Next Generation Protocol:
Innovating a Resilient Future

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Abstract

Conventional practices do not account for product life beyond end-of-sale – these practices are not sustainable. We have developed an end-of-life protocol that includes a metric that we call the Recovery Rating. The objectives of this Next Generation Protocol, beyond supporting the United Nations' Sustainable Development Goals, are to encourage the production of goods designed for recovery and to promote the collaboration between consumers, the public, and the private sector to recover goods at their end-of-life. The Recovery Rating that we propose evaluates and quantifies recovery potential of products. The Recovery Rating, which is normed against embodied energy from the Cambridge Engineering Selector by Granta Design, accounts for different tiers of recovery: product, component, and material, and different recovery methods at each tier and material family. We will present the results of our Next Generation Protocol using three case studies: 1) disposal, single use PET bottle, 2) Nalgene® reusable bottle, and 3) vacuum insulated, reusable metal bottle. The findings indicate the Next Generation Protocol produces a viable Recovery Rating for the material tier. We will also present survey data on potential user reactions to symbolic, numerical, and graphical versions of the Recovery Rating. The Recovery Ratings for the product and component tiers require considerations that have yet to be accounted for, such as number of uses and production/processing methods, which we present for future recommendations.

1. Introduction

The four basic phases of the life cycle include raw material allocation, manufacture, use, and disposal (Figure 1). At each of these phases, resources are invested into processes, such as mining ore, giving a product embodied energy. Thus, embodied energy is accumulated at each stage over a product's life cycle. Waste is also produced as consequences of each of these processes, such as CO2 emissions. With most products going to a landfill at the end of their life, the embodied energy invested in each product is entirely lost. Following this cycle, more resources must be used, in turn generating more waste, each time a new product is made. This paradigm of product life cycles is inherently unsustainable by nature. The Global Footprint Network estimates that it takes the Earth one year and six months to replenish the resources that humanity uses in one year [1]. At this rate, humanity is using renewable resources at a faster rate than they can be replenished, making the current life cycle paradigm unsustainable as defined by Herman Daly.

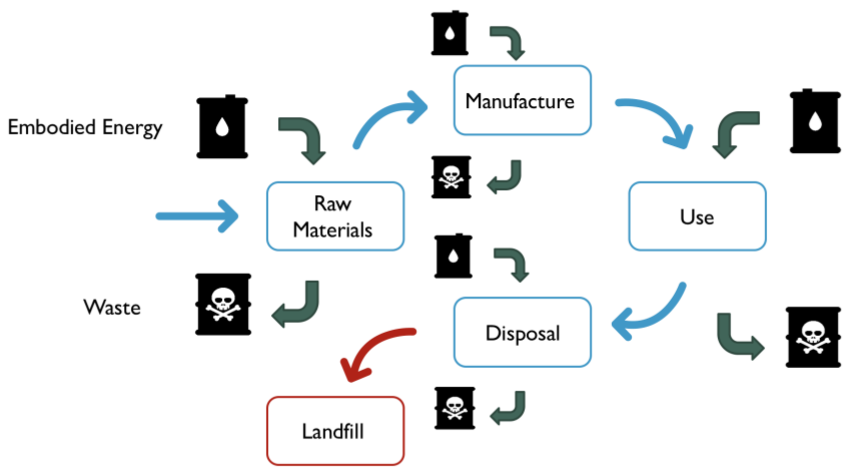

Figure 1: Inputs and outputs are required at each phase of a product's life cycle, perpetually drawing resources from the Earth and generating pollution.

Roland Geyer estimates that 6.3 billion metric tons of plastic waste has been generated between 1950 and 2015 [2]. This number is predicted to grow to 12 billion metric tons by 2050. Disturbingly, this study also estimates that only 9% of plastic has been recycled, and only 12% of plastic has been incinerated to recover any fraction of embodied energy [2]. This leaves over 5 billion metric tons of plastic as waste that cannot be metabolized to non-toxic and/or useful materials.

There are possibilities to shift this paradigm towards a sustainable future. Recycling plays a large role in offsetting resource consumption. The fundamental benefit of recycling is preventing the need to extract raw materials from the Earth. However, while offsetting virgin material streams is an important step towards saving resources, intervening at other phases in a product lifecycle can lead to even greater impacts. Remanufacturing and reusing components, or whole products, can save energy and material waste by extending their individual life cycles [3]. The closer products, components, or materials can be redirected towards re-use, the more embodied energy can be recovered.

Some companies are already aware of the potential benefits and importance of utilizing "extending producer responsibility" (EPR) frameworks and have integrated them into their business models [3]. EPR frameworks, such as buy-back programs, can lead to the reuse, remanufacture, and recycling products back into their business, extending the life of the invested embodied energy. These programs can aid in the shift away from the paradigm of constantly drawing resources by recycling materials and reusing components. Companies like Patagonia and Apple offer programs that incentivize customers to "sell" their used, but functional, products back to these companies in exchange for credit. For the customers, they are monetarily incentivized to steer unused goods away from a landfill towards a second life cycle. For the corporations, they see expense savings as a driver towards sustainable change.

Before suggesting solutions, the most influential players at hand must be identified. By mapping the product life cycle, there are two clear parties that have power over a product's lifetime: Designers and users (Figure 2). Designers include all individuals along the production process from product development to manufacturers. Users refers to customers and general consumers that purchase, use and dispose of products. At the point of sale, the responsibility of a product immediately shifts from the designers to users. In the current paradigm, this suggests that designers do not play a role in the life cycle during use or disposal phases, thus they are not required to think of them [4]. Because of this lack of communication between parties, any attempt by designers to embed sustainable aspects of a product during use or disposal could fail [4]. This division and lack of communication has barred the life cycle from being truly cyclical. Designers and users should work together throughout the entire life cycle, ensuring every product is designed for user-friendliness and to maximize their end of life potential. It is imperative for these entities to collaborate because while this flow of a product's life cycle has thrived for generations, it has also supported a trend of generating waste at an exponential rate.

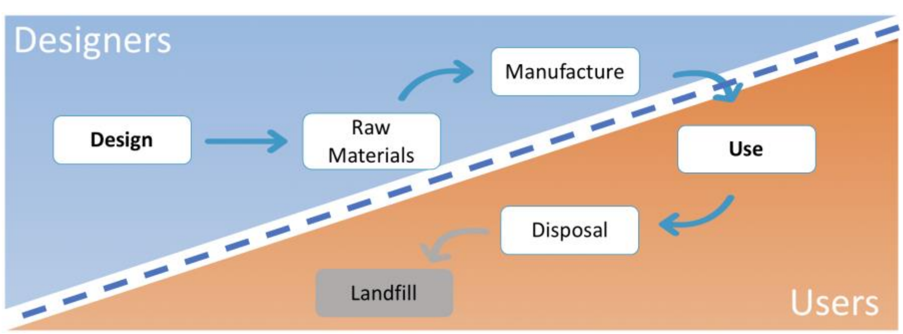

Figure 2: In the current paradigm of product life cycles, designers possess little to no responsibility for products after sale.

After identifying the immediate players, the nested systems were identified (Figure 3). Intuitively, the business system - business models, design cycles, manufacturing processes - have a direct impact on the development and production of products. Additionally, business practices can include the use phase of a product, impacting how individuals use these products. However, most businesses fail to be involved in the disposal part of the life cycle. Instead, disposal methods are nested within public policy. Policy dictates where waste can go, how it is regulated, and what services are available to treat waste. Additionally, policy affects how businesses can operate in their material acquisitions, manufacturing processes, and intended use. In restoring a circular lifecycle, policy can aid in redirecting goods away from landfill. For example, the European Union is currently adhering to the End of Life Vehicle directive, which mandates that 95 wt.% of all qualifying vehicles must be recovered at the end of their life [5]. Finally, the previously mentioned points of intervention are nested within the educational system. The education system includes all methods in which people learn, from formal education to societal and cultural interactions. After breaking down a life cycle and considering the whole system, the team found that education impacts how design is considered, informs the users on the best end of life practices for the products they use, and influences policy makers to develop legislation to strengthen a push towards sustainability. The team identified that the education loop has the strongest influence over all the other present systems because it has the largest potential to leverage long-term change.

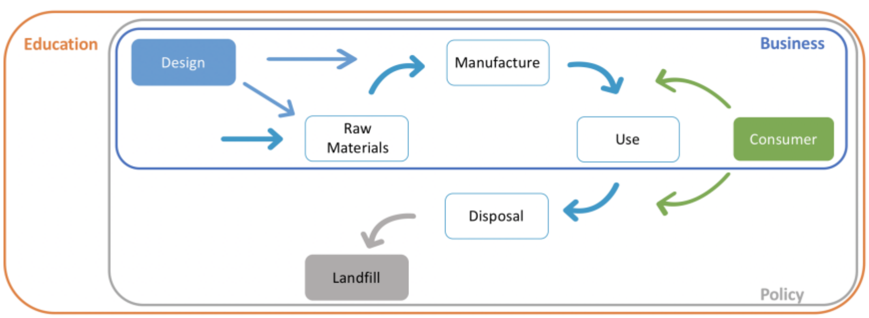

Figure 3: Several systems overlap over a product's lifetime, influencing its development, use, and disposal.

Donella Meadows ranks twelve areas where intervention in a system is possible in decreasing effectiveness [6]. As a solution to intervene in the product life cycle, a protocol and metric have been developed. These are aimed to immediately intervene at three points: changing the structure of information flows, introducing positive feedback loops, and interrupting the structure of material stocks, respectively. The protocol is aimed to educate designers to improve the sustainable design of their products. The metric is meant to be a tool to audit sustainable design, developing a feedback loop for designers to measure improvements. Additionally, the metric informs users about the products they purchase and use. Finally, as recovery rates of materials and components increases with the adoption of this protocol, the flows of virgin material for use should be interrupted with introduction of recycled materials. In the long term, continuous improvement and adoption of a protocol could lead to intervention at more effective points. These long-term changes could include new legislation proposals, or changes in the overall system mindset

The goal of our Next Generation Protocol is to reconnect users and designers over a product cycle. By auditing products for their recoverability, the protocol is aimed to empower users by providing information about the products they purchase and how to dispose of them. For designers, the protocol will serve as an auditing tool providing insight for how products can be changed for improved recoverability. For users, the protocol will inform users how dispose of their products at the end of their lives. With regards to disposing of products, responsibility for users should be emphasized on disposing of products correctly and efficiently. On the other hand, designers should be responsible for using materials and designs that are sustainable and can be recovered.

1.1. Broader Impacts

If a protocol is adopted to intervene over a product's life cycle, several parties can be impacted by its effects. An informational feedback system could be developed for users about the products they use; informing them about the ecological footprint of the product itself and how to sustainably use their products and dispose of them at the end of their current use. Designers will be encouraged to design products more sustainably by designing them to be recovered. These design changes support the development of new economies around recovered and refurbished products. These new economies would have a fundamentally lower environmental impact relative to an economy of extracted raw materials. Waste management facilities will be affected by having to adapt to potentially new recovery and recycling processes. If policymakers see potential from widespread implementation, legislation can be drafted to promote new economies and business models.

1.1.1. Education

In the current education model followed in the United States, engineers are taught following the deterministic approaches to engineering problems, meaning they are taught to solve the problem at hand. This often boils down to receiving problem handouts, following the methods taught by their professors, and crunching numbers until the 'correct' value is found. This method of solving for the correct variables in the desired manner has taught engineers that the final answer is more important than the process. Moreover, that it is more important than the impacts and implications the solution may have. The traditional four-year programs are churning out problem solvers, not the problem definers, the critical thinkers, and engineers with the ability to determine multi-disciplinary solutions that are needed.

The issue with the current educational model extends far beyond engineers. In a perfect world, a focus on sustainability and general care for this planet would be taught at every level in education. Including sustainability in curricula for all ages, instead of just focusing the specific branch of collegiate engineers, would foster a generation of sustainable decision makers. By introducing these subjects at every point in the typical K-12 (and beyond!) educations, the list of environmentally conscious workers would grow from engineers, scientists, and technologists, to including lawyers, politicians, economists, educators and experts in all other fields. It would, ideally, cultivate a new generation ready and able to meet and redefine the goals of sustainable development. The impacts such a generation could have would be massive.

1.1.2 Business

A buzzword and idea that has been popular in the business world is a circular economy. A circular economy is the idea of keeping goods, materials, and resources in use for as long as possible and recovering them at the end of each useful life. A circular economy would change businesses by opening underserved areas like waste management, to more investment, employment, and profit opportunities. This project and its end products will help the business world work towards a truly circular economy. Businesses would have a secure supply chain that they would be invested in for the full life-cycle of a product. As recovered materials could require less processing, businesses could long term save money. Also, by moving towards a truly circular economy, businesses can secure a supply chain that will last for decades.

1.1.3 Design

There are several potential implications for design with the implementation of the Next Generation Protocol. The protocol will serve as an educational tool for designers to inspect and audit their products prior to final production. By following the checklist, designers will gain insight for where their designs enable or prevent recovery at the end of a product's use. Currently, there are countless examples of engineering designs in consumer products that do not allow for recovery at the end of their use. This newly formed information stream could lead to dramatic changes in engineering design that would allow for component or material recovery. Additionally, designers will begin to consider the life of a product after its first use. Considering the next generation of a product will be a reinforcing loop in the effort of changing the paradigm. However, as the protocol itself develops, it may put difficult limitations on designers in the future. For example, polymers occasionally require toxic additives, such as flame retardants, preventing the bulk material from being recyclable. This could lead to unknown consequences; either designers feel unmotivated to make the remaining components recoverable, or they become driven to develop a new design that does not require toxic materials.

1.1.4. Policy

Sustainable development faces a compilation of challenges that multiply with each generation. If the protocol is reinforced and complemented by public policy, then impacts could be made across systems. Public policy can aid the protocol by banning the use of toxic chemicals and materials that inhibit product, component, and material recovery and disassembly. Similarly, law can require newly manufactured products to have a specific amount of the product by mass made from recovered sources. By adopting such policies, people involved in the production of products and users will be given an impetus for sustainable development and responsible end-of-generation treatment. Likewise, public policy could set the legal foundation for a closed-looped supply chain.

2. Literature Review

2.1. Education

The global public has, in recent decades, become more aware of the lack of sustainable consciousness in society. Scholarly interest has sparked around the importance of sustainability in higher education, workforce development, agencies, and government [7], [8], [9], [10]. There are no current specific guidelines for the inclusion of sustainability into education and engineering education, so it varies from institute from institute, leading to an imbalance in education. Some faculty believe that the deterministic approaches to education of the past are sufficient, without including sustainability [11]. Others believe engineering programs require the inclusion of sustainable development into their curriculum, as engineers design, build, plan and construct the world of tomorrow. Engineers are pragmatic and logical, but ethics and morality cannot be lost in their education [12]. Numerous scholars in this emerging field agree, engineering education needs to change to account for ethical and sustainable practices. These scholars from leading liberal arts and research institutions argue that various frameworks for sustainability need to be incorporated into education to produce engineers capable of solving the problems this world currently faces [13].

A group of researchers from Stanford University and Pennsylvania State University created a framework for including sustainability in education. These researches defined five meta-competencies to be implemented in engineering programs—systems thinking, temporal thinking, interpersonal literacy, ethical literacy and creativity/imagination [17].The authors did not include what they call ‘foundational competencies’ in the meta-competencies, as they are already embedded in typical engineering educations [17]. The inclusion of meta-competencies in education develops a common ground for discourse, discussion and responsible decision making for sustainable development within organizations.

Another criterion set to guide engineering activity was published through the University of Cambridge which outlined eight topics which must be addressed to receive a well-rounded, sustainably focused engineering education.[1] This research found that an expanded framework, including sustainability as a core subject, leads students towards finding solutions for real world problems [14].

A study done by the Department of Petroleum and Chemical Engineering, Sultan Qaboos University, found that sustainable development in education would lead to solutions for tangible issues such as minimizing resource depletion and environmental impact [12]. The studies found that stand-alone courses that educate on the historical and societal evolutions of sustainable development must be included for young engineers to fully understand the concept. Sustainability must be embedded in upper-division engineering courses, so as it is continuously developed throughout the education.

There is a continually growing understanding that sustainability must be included in modern engineering curriculum to best prepare engineers to be effective in their careers. Both the Association for the Advancement of Sustainability in Higher Education (AASHE) and the Accreditation Board of Engineering Training (ABET) are beginning to include sustainability in their curriculum requirements, pushing more programs towards sustainable development. The inclusion of sustainability frameworks in curriculum is a high leverage point to catalyze change in education. Continuing research into these areas of study is vital for the development of sustainably driven problem definers and solvers [12]. Incorporating sustainability directly into an engineering curriculum would further educate future designers, manufacturers and user on how their designs and products interact with and affect this planet.

2.2. Business

Business and trade has been vital to the development of our society and will remain important for humans. Sustainable development is needed to secure a future for coming generations and for ecosystems that have been damaged by human interaction. Therefore, business will play an integral role in the building of a sustainable society.
For global business to move towards a sustainable future, there will have to be many

[1] These included ethical foundation, justice through participation, efficient coordinated infrastructures, maintenance of natural capital, holistic financial accountability, systems context, interlinking scales, and future vision.

changes. One necessary shift is that business and sustainability are commonly seen as opponents but must be viewed as working together if for a truly sustainable economic future [15]. Some describe this as the "business case" for sustainability, which is the idea that environmental and social conscious operational changes lead to greater financial success [16]. Unfortunately for a truly scientific "business case" for sustainability there must be more research carried out that works at a broad scale over many different industry sectors [16].

Another change to be addressed is the managerial styles of business operations. Sustainability is a large, daunting, and complex problem that classic top-down hegemonic managerial styles may not be able to handle [17]. Some large companies, like Toyota Motor Company and Nike, have explored other managerial styles that are more equipped to handle today's complex business operations and could be used to address sustainability in business as well. Toyota has changed to allow more localized decision-making instead of requiring areas to go through the corporate headquarters [17]. This localized focus can be important to dealing with sustainable development in local areas that regional areas of business would have better understanding of than a headquarters in another country.

Localized decision making can also aide in better products for customers. How consumers use and dispose of products has a big impact on the environment [18]. Designers can influence how consumers use products and can therefore influence goods to be used in an optimally sustainable manner [18]. No literature was found on how designers influence how a product is disposed of, exposing a gap between designers and users where information needs to be relayed for a sustainable future. The protocol proposed in this paper has the ability to bridge this informational gap and allow consumers to better understand how to sustainably dispose of products.

A more sustainable future requires better management of waste from operations and from consumers [19]. There are opportunities in waste streams for new product development and therefore business. In developing countries, a growing hazardous waste stream is vehicle tires. This waste stream can be diverted by businesses that take used tires and retread them, extending their useful life. Tire's useful life can be extended further as some business take tires and transform them into rubber that can be used in playgrounds or turf fields [19]. This protocol can aid in the formation of well tracked waste material streams, opening business opportunities for "raw" materials sourcing for other operations.

2.3. Design

User-centered design (UCD) is a powerful design methodology that can be used as a model for how the Next-Generation Protocol can change the paradigm of waste in the current product lifecycle. UCD is a unique methodology that places emphasis on integrating users early in the design process [20]. According to a survey of 103 designers with an average of 8 years of experience using UCD, its nature leads to designers developing a strong sense of ownership of the product by the time it is completed [21]. This is important to changing the current division between users and designers because designers often feel more connected to the products and users when implementing UCD. The design process utilizes five collaborative and iterative steps until a product satisfies all user needs: observation, idea generation, prototyping, testing, and evolution [20]. These repeated steps often lead to products with higher satisfaction and less evolutions after product release [21]. These statistics are helpful because they show more effective products are developed by uniting users and designers in the design phase. In turn, this could potentially lead to more sustainable product life cycles by uniting these two parties.

Despite a lack of frameworks within UCD for sustainable material selection, there has been research for encouraging sustainable product use built from UCD principles. Behavior adaptation frameworks including eco-feedback, scripting, and forced functionality, show potential in influencing user-product interactions [22]. By understanding the impact of designers embedding sustainable intentions within their products, insights may be found that can apply to the protocol.

Eco-feedback is a technique used by designers where a feedback loop is embedded into the product to inform users. This is a powerful tool because effective indicators allow users to make informed decisions with their product. In 2006, Koens and Groeneveld completed a study in the Netherlands where residents were given meters that relay household energy usage in real-time [23], [24]. At the end of the study, those using the meter saw a decrease in energy usage by 7% on average, a significant impact if applied to a larger population [23], [24]. However, when implementing eco-feedback, it is important to choose a few, effective indicators so that the users are informed but not overwhelmed. This is important for the protocol with regards to relaying metric scores to users. With the correct information provided in an understandable way, users show improvements in sustainable product use.

Scripting and forced functionality are other techniques where designers embed their intentions within products. Verbeek and Kockelkoren define scripting as a “product layout guiding the behavior of the user…to comply with values and intentions inscribed into the product by its designer,” [25]. Through scripting, designers can set sustainable features within a product, such as a low-power setting, as the default [22]. However, users could still use a product with no intention of maintaining sustainable usage. Forced functionality is the strongest level of intervention for designers by preventing user intervention with certain product features. By removing users, the potential for irresponsible utilization can be avoided, such as intelligent systems like Honda's integrated motor assist [22]. However, implementing forced functionality removes accountability from the users' perspective, thus not generating a positive feedback loop that encourages sustainable behavior. With regards to the protocol, forced functionality could come as legislative requirements that are levied on designers, but not users, such as the ELV directive [5]. When implementing this protocol, it is important to realize the consequences of scripting and forced functionality because the goal is to develop new feedback loops for users to encourage sustainable use.

2.4. Policy

EOL policies often honor Thomas Lindhqvist's principles of Extended Producer Responsibility [26]:

> Extended Producer Responsibility (EPR) is a policy principle to promote total life cycle environmental improvements of product systems by extending the responsibilities of the manufacturer of the product to various parts of the entire life cycle of the product, and especially to the take-back, recycling and final disposal of the product. Extended Producer Responsibility (EPR) is implemented through administrative, economic and informative policy instruments.

The EU's End-of-Life Vehicles (ELV), Release of Hazardous Substances (RoHS), and Waste of Electrical and Electronic Equipment (WEEE) are prime examples. The objective of ELV is to maximize recovery of vehicles at the end of consumer use, reduce waste, and improve environmental performance. The ELV policy has for general demands for manufactures: (1) reduce hazardous materials when designing vehicles, (2) vehicles must be designed and produced to facilitate the 3R's – reuse, recovery, and recycle, (3) increase amount of materials obtained from the 3R's, and (4) components of vehicles that enter the market after 2003 cannot contain mercury, hexavalent chromium, cadmium, and/or lead [26].

Since the inception of ELV in the EU, Japan, Korea, and China have adopted similar ELV policies (Table I) [27]. ELV policies generally makes 95% recovery the target through automobile shredding residue (ASR) recovery, and reusing, recovering, and recycling components and metals. Sakai, et. al. agree that product design in the early manufacturing stages has the most influence on this EOL strategy [27]. China is the largest single country with legislative ELV policies [28]. All in all, the policies forces firms and manufactures to consider environmental constraints in product development as well techniques that facilitate recovery.

Table I: Legislative ELV Policies in Countries		
Country	*Policy*	*Date Adopted*
EU	Directive 2000/53/EC of the European Parliament and the European Council on ELVs	September 2000
Japan	Law for the Recycling of End-of-Life Vehicles	July 2002
Korea	Circulation of Resource from ELV and WEEE	August 2007
China	Technology Policy for Automotive Products Recycling	February 2006

2.5. Embodied Energy

Embodied energy is energy that has been sequestered in “materials during all processes of production”, manufacturing, and disposal and waste treatment [29]. Operating energy is energy “expended in maintaining”, powering, and operating devices. Although Dixit, et. al. focus on building construction, their discussion on embodied energy can be applied across the board. Dixit, et. al. argue that for researchers, professionals, and manufactures to maximize efficiency, embodied energy inventories and methodologies need to be complete and accurate. Doing so may decrease the fact buildings contain 20 to 50 times the embodied energy than the annual operating energy of those buildings. They argue the most promising solution is a protocol that standardizes data collection of embodied energy. Amanda D. Cuellar and Michael E. Weber agree the amount of embodied energy needs to be decreased. In their investigation on wasted energy in food, Cuellar and Weber found the embedded energy in the food industry accounts for 2% of the annual energy consumed in the US alone. The authors argue that to decrease embodied energy and wasted energy industry must be redesigned so that less energy is introduced. Moreover, since the data is incomplete, they propose new methods and policies be formed to account for energy [30].

3. Next Generation Protocol

Designers must be conscious of the recoverability of their products throughout the design process. To aid designers and all others involved in the production of goods a protocol was produced, in the form of a flowchart, to encourage more thoughtful design (Figure 4). To produce goods that are more recoverable and more sustainable designers should aim for the most embodied energy to be diverted from landfills. To maximize returned embodied energy, products should aim to land higher on the flowsheet. This flowsheet can be used in prototyping as a test to run products, components, and materials through to find weaknesses in the good. Designers must consider three principles throughout their process: design for disassembly, reduce toxicity, and be conscious of material selection.

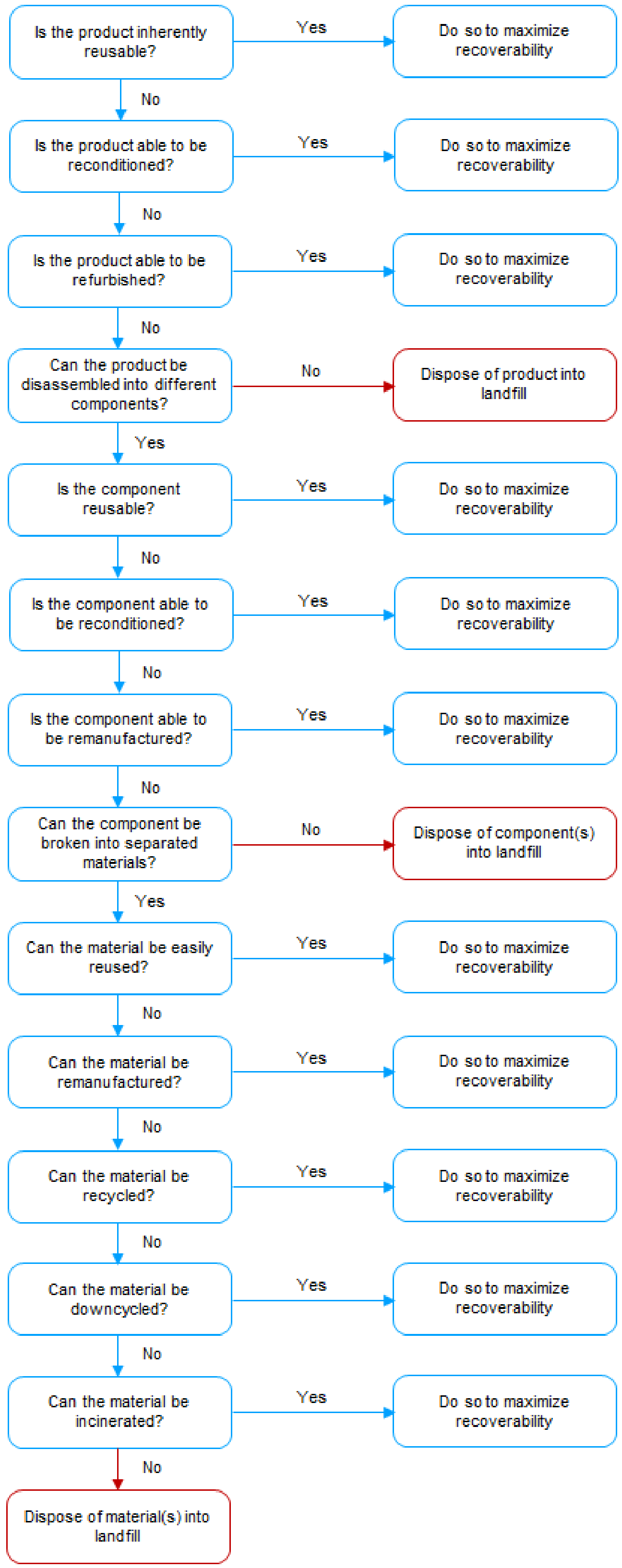

Figure 4: Next Generation Protocol Flowsheet

4. Methods

4.1. Methodology

Quantitative and qualitative methods are used in this project. Quantitative methods in the form of a top to bottom rating system are used to generate Recovery Ratings. A combination of secondary sources, such as peer-reviewed articles and Granta Design's CES EcoAudit tool, were used to generate scores, as well as distinguish recovery methods.

Qualitative methods in the form of three case studies are used to validate the metric. The case studies are on three water bottles: 1) metal, reusable bottle, 2) plastic, reusable bottle, and 3) single-use, plastic bottle. Moreover, an unscientific survey was conducted to gage responses to different delivery methods of scores; the delivery methods tested were numerical, graphical, and symbolic.

4.2. Methods

The metric is intended to communicate the recovery potential of embodied energy of products. To simplify and quantify easily the recovery potential of products, the metric is on a weight percent recovery basis. The metric is broken into different tiers in order of decreasing maximum return of embodied energy: 1) product-level, 2) component-level, and 3) material-level. Each tier has variations in recovery methods, and the material tier has a distinct recovery scheme for each material family (Table II). Due to the variation and inconsistency in recovery methods for natural materials, they do not have a definite breakdown of recovery methods recovery potential scores. Some natural materials, like wood and bamboo, are used in consumer products therefore better data will be required for a future metric that includes natural materials.

Due to the tremendous amount of materials in each material family, ten common materials were selected for each group to generate scores for each recovery method. Second, due to the property variations in material families, the 1) metals were divided into ferrous and non-ferrous metals, and 2) polymers were organized into thermoplastics, thermosets, as well as thermoplastic and thermoset elastomers. As for ceramics and glasses, they were combined into a single category. The materials used for each group, as well as their recoverability factors can be found in Appendix 5.

Table II: Recovery Tiers & Recovery Methods			
Recovery Tiers	Product	Component	Material
Recovery Methods	Reuse	Reuse	Reuse
	Recondition	Refurbish	Remanufacture
	Refurbish	Remanufacture	Recycle
	Recycle	Recycle	Downcycle
	Incineration	Incineration	Compost
	Landfill	Landfill	Incineration
			Landfill

5. Results

5.1. Metric Development

The Next Generation protocol breaks items up into three distinct tiers--product, component, and material. Scores at each tier are based on the amount of recoverable embodied energy and minimization of additional inputs and outputs. For example, if a product is totally reusable, reusing it minimizes any additional energy needed for its next generation of use and thereby gives it the maximum rating. At the product and component tiers, scores are graphically represented. At the product tier, the products are rated from 4 stars to 1 star. At the component tier, the components are rated with a system inspired by health care. In health care, a series of emoticon faces (from happy to sad), are used to rank a patient's pain. For the component tier, the emoticon faces represent the end of life recovery method hierarchy for components (Figure 5).

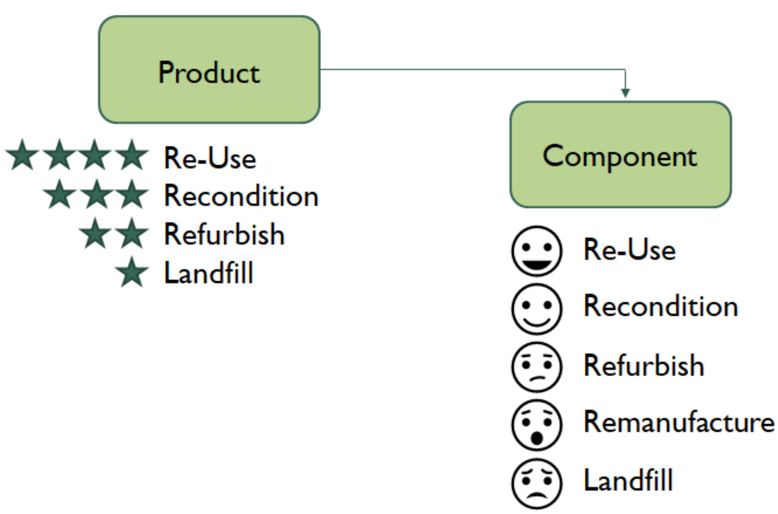

Figure 5. The rating systems for the product and component tiers.

At the material tier, the CES EcoAudit tool was used to find recovery scenarios and generate recovery potential scores on a 1 kg basis. Unique recoverability factors (β_i) were calculated by averaging the values of recoverable energy in each end of life scenario for the following material families: non-ferrous and ferrous metals, thermoplastics, thermosets, elastomers, and glasses and ceramics (Figure 6). To facilitate the easy use of the metric, an End of Generation flow sheet was written (Appendix I).

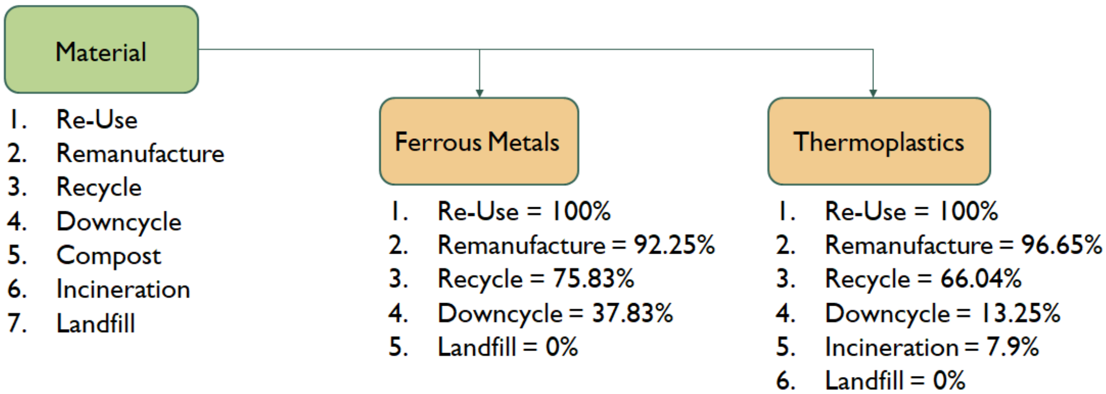

Figure 6. Recoverability factor (β_i) examples for two material families.

An equation was derived to calculate EOL values (Equation 1). To use the metric, a product is broken down into its most basic material levels. The material families are weighed, producing a weight fraction of the total products' weight. The fractions are multiplied by the appropriate end of life method recoverability factor and summed within each material family. The scores of all material families are summed, yielding an end of life value out of 100.

$$\sum_{j=1}^{All\ j\ Material\ Families}\left(\sum_{i=1}^{i\ EOL\ Scenario}(f_i \times \beta_i)\right) = \text{EOL Value}$$

Where,
$f_i = weight\ fraction$
$\beta_i = EOL\ method\ recoverability\ factor$

Equation 1. Calculating EOL Values with the metric

5.2 Case Study

The case study observed three different types of water bottles, a reusable metal bottle, a reusable plastic bottle, and a single use polyethylene terephthalate bottle (PET) (A.2.). The metal insulated bottle was modeled after the Hydro Flask brand bottles. Hydro Flask's are made from two main components, the body and the lid. The body is assumed to be composed of one material, a ferrous metal. The lid has two material pieces, a silicone seal near the threads and a thermoset top. The reusable plastic bottle is modeled after Nalgene brand plastic bottles. These bottles are composed of two components, the body and the lid which, are composed of Tritan thermoplastic and another thermoplastic respectively. The single use bottle has a PET body and a polyethylene (PE) lid. The considerations for these inputs for the product, component, and material tiers of the water bottle products tested the viability of the metric and protocol.

At the product level the metal bottle receives the highest score, 4 stars (Table III). Both components of the Hydro Flask are reusable on their own resulting in the highest score at this tier, a smiley face. The body of the metal bottle is assumed to be comprised of 95% of the product weight and is made of one material and is inherently reusable as a cup, even without a lid, therefore at the material level the ferrous metal body is reusable. Breaking the lid of the Hydro Flask into individual materials produces a thermoset top and a thermoset elastomer silicone seal. The material properties of this family limit the end-of-life possibilities and results in these materials, 5 wt.% of the product, being disposed of in the landfill. Overall the metal bottle received a material score of 95/100.

Table III: Case Study Results

			
Product	★★★★	★★★★	★
Component			
Material	95	94.9	76

The reusable plastic bottle receives 4 stars at the product level because of its design for reuse. The Nalgene components are mostly reusable so at this level it also receives the highest score, a smiley face. The Tritan plastic body makes up 85 wt.% of the product, is made of one material and is inherently reusable as a cup. The thermoplastic lid, being 15 wt.% of the product, has components that could break easily and would be less reusable without a Nalgene bottle body therefore it is assumed that the lid would be recycled at its end-of-life. Overall the Nalgene bottle receives a material EOL value of 94.9/100.

Lastly, the single use plastic bottle was assumed to be landfilled at the end-of-life, resulting in a product score of 1 star. Similarly, the components would be landfilled at the end-of-life resulting in the lowest score at that tier, a frowning face. The body and lid of single use plastic bottles are made of recyclable thermoplastics PET and PE respectively. Inputting this data into the metric calculator resulted in an EOL value of 76/100 for the single use bottle.

5.3. Survey

To better understand how scores of the ratings might be perceived by the general public, a recoverability survey was made public to Cal Poly students through the Cal Poly Class of 2018 Facebook page. The survey consisted of 5 questions (Appendix A.3.). One of the 5 questions showed the participant three representations of the scores: symbolic, numerical and graphical (Figures 7, 8, and 9).

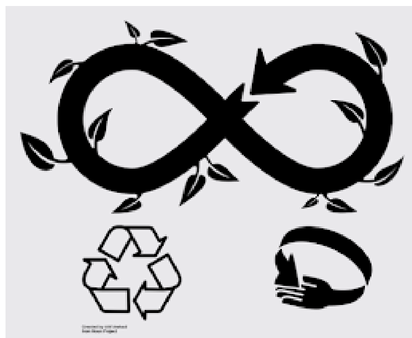

Figure 7: Symbolic representation of the recoverability rating

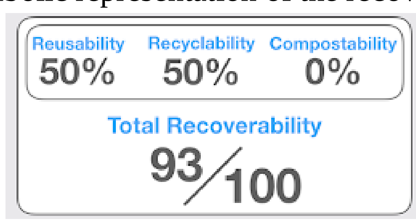

Figure 8: Numerical representation of the recoverability rating

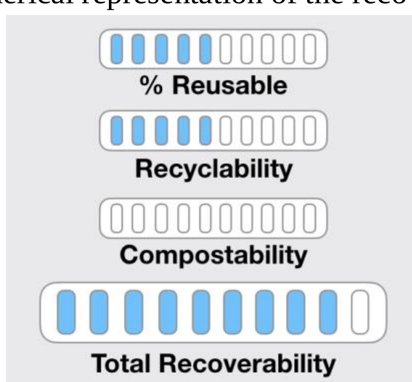

Figure 9: Graphical representation of the recoverability rating

The results showed that most participants preferred the numerical representation of the score, second to the graphical representation. Due to the small sample size of 48 students, further analysis is required to find the optimal method to communicate scores to designers and users.

6. Discussion

The case study showed that the protocol and metric have viability as both reusable bottles scored higher across all tiers than the single use bottle. These scores can be relayed to those involved in the production of goods, allowing for improved designs to result in higher scores. Consumers can best understand these scores if they are relayed numerically, according to the survey conducted. The resulting scores from the protocol and metric should be shown on product labels to relay information about the sustainability of products between designers and consumers

The case study also showcased shortcomings of the protocol and metric. There are limitations on the product and component levels in their current state, as the scores are graphical instead of numerical. The product and material tiers also do not consider recycling as a possible end-of-life scenario. Recycling was initially not included in these tiers because of its inclusion in the material tier. Those two levels also don’t share the same complexity as the material tier, which considers seven end of life recovery methods instead of four and five, respectively.

For all three tiers there is currently no way to track compostability. Because the quantitative data collection relied primarily on CES EcoAudit base, which did not include composting as a recovery method, it was not considered in the scoring for the material tier.

As the survey had only 48 responses, it represented only a small sample within Cal Poly students. This did not allow statistically significant conclusions to be drawn. Most participants preferred the numerical representation of the recoverability rating, which is not to say that the entire Cal Poly population would prefer the numerical rating.

The protocol and metric both have the ability to change how purchasers and users view the products they are using daily. Should the rating systems be adopted and used on daily-use items, purchasers will be able to see the ratings and make more informed decisions on what they are purchasing. The protocol would then be akin to the Energy Star rating system, which helps purchasers buy appliances which are more eco-friendly and cost-efficient.

7. Conclusions

7.1. Conclusions

- CES Eco-Audit tools allows for accurate calibration of metric scales at material-tier.
- The product- and component-tiers should be re-evaluated to improve effective rating scales.
- Currently, Cal Poly students prefer numerical rating systems for relaying recoverability scores.
- The case studies showed that the metric can potentially be a viable tool to assess the recoverability of products.

7.2. Future Work

For the next iteration of the metric and protocol, more data collection on recovery methods for other material families is required. As an example, the CES EcoAudit tool did not have accurate data for natural materials, so they were not included as a material family in this protocol. Similarly, investigating calculation methods to include composting processes as recovery methods is crucial for the next iteration.

Considering the discrepancy between recovery potential and known recovery rates would be valuable as future work. In the case study, the plastic bottle was assumed to be recycled. In reality, most plastic water bottles are landfilled at the end of their useful lives. The case study showed that a sample of Cal Poly students preferred the numerical representation of the score, but further analysis should be done to find the most effect methods of communicating scores to users and producers. Finally, developing a user interface to allow producers to use the metric to audit their own products would allow for eco-feedback during prototyping.

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9. Appendices

A.1. Glossary

Sustainability: the simultaneous pursuit of human health and happiness, environmental quality, and economic well-being for current and future generations

> Alter, T., Barsom, S., Engle, E., Sterner, G., & Vandenbergh, L. (2016) “Developing a Framework for Sustainability Meta-Competencies”, *Pennsylvania State University.*

Sustainability meta-competencies: overarching competencies, within which are sub-competencies that provide specific applications for the overarching competencies

- Sustainability meta-competencies:
  - Systems Thinking: the ability to analyze complex systems across multiple domains and at different scales
  - Temporal Thinking: the ability to draw upon and anticipate states and narratives of past and future societies and environments
  - Interpersonal literacy: the ability to comprehend, motivate, enable, relate to and communicate across diverse individuals, political systems and organizations
  - Ethical literacy: the ability to identify and assess ethical issues and controversies (related to sustainability) and to discuss, respond to, and reconcile them, applying personal and societal values and goals
  - Creativity/ imagination: ability to envision, develop and apply innovative and strategic solutions and frameworks to adapt to changing and challenging situations
  - Foundational competencies: expected capabilities based on education and adaptation. Include: logical thinking, critical thinking, quantitative analysis and numerical reasoning, reading and writing

> Alter, T., Barsom, S., Engle, E., Sterner, G., & Vandenbergh, L. (2016) “Developing a Framework for Sustainability Meta-Competencies”, *Pennsylvania State University.*

Corporate sustainability management: “a strategic and profit-driven corporate response to environmental and social issues caused through the organization’s primary and secondary activities”

> Salzmann, Ionescu-Somers, & Steger. (2005). The Business Case for Corporate Sustainability: Literature Review and Research Options. European Management Journal, 23(1), 27-36.

Economic development: seeks ‘‘to improve the economic well-being and quality of life for a community by creating and/or retaining jobs that facilitate growth and provide a stable tax base’’

> Grodach, C. (2011). Barriers to sustainable economic development: The Dallas–Fort Worth experience. Cities, 28(4), 300-309.

Sustainable economic development: consists of three elements or overarching goals: an improved standard of living over time for all, the reduction of social and spatial inequality, and sustainable resource use and production. Moreover, sustainable economic development may be distinguished from the conventional approach in that it considers economic, environmental, and equity impacts together rather than prioritizing economic growth.

Salzmann, Ionescu-Somers, & Steger. (2005). The Business Case for Corporate Sustainability: Literature Review and Research Options. European Management Journal, 23(1), 27-36.

User Centered Design: Process outlining the phases throughout a design and development life-cycle all while focusing on gaining a deep understanding of who will be using the product.

Usability.gov

Scripting: Influencing user-product interactions to match those of the designer by embedding features.

Eco-Feedback: A technique for designers to provide feedback to users regarding energy usage for a given product to encourage sustainable behaviors.

Forced Functionality: A technique by designers to bypass user-product interacts to ensure the functionality of a feature is unhindered.

Design for Environment: The systematic consideration of design performance with respect to environmental, health, and safety objectives over the full product and process life cycle.

Fiksel, Joseph, *Design for Environment: Creating Eco-efficient Products and Processes*, McGraw-Hill, New York, 1996.

Sustainable Development: “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”

UN. Chapter 2, “Towards Sustainable Development,” in “Our Common Future: Report of the World Commission on Environment and Development,” (report: *UN Documents*, 1987)

Embodied Energy: energy spent during “all processes of production”, manufacturing, transport, and disposal and waste treatment

Manish Kumar Dixit, José L. Fernández-Solís, Sarel Lavy, Charles H. Culp, “Identification of parameters for embodied energy measurement: A literature review,” *Energy and Buildings* Vol. 42 (2010): 1238-1247.

Operating Energy: energy "expended in maintaining", powering, and operating devices

Manish Kumar Dixit, José L. Fernández-Solís, Sarel Lavy, Charles H. Culp, "Identification of parameters for embodied energy measurement: A literature review," *Energy and Buildings* Vol. 42 (2010): 1238-1247.

Extended Producer Responsibility (EPR): "a policy principle to promote total life cycle environmental improvements of product systems by extending the responsibilities of the manufacturer of the product to various parts of the entire life cycle of the product, and especially to the take-back, recycling and final disposal of the product"

A. Gehin, P. Zwolinski, and D. Brissaud, "A tool to implement sustainable end-of-life strategies in the product development phase," *J. of Cleaner Production* Vol. 16 (2008): 566-576.

Product Recovery: "to retrieve a product's value when the product no longer fulfills the user's desired needs"

M. Lindahl, et. al., "Concepts and definitions for product recovery – Analysis and clarification of the terminology used in academia and industry," *Innovation in Life Cycle Engineering and Sustainable Development* (2006): 123-138.

Remanufacturing: "an industrial process in which worn-out products are restored to like-new condition", as well product components and parts

M. Lindahl, et. al., "Concepts and definitions for product recovery – Analysis and clarification of the terminology used in academia and industry," *Innovation in Life Cycle Engineering and Sustainable Development* (2006): 123-138.

Reuse: "the process of disassembling products to recover usable parts and assemblies for the purpose of utilizing them in newly manufactured products"

M. Lindahl, et. al., "Concepts and definitions for product recovery – Analysis and clarification of the terminology used in academia and industry," *Innovation in Life Cycle Engineering and Sustainable Development* (2006): 123-138.

Reconditioning: "the process of restoring components to a functional and/or satisfactory state but not above original specification using such methods as resurfacing, repainting, sleeving, etc."

M. Lindahl, et. al., "Concepts and definitions for product recovery – Analysis and clarification of the terminology used in academia and industry," *Innovation in Life Cycle Engineering and Sustainable Development* (2006): 123-138.

Refurbishment: "the process in which a product or component is cleaned and repaired in order to make a resell"

M. Lindahl, et. al., "Concepts and definitions for product recovery – Analysis and clarification of the terminology used in academia and industry," *Innovation in Life Cycle Engineering and Sustainable Development* (2006): 123-138.

Component Cannibalization: "the process in which a limited number of components are extracted from a product for recovery"

> M. Lindahl, et. al., "Concepts and definitions for product recovery – Analysis and clarification of the terminology used in academia and industry," *Innovation in Life Cycle Engineering and Sustainable Development* (2006): 123-138.

Material Recycling: "the process by which materials otherwise destined for disposal are collected, processed, and re-manufactured into new products. Composting is a form of recycling"

> M. Lindahl, et. al., "Concepts and definitions for product recovery – Analysis and clarification of the terminology used in academia and industry," *Innovation in Life Cycle Engineering and Sustainable Development* (2006): 123-138.

A.2. Case Study: Protocol and Metric in use

An example of how the metal reusable bottle from the case study would be run through the metric and protocol:

- As a product, Hydro Flasks are designed to be reused. Therefore, this product retains the highest possible recoverability in the flowchart and as a score, a 4-star rating (Table IV).
- At the component tier, both the lid and the ferrous metal body are reusable. Therefore, the components return the highest amount of embodied energy to the system resulting in the highest possible score at this tier, a smiley face (Table IV).
- The materials that make up the product are broken up as follows (Table IV):
    - Ferrous metal body, reused: 95wt%, $f_i=.95$, $B_i=100$
        - Using Eq 1. .95*100= 95 EOL value
    - Silicone seal from lid, landfill: 1 wt.%, $f_i=.01$, $B_i=0$
        - Using Eq 1. .01*0= 0 EOL value
    - Thermoset top from lid, landfill: 4 wt.%, $f_i=.04$, $B_i=0$
        - Using Eq 1. .04*0= 0 EOL value
    - Total material EOL value= 95 + 0 + 0 = 95/100

Table IV. Results from Case Study for Reusable Metal Bottle

	
Product	★★★★
Component	☺
Material	95

A.3. Recoverability Survey

1. What is your field of study?
    a. Engineering
    b. Business
    c. Agriculture, Food, and Environmental Sciences
    d. Architecture and Environmental Design
    e. Liberal Arts
    f. Science and Mathematics
    g. Other

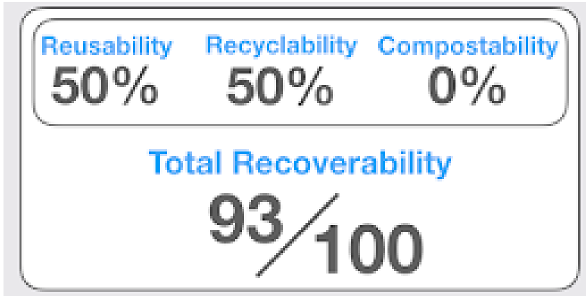
2. Can you differentiate between recovery, recycling, composting, and reusing?
    a. Yes
    b. No

3. What factor influences your decision most when purchasing a product?
    a. Price
    b. Product Reviews
    c. Brand
    d. Environmental Friendliness (Sustainability)
    e. Other

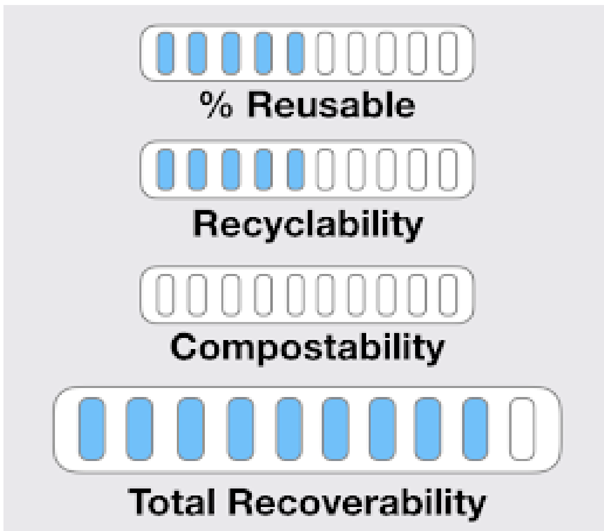
4. How important is sustainability of a product when you are purchasing it?
    a. Ranking from 1 (not considered) to 5 (top priority)

5. Which scoring system is most helpful for you?
    a. Option 1

b. Option 2



c. Option 3



d. None of the above are helpful

A.4. Recoverability Factors for the included Material Families

Table V: Recovery Methods and Recoverability Factors (%) for Metals		
	Ferrous Metals	**Non-Ferrous Metals**
Reuse	100.00	100.00
Remanufacture	92.20	97.01
Recycle	75.83	82.11
Downcycle	37.83	40.95
Landfill	0.00	0.00

Table VI: Recovery Methods and Recoverability Factors (%) for Polymers				
	Thermoplastics	**Thermosets**	**Thermoplastic Elastomers**	**Thermoset Elastomers**
Reuse	100.00	100.00	100.00	100.00
Remanufacture	96.65	96.95	97.06	95.48
Recycle	66.04	0.00	33.05	0.00
Downcycle	13.25	5.64	11.65	0.14
Incinerate	7.90	0.12	2.59	0.00
Landfill	0.00	0.00	0.00	0.00

Table VII: Recovery Methods and Recoverability Factors (%) for Ceramics and Glasses	
Reuse	100.00
Remanufacture	78.78
Recycle	6.04
Downcycle	0.71
Landfill	0.00

A.5. Materials Used to Calculate Scores for Each Material Family

- **Ferrous