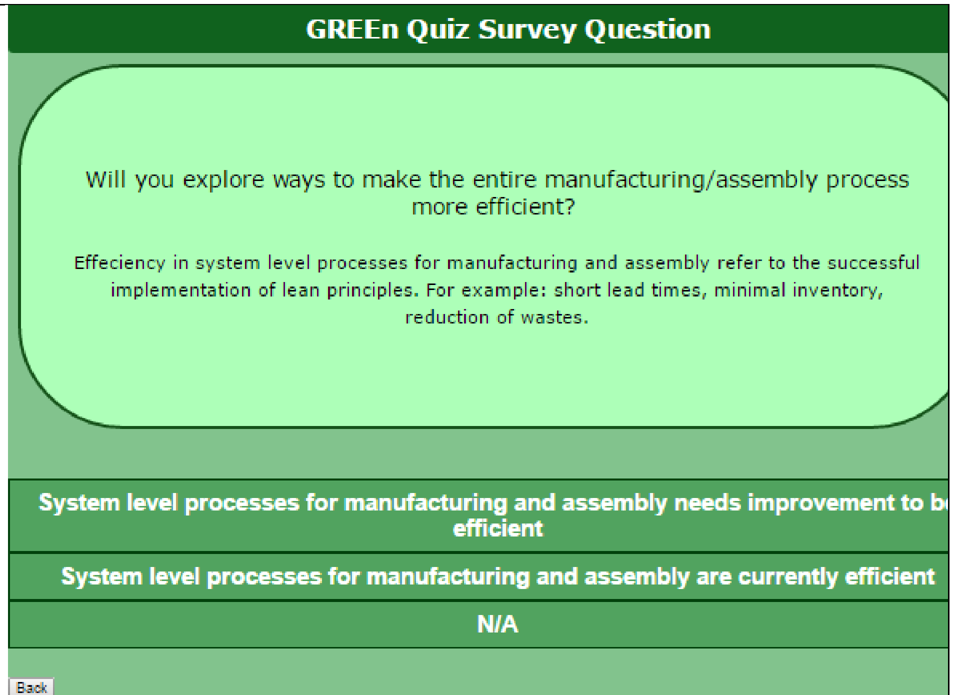
22


GREEn Quiz Survey Question
Will the product be WEEE/EWRA and/or RoHs Compliant?
WEEE stands for Waste Electrical and Electronic Equipment. This compliance was formed in Europe under the WEEE directive. EWRA stands for Electronic Waste Recycling Act, which is a state law in California that enacts the same regulations that the WEEE directive puts in place. RoHs stands for Restriction of Hazardous Substances. RoHs is closely linked to the WEEE directive. Together they attempt to reduce hazardous materials and provide a method of disposing of hazardous waste found in electronics.
No
Yes
N/A
Back

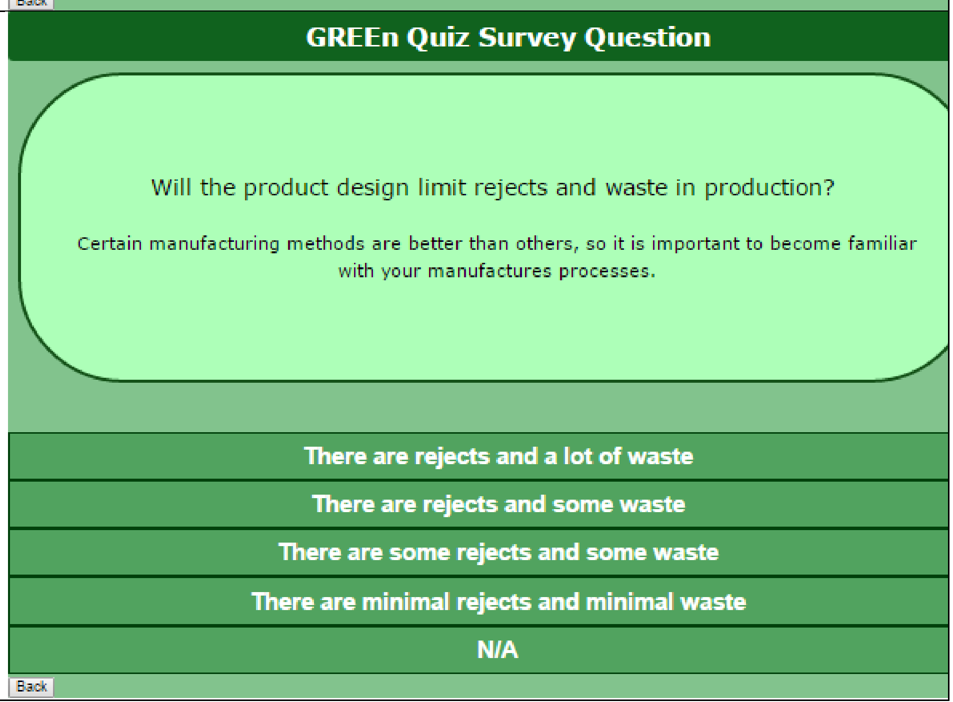
23

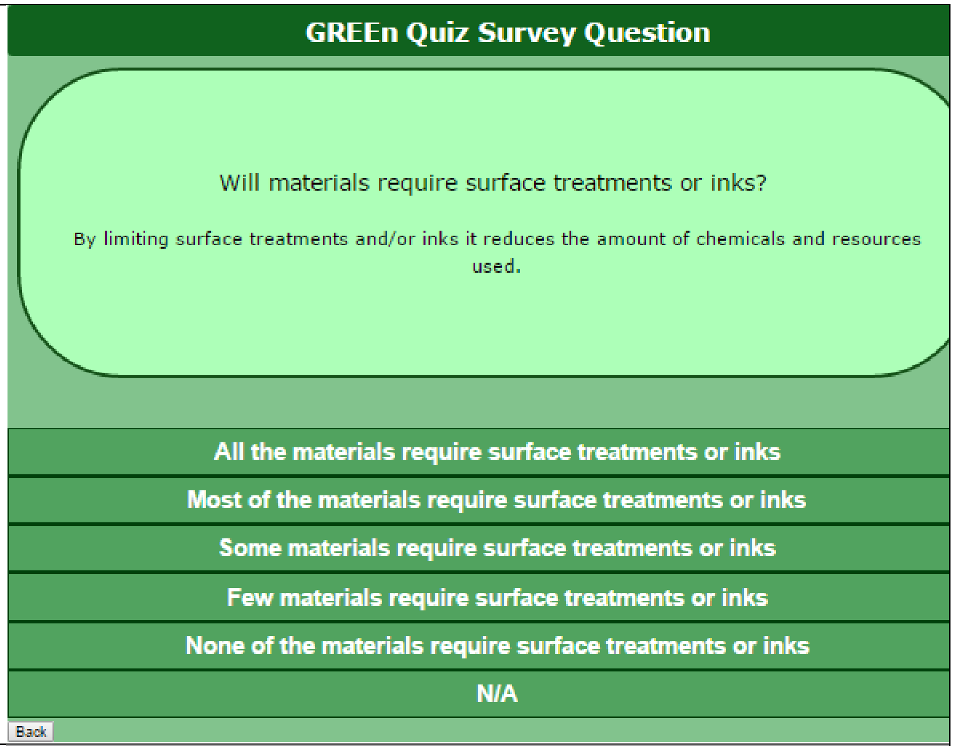
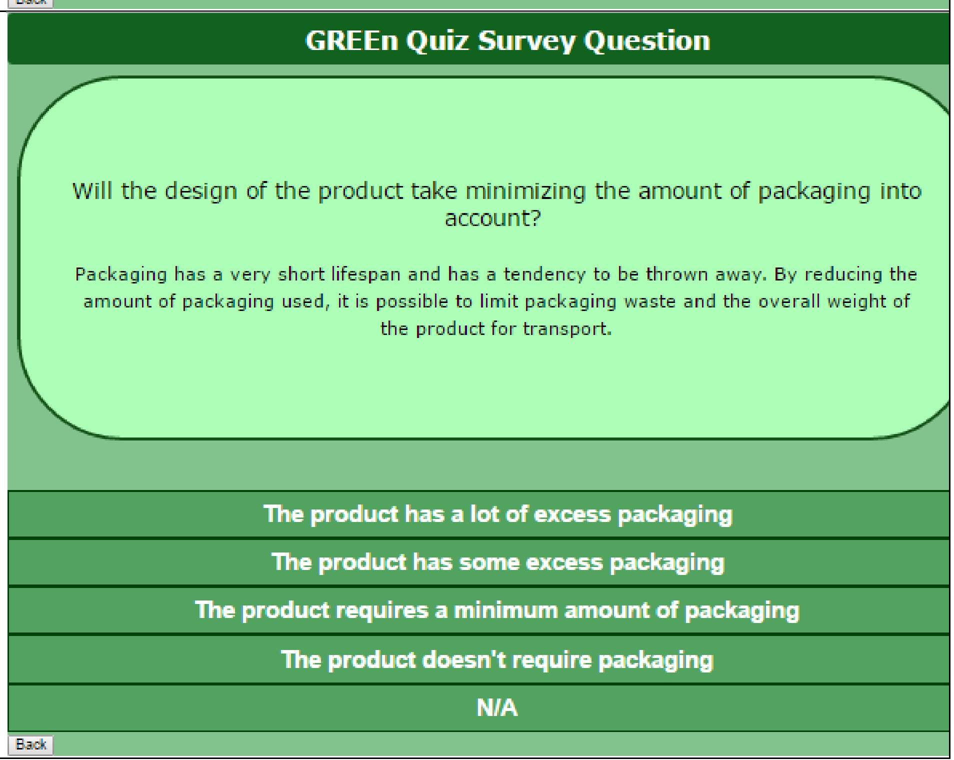

GREEn Quiz Survey Question
Will energy-efficient manufacturing processes be used?
These are processes that require a minimum number of steps that are not resource intensive.
Efficient manufacturing processes will not be specified
Efficient manufacturing processes will be specified
N/A
Back

24


GREEn Quiz Survey Question
Will you explore ways to make the entire manufacturing/assembly process more efficient?
Effeciency in system level processes for manufacturing and assembly refer to the successful implementation of lean principles. For example: short lead times, minimal inventory, reduction of wastes.
System level processes for manufacturing and assembly needs improvement to b efficient
System level processes for manufacturing and assembly are currently efficient
N/A
Back

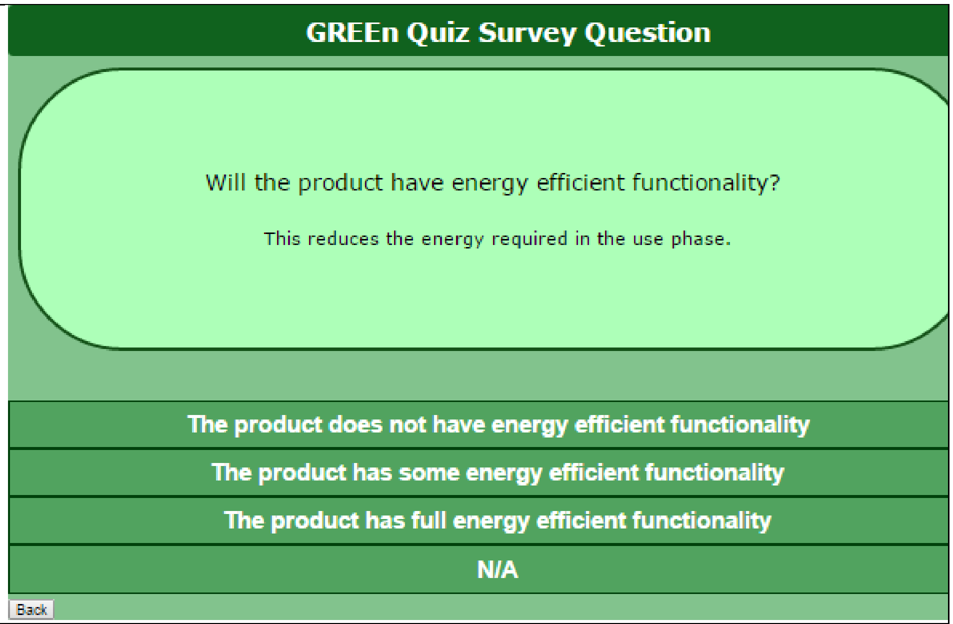
25


GREEn Quiz Survey Question
Will the product design limit rejects and waste in production?
Certain manufacturing methods are better than others, so it is important to become familiar with your manufactures processes.
There are rejects and a lot of waste
There are rejects and some waste
There are some rejects and some waste
There are minimal rejects and minimal waste
N/A
Back

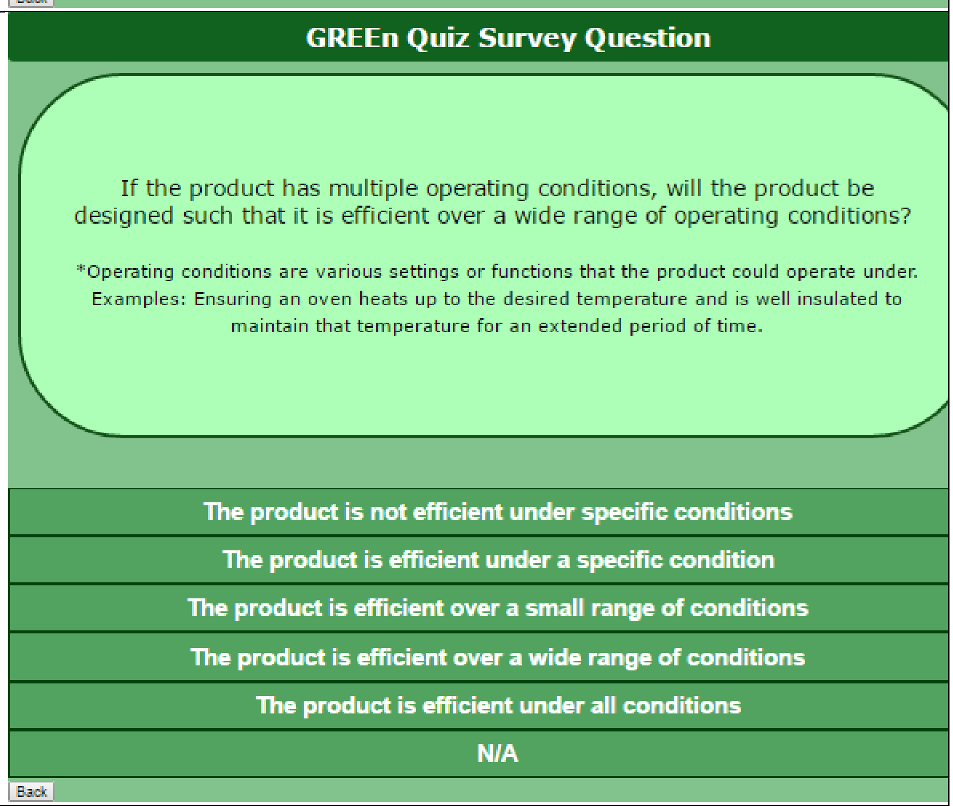
<table>
<tr>
<td>26</td>
<td>
</td>
</tr>
<tr>
<td>27</td>
<td>
</td>
</tr>
</table>

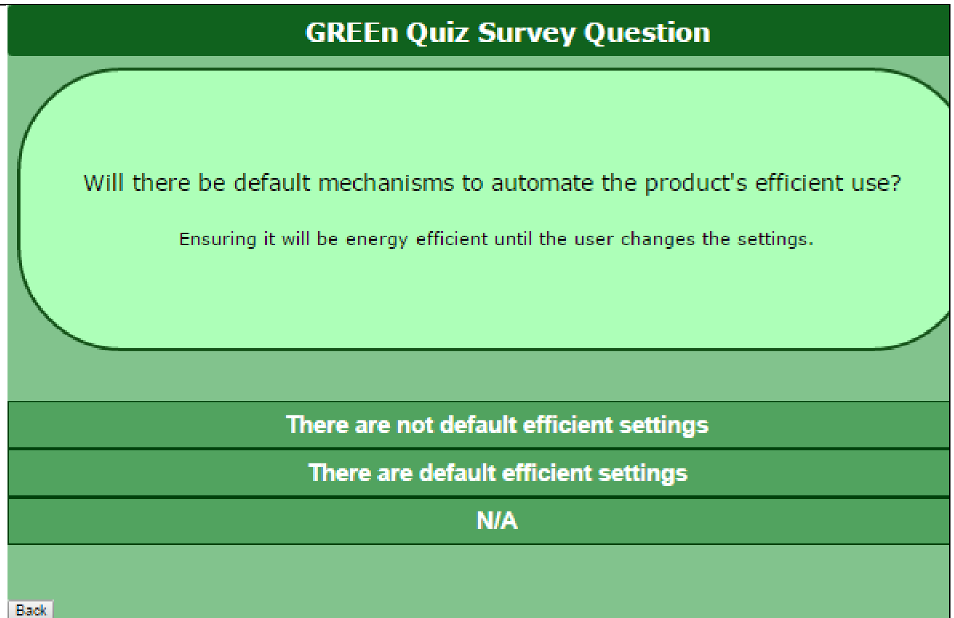
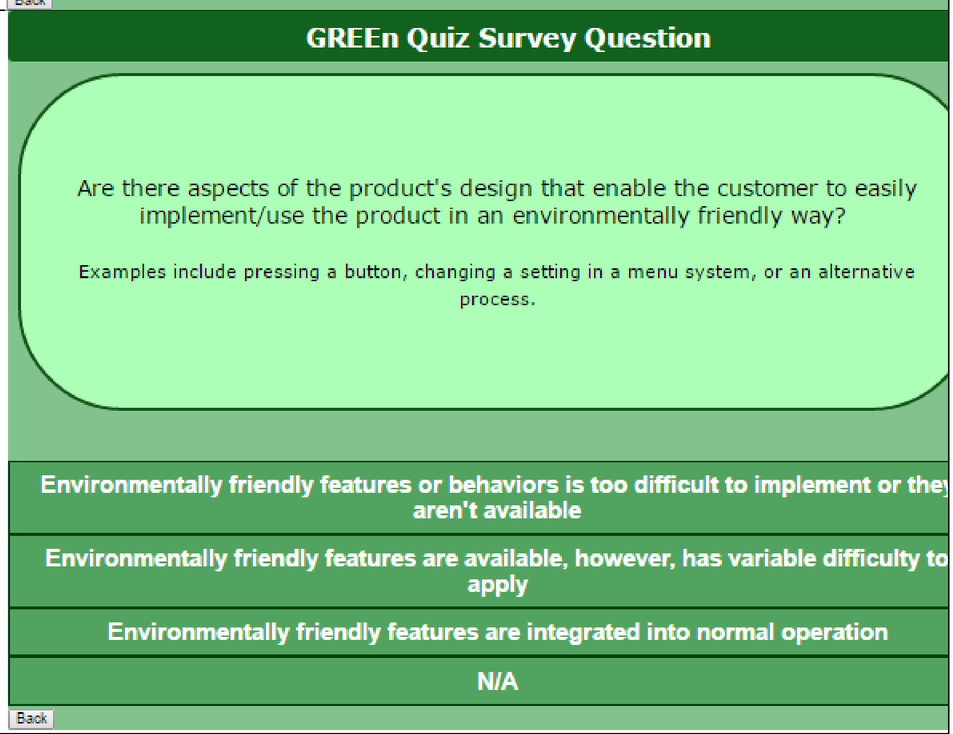
28	**GREEn Quiz Survey Question** Will folding, nesting, or disassembly be used to transport the products (i.e. from the warehouse to distributors/consumers) in a compact state? This can reduce packaging, save cost in fully assembling the product, and reduce the size of the produce for transport. **The product cannot be distributed in parts** **The assembled product is just as compact as being folded or nested** **The product will be folded, nested, or disassembled for distribution** **N/A** Back
29	**GREEn Quiz Survey Question** Will there be preventative design measures that reduce heat and material losses? Are there preventative measures to ensure that possible materials and energy used or in the product are not lost? **There are no fail safes to prevent any loss of materials and/or energy** **There are some fail safes to prevent any loss of materials and/or energy** **There are enough fail safes to prevent any loss of materials and/or energy** **N/A** Back

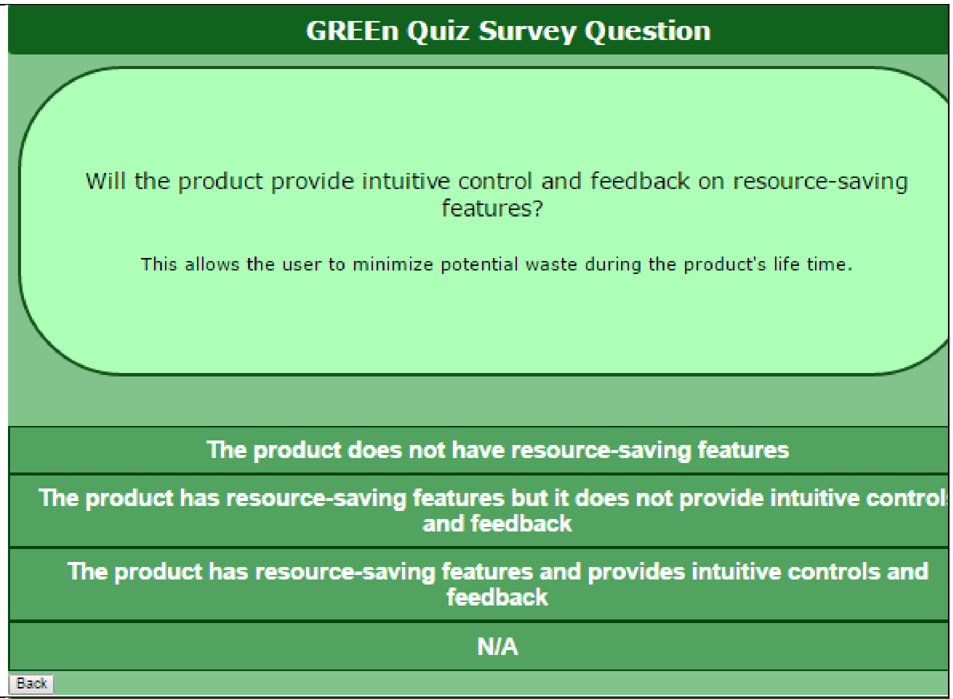
30

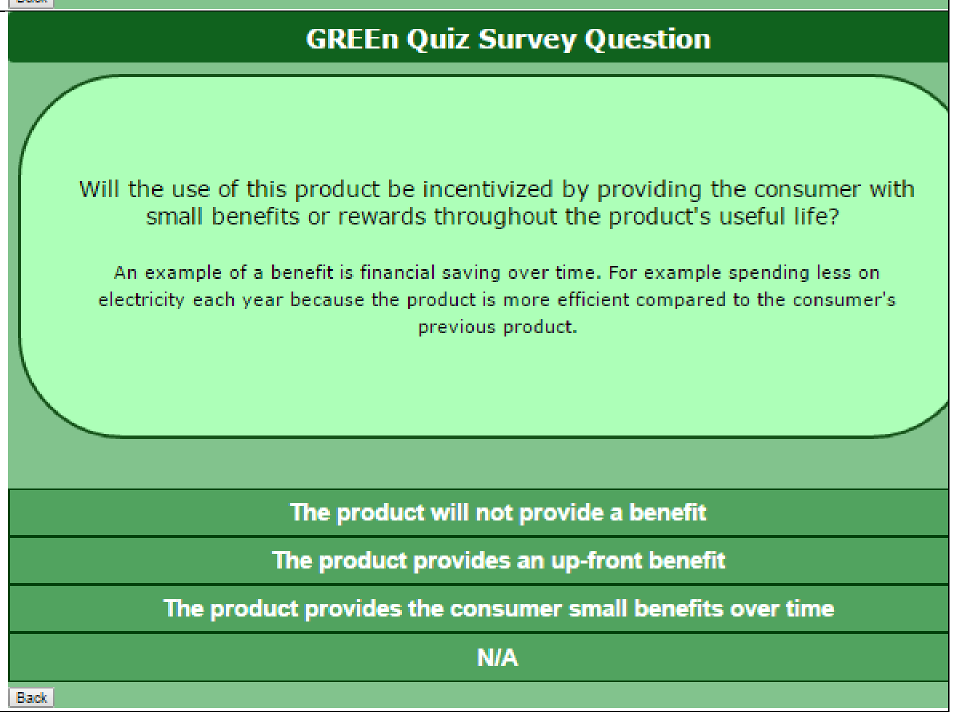

GREEn Quiz Survey Question
Will the product have energy efficient functionality?
This reduces the energy required in the use phase.
The product does not have energy efficient functionality
The product has some energy efficient functionality
The product has full energy efficient functionality
N/A
Back

31

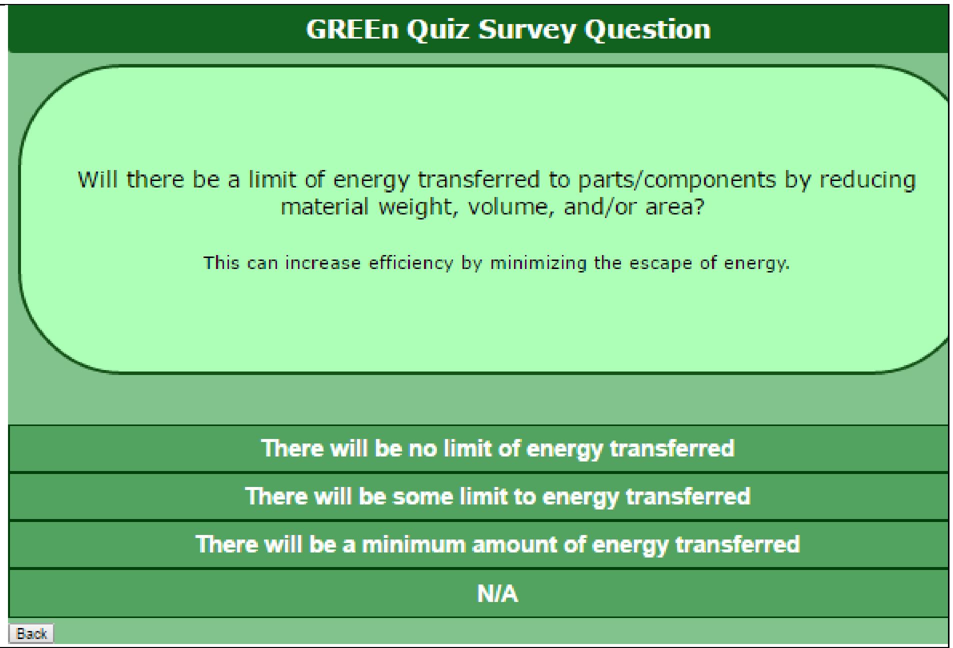

GREEn Quiz Survey Question
If the product has multiple operating conditions, will the product be designed such that it is efficient over a wide range of operating conditions?
*Operating conditions are various settings or functions that the product could operate under. Examples: Ensuring an oven heats up to the desired temperature and is well insulated to maintain that temperature for an extended period of time.
The product is not efficient under specific conditions
The product is efficient under a specific condition
The product is efficient over a small range of conditions
The product is efficient over a wide range of conditions
The product is efficient under all conditions
N/A
Back

32	GREEn Quiz Survey Question Will there be default mechanisms to automate the product's efficient use? Ensuring it will be energy efficient until the user changes the settings. There are not default efficient settings There are default efficient settings N/A Back
33	GREEn Quiz Survey Question Are there aspects of the product's design that enable the customer to easily implement/use the product in an environmentally friendly way? Examples include pressing a button, changing a setting in a menu system, or an alternative process. Environmentally friendly features or behaviors is too difficult to implement or they aren't available Environmentally friendly features are available, however, has variable difficulty to apply Environmentally friendly features are integrated into normal operation N/A Back

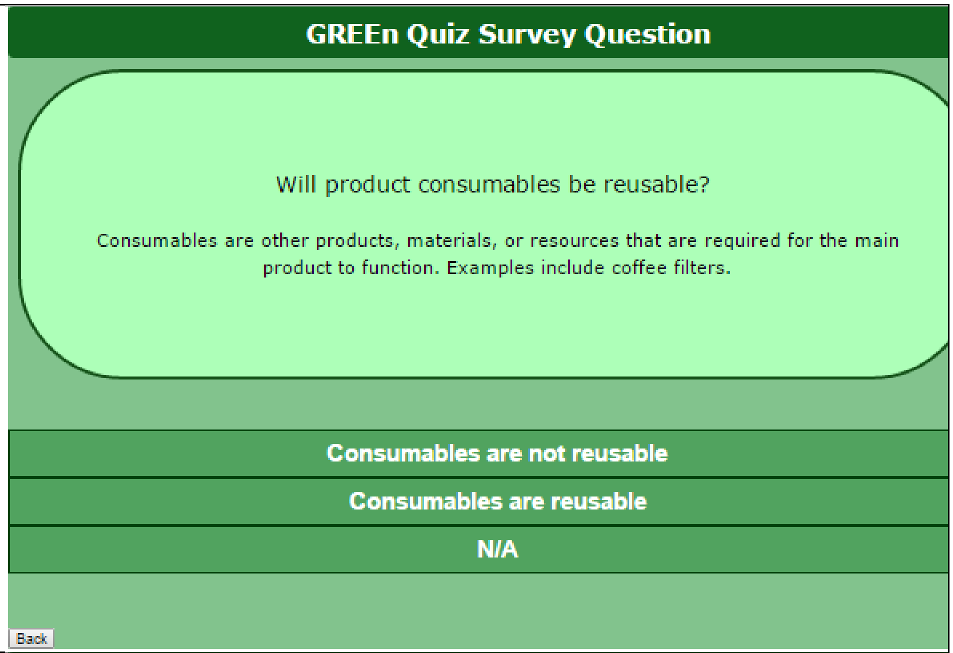
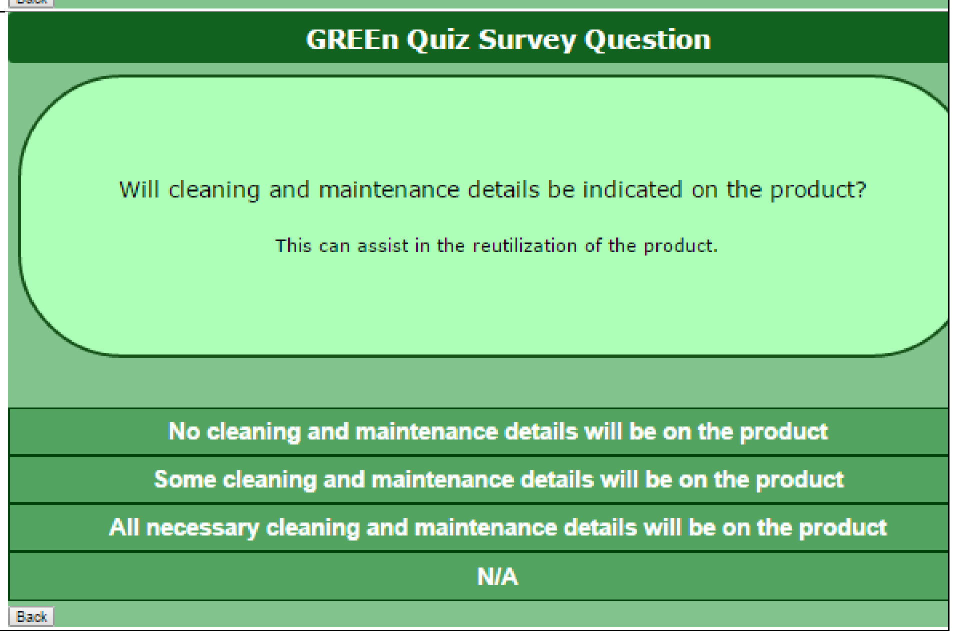
<table>
<tr>
<td>34</td>
<td>


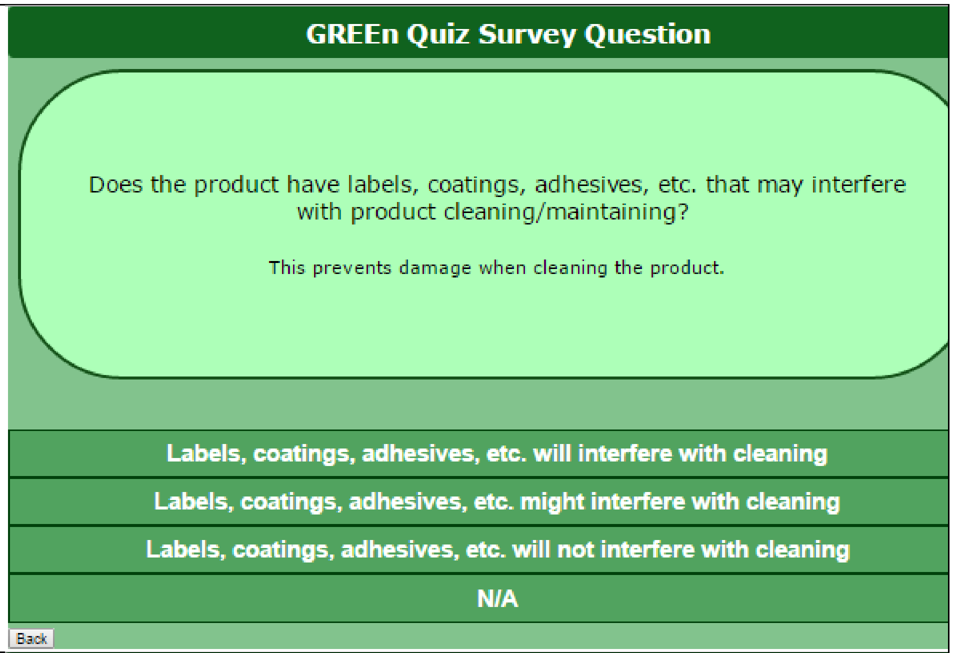
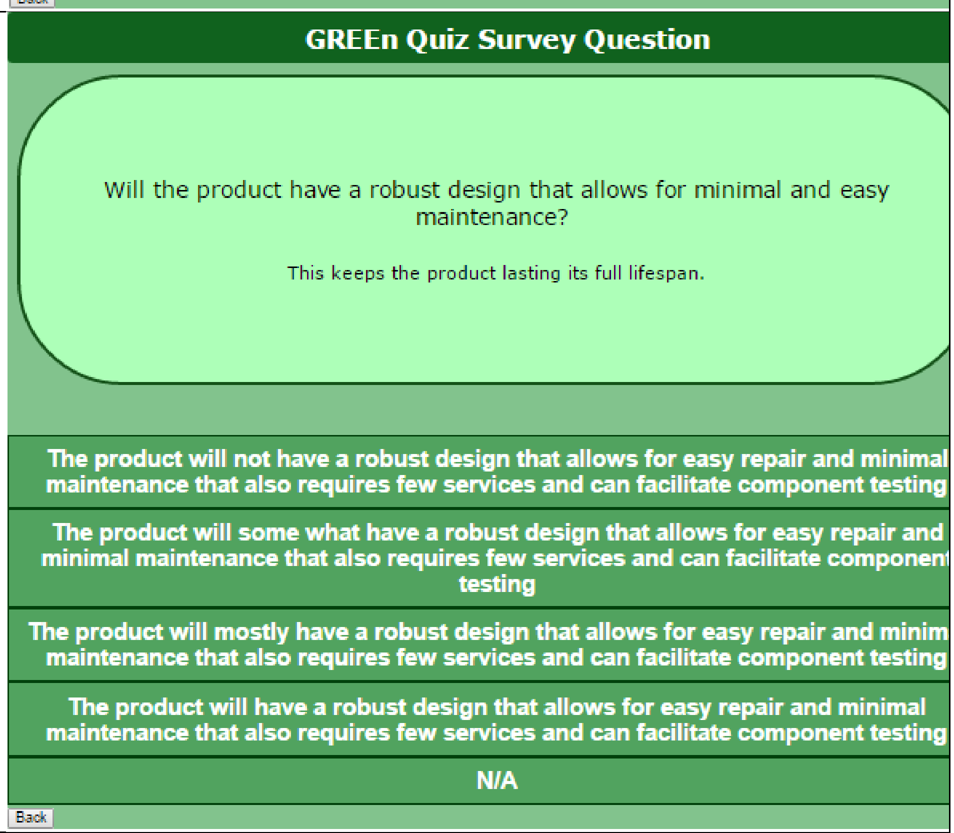
</td>
</tr>
<tr>
<td>35</td>
<td>


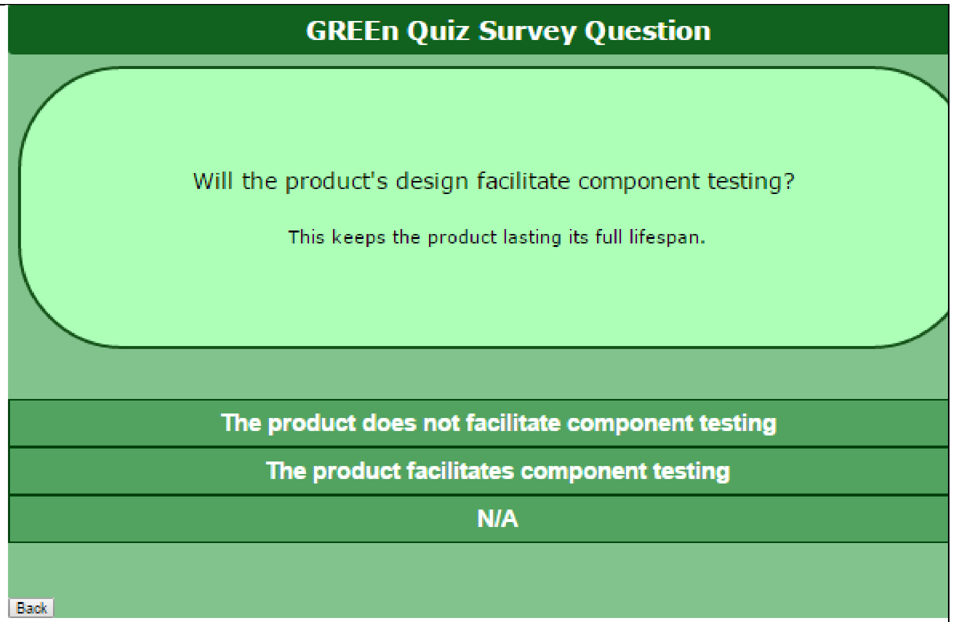
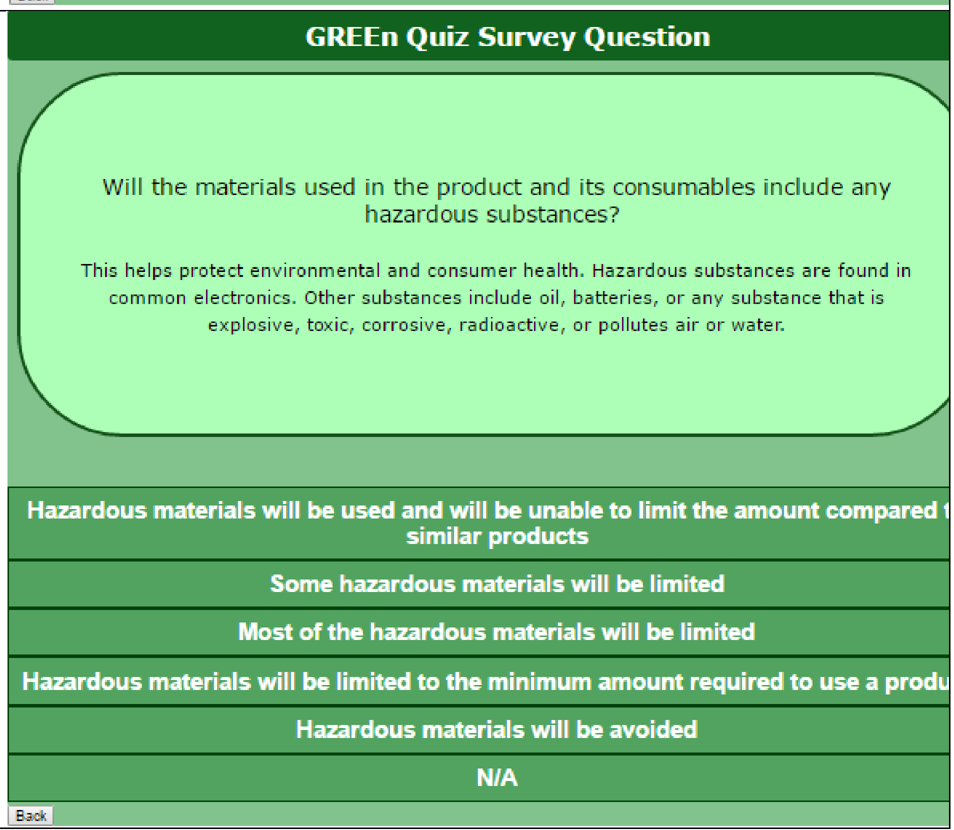
</td>
</tr>
</table>

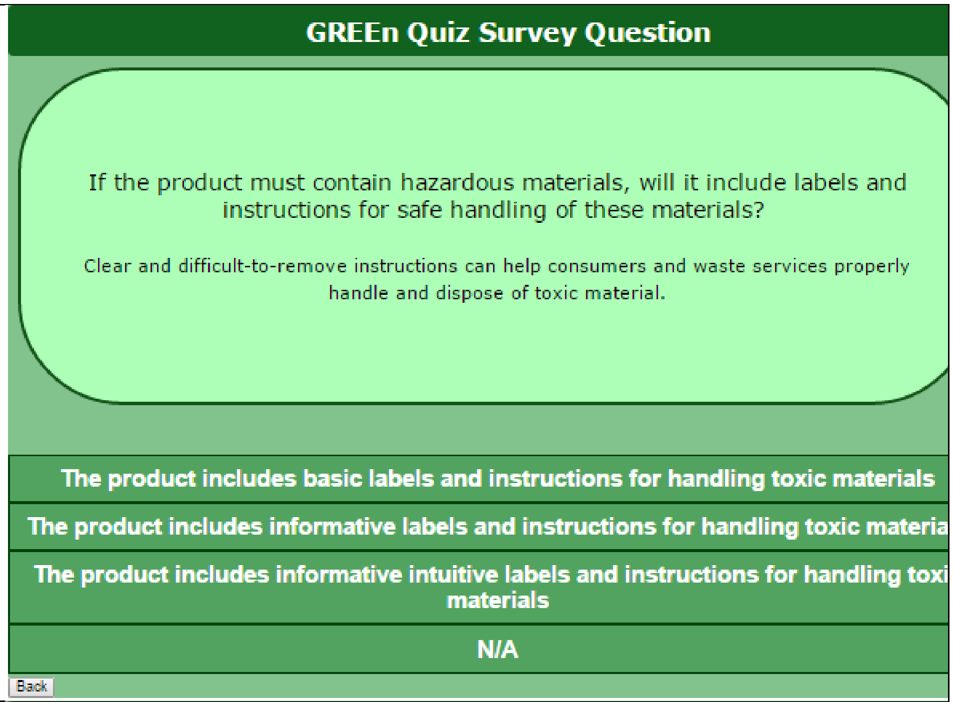
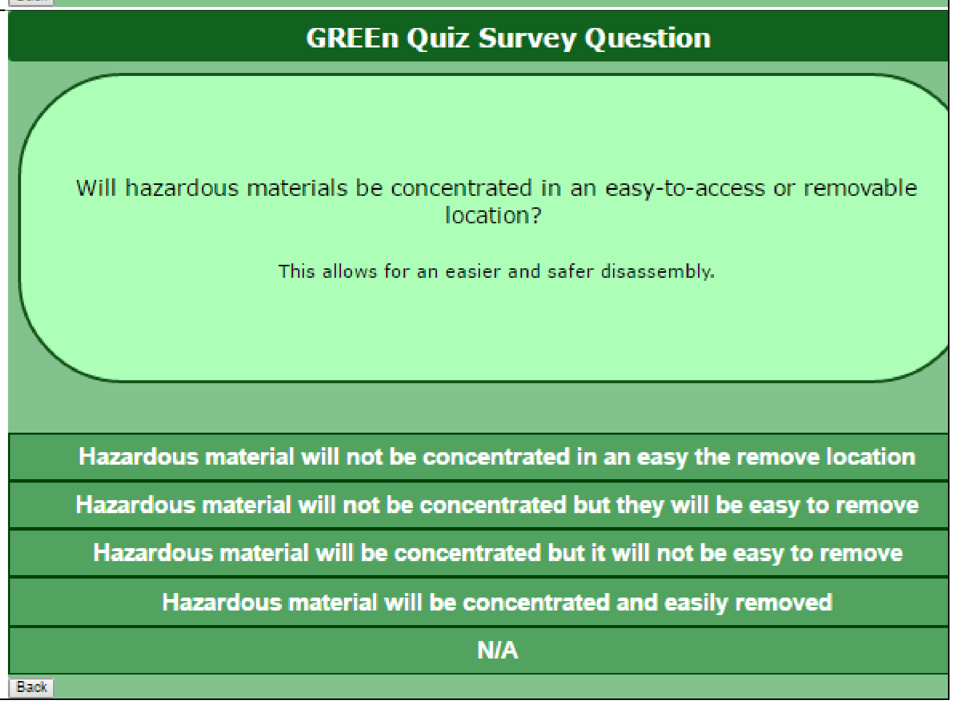
36	GREEn Quiz Survey Question Will there be a limit of energy transferred to parts/components by reducing material weight, volume, and/or area? This can increase efficiency by minimizing the escape of energy. There will be no limit of energy transferred There will be some limit to energy transferred There will be a minimum amount of energy transferred N/A Back
37	GREEn Quiz Survey Question Will the product incorporate features that prevent waste of materials by the user? This will also help keep a product being used as intended. There are no waste prevention features There are some features that help prevent waste The product forces the user to prevent waste N/A Back

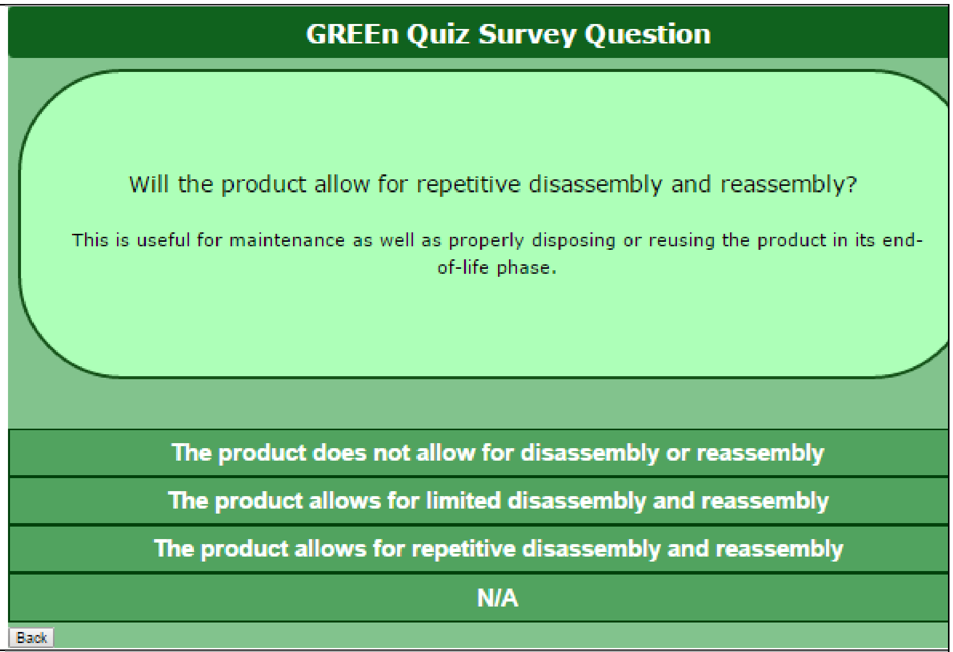
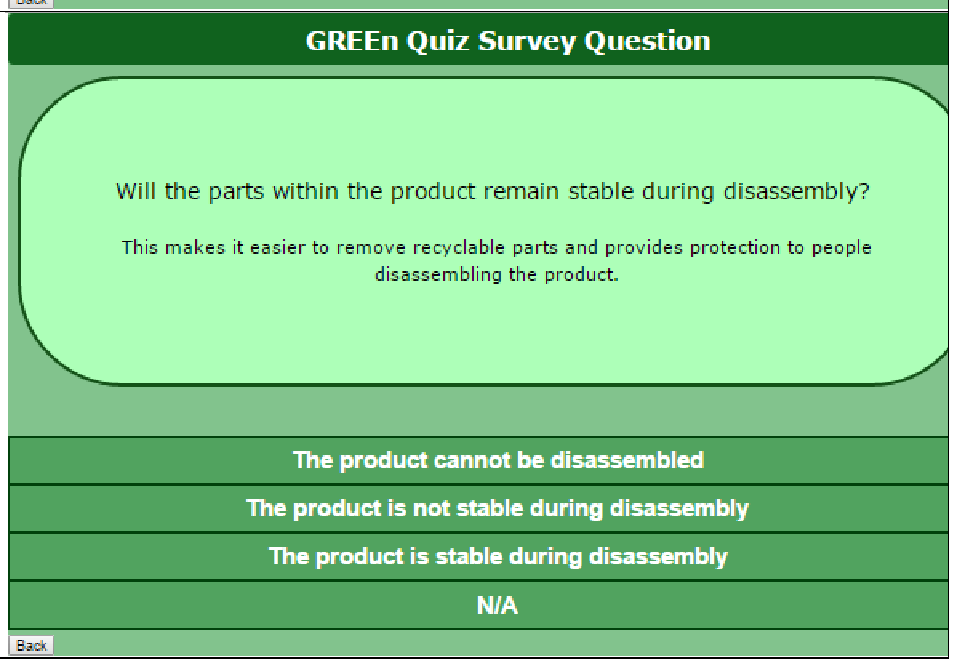
38	**GREEn Quiz Survey Question** Will any potential wastes produced by the product be water-based or biodegradable? This ensures that the wastes the product produces will be able to enter the environment with minimum detrimental effects. **Wastes will not be water-based or biodegradable** **Some waste is biodegradable and/or water-based** **Most waste is biodegradable and/or water-based** **All waste is biodegradable and/or water-based** **There is no waste** **N/A** Back
39	**GREEn Quiz Survey Question** Are the product's consumables designed to be compostable, biodegradable, or recyclable? Compostable means that the materials can biodegrade and bring nutrients to the soil. **Product consumables are designed to be thrown in a landfill** **Product consumables are recyclable** **Product consumables are compostable** **N/A** Back

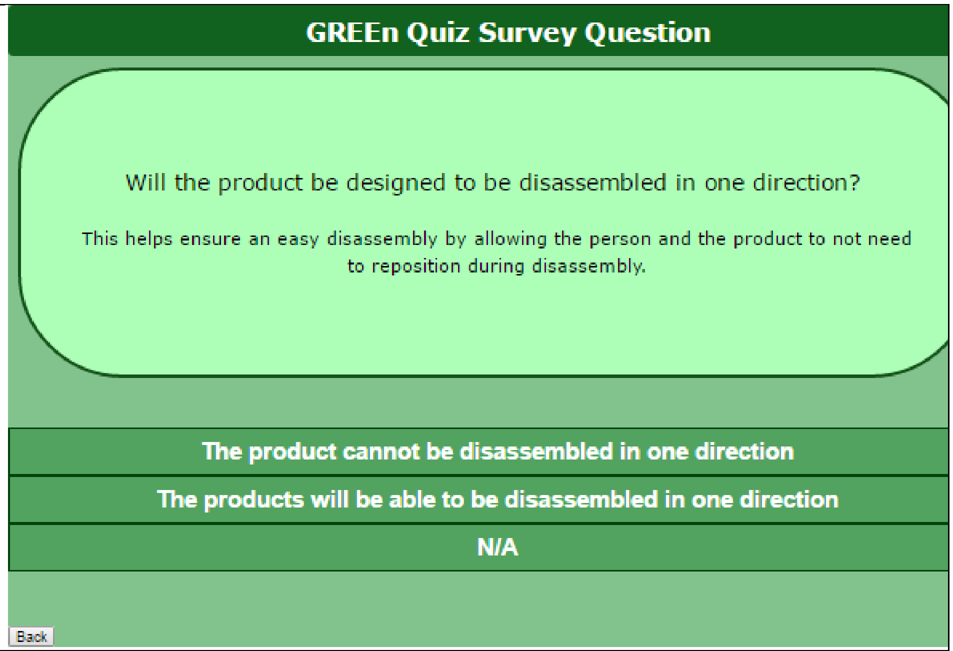
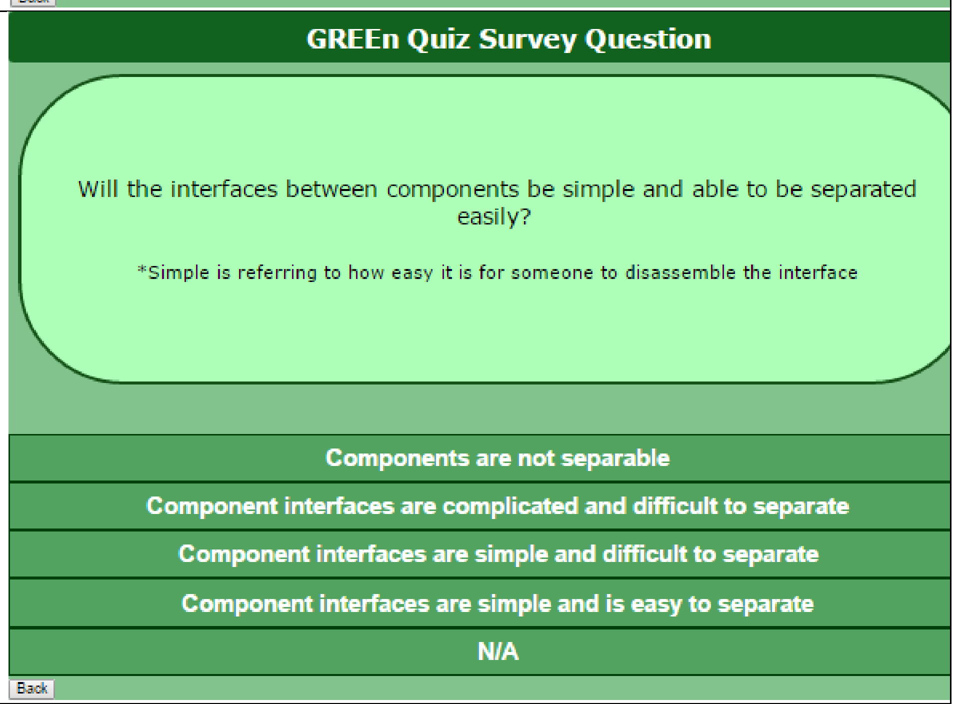
<table>
<tr><td>40</td><td>
</td></tr>
<tr><td>41</td><td>
</td></tr>
</table>

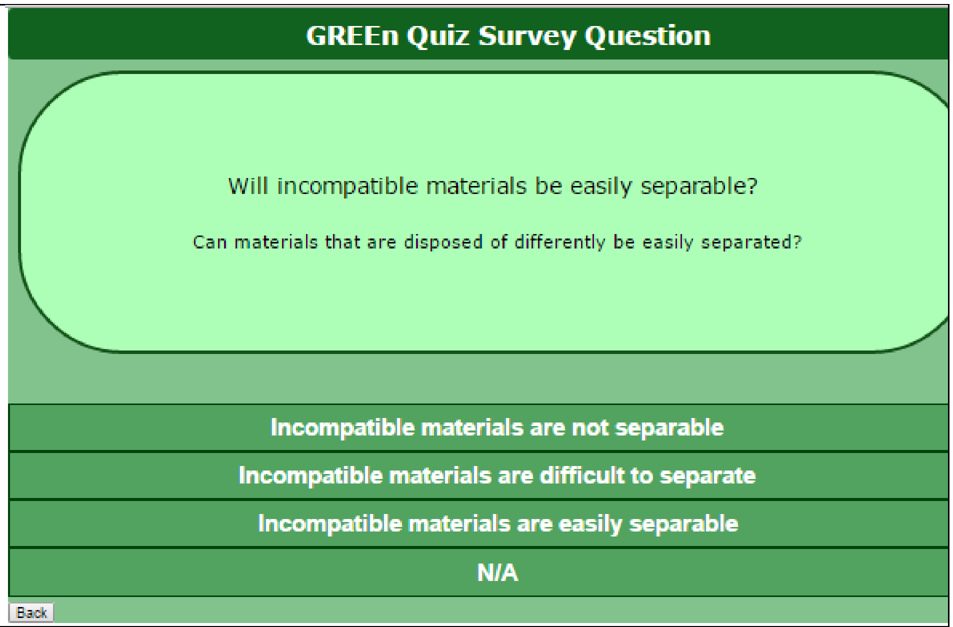
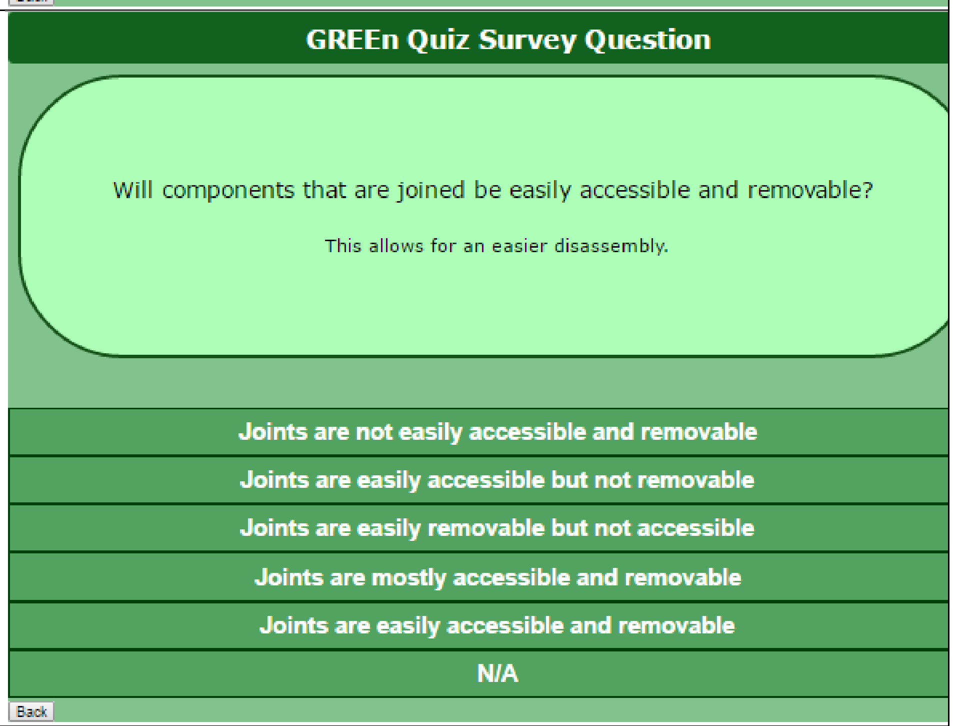
<table>
<tr><td>42</td><td>
</td></tr>
<tr><td>43</td><td>
</td></tr>
</table>

44	GREEn Quiz Survey Question Will the product's design facilitate component testing? This keeps the product lasting its full lifespan. The product does not facilitate component testing The product facilitates component testing N/A Back
45	GREEn Quiz Survey Question Will the materials used in the product and its consumables include any hazardous substances? This helps protect environmental and consumer health. Hazardous substances are found in common electronics. Other substances include oil, batteries, or any substance that is explosive, toxic, corrosive, radioactive, or pollutes air or water. Hazardous materials will be used and will be unable to limit the amount compared similar products Some hazardous materials will be limited Most of the hazardous materials will be limited Hazardous materials will be limited to the minimum amount required to use a Hazardous materials will be avoided N/A Back

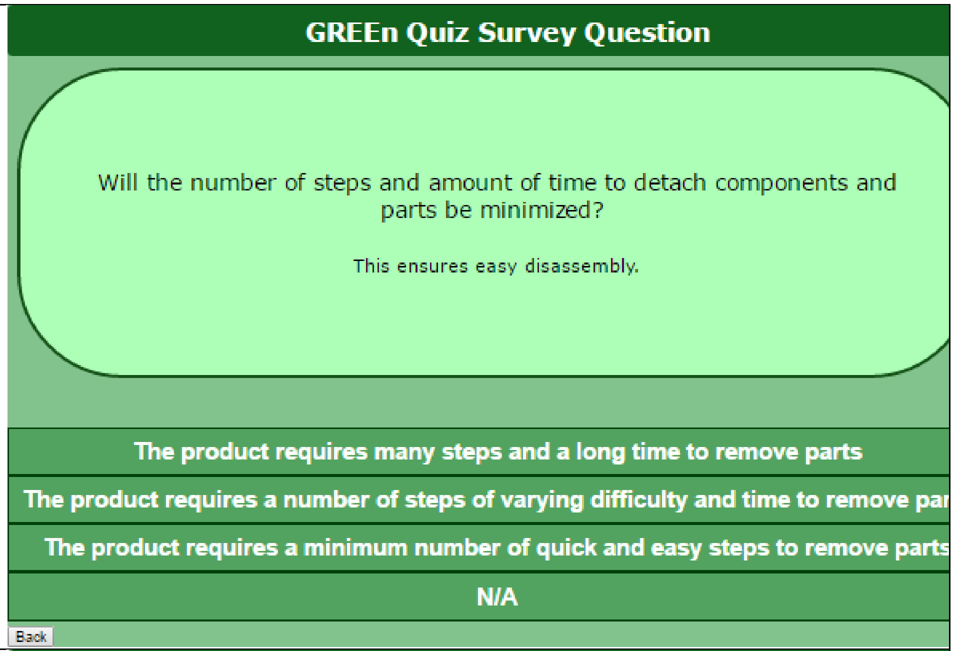
46	GREEn Quiz Survey Question If the product must contain hazardous materials, will it include labels and instructions for safe handling of these materials? Clear and difficult-to-remove instructions can help consumers and waste services properly handle and dispose of toxic material. The product includes basic labels and instructions for handling toxic materials The product includes informative labels and instructions for handling toxic materia The product includes informative intuitive labels and instructions for handling toxi materials N/A Back
47	GREEn Quiz Survey Question Will hazardous materials be concentrated in an easy-to-access or removable location? This allows for an easier and safer disassembly. Hazardous material will not be concentrated in an easy the remove location Hazardous material will not be concentrated but they will be easy to remove Hazardous material will be concentrated but it will not be easy to remove Hazardous material will be concentrated and easily removed N/A Back

<table>
<tr>
<td>48</td>
<td>
</td>
</tr>
<tr>
<td>49</td>
<td>
</td>
</tr>
</table>

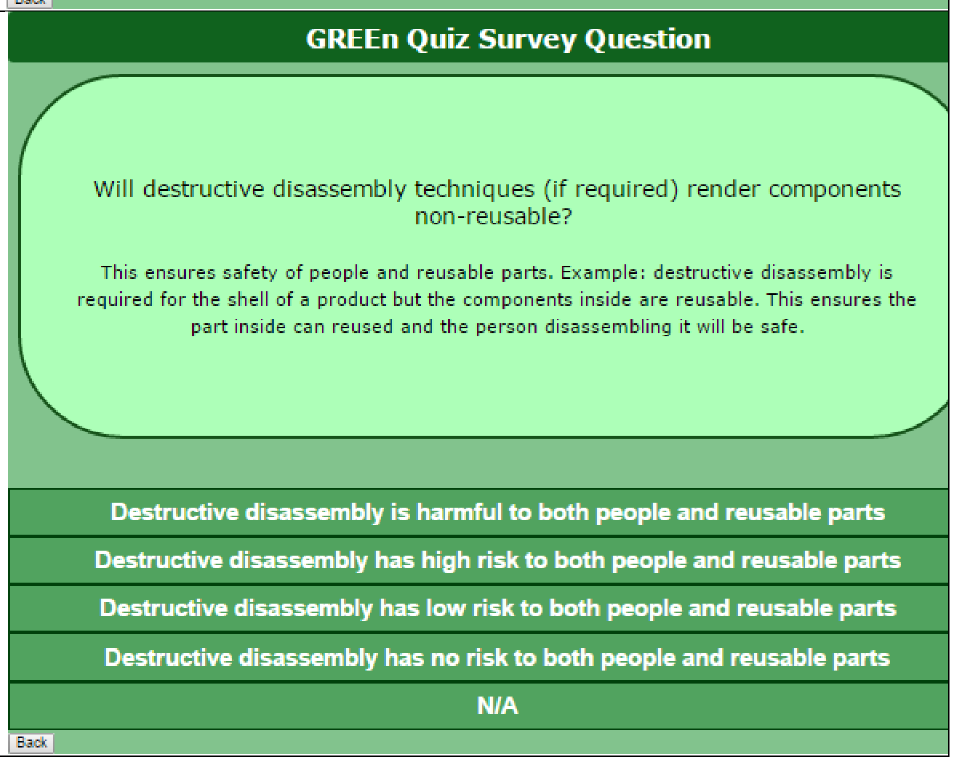
50	 GREEn Quiz Survey Question Will the product be designed to be disassembled in one direction? This helps ensure an easy disassembly by allowing the person and the product to not need to reposition during disassembly. The product cannot be disassembled in one direction The products will be able to be disassembled in one direction N/A Back
51	 GREEn Quiz Survey Question Will the interfaces between components be simple and able to be separated easily? *Simple is referring to how easy it is for someone to disassemble the interface Components are not separable Component interfaces are complicated and difficult to separate Component interfaces are simple and difficult to separate Component interfaces are simple and is easy to separate N/A Back

<table>
<tr><td>52</td><td>
</td></tr>
<tr><td>53</td><td>
</td></tr>
</table>

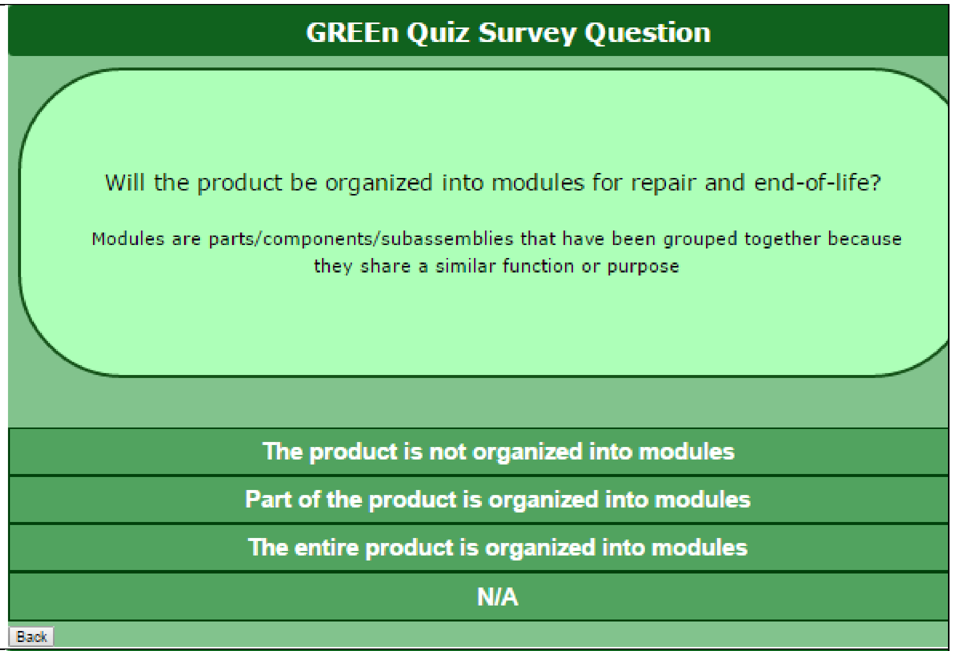
54


GREEn Quiz Survey Question
Will the number of steps and amount of time to detach components and parts be minimized?
This ensures easy disassembly.
The product requires many steps and a long time to remove parts
The product requires a number of steps of varying difficulty and time to remove par
The product requires a minimum number of quick and easy steps to remove parts
N/A
Back

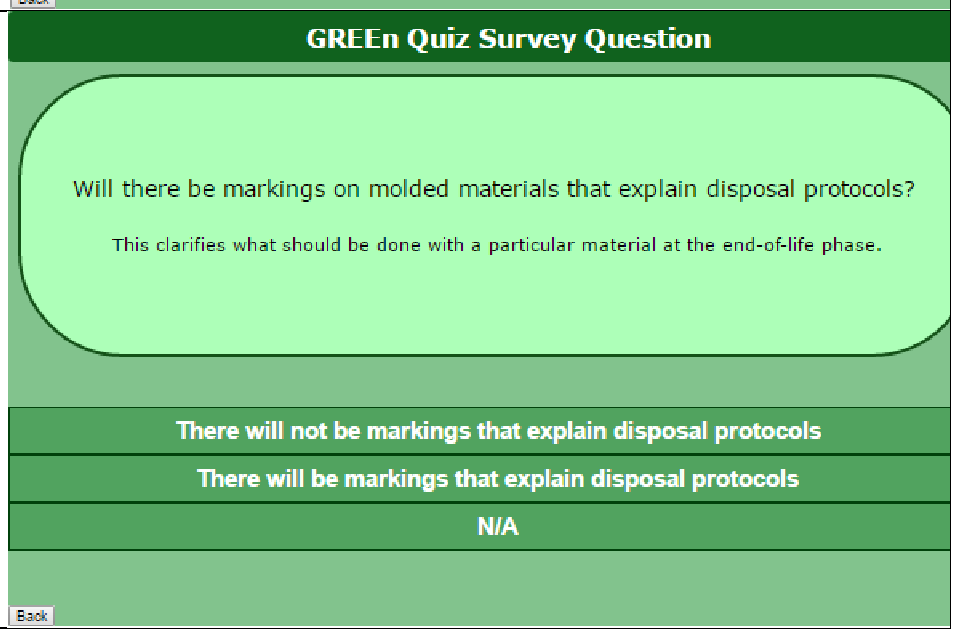
55


GREEn Quiz Survey Question
Will destructive disassembly techniques (if required) render components non-reusable?
This ensures safety of people and reusable parts. Example: destructive disassembly is required for the shell of a product but the components inside are reusable. This ensures the part inside can reused and the person disassembling it will be safe.
Destructive disassembly is harmful to both people and reusable parts
Destructive disassembly has high risk to both people and reusable parts
Destructive disassembly has low risk to both people and reusable parts
Destructive disassembly has no risk to both people and reusable parts
N/A
Back

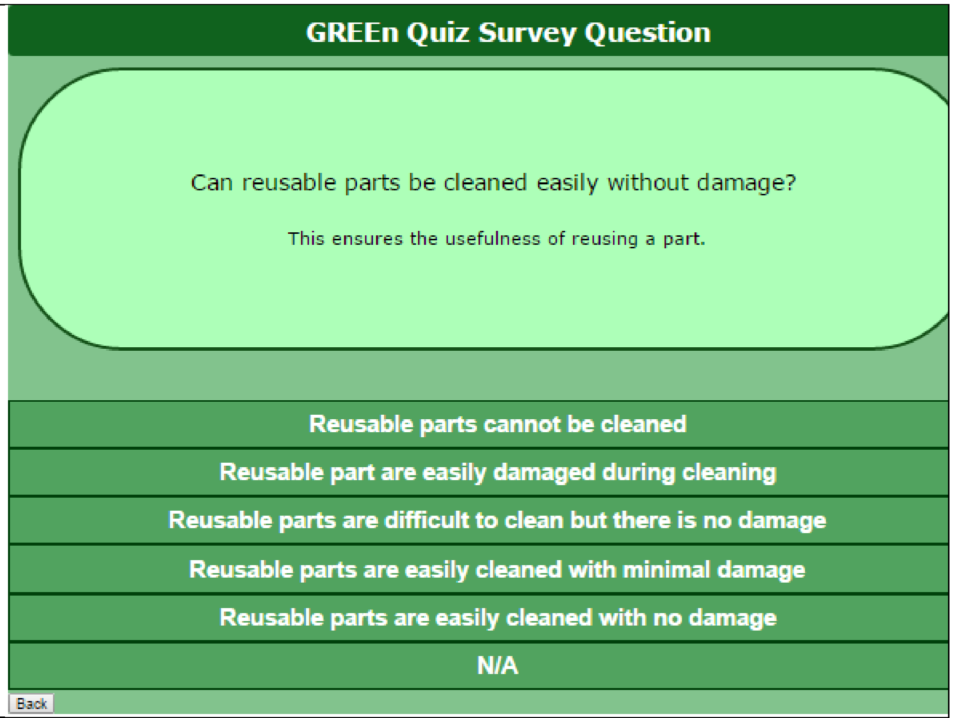
56


GREEn Quiz Survey Question
Will the product be organized into modules for repair and end-of-life?
Modules are parts/components/subassemblies that have been grouped together because they share a similar function or purpose
The product is not organized into modules
Part of the product is organized into modules
The entire product is organized into modules
N/A
Back

57


GREEn Quiz Survey Question
Will there be markings on molded materials that explain disposal protocols?
This clarifies what should be done with a particular material at the end-of-life phase.
There will not be markings that explain disposal protocols
There will be markings that explain disposal protocols
N/A
Back

58	**GREEn Quiz Survey Question** Will the product incorporate reusable/swappable platforms, modules, and components? This can prolong the lifespan of the product as well as add more utility or functionality. **The product does not incorporate any reusable/swappable components** **The product incorporates a minimal amount of reusable/swappable components** **The product incorporates a few reusable/swappable components** **The product incorporates a large amount of reusable/swappable components** **The product will incorporate as many reusable/swappable components as possibl** **N/A** Back
59	**GREEn Quiz Survey Question** Will high-embedded-energy components be able to be reused or reutilized? High-embedded energy components are components that required a lot of energy to produce and by reusing or reutilizing them would prevent new high-embedded energy components from being made. **None of the high-embedded energy components will be reused or reutilized** **Few high-embedded energy components will be reused or reutilized** **Some of the high-embedded energy components will be reused or reutilized** **Most of the high-embedded energy components will be reused or reutilized** **All of the high-embedded energy components will be reused or reutilized** **N/A** Back

60	

GREEn Quiz Survey Question
Can reusable parts be cleaned easily without damage?
This ensures the usefulness of reusing a part.
Reusable parts cannot be cleaned
Reusable part are easily damaged during cleaning
Reusable parts are difficult to clean but there is no damage
Reusable parts are easily cleaned with minimal damage
Reusable parts are easily cleaned with no damage
N/A
Back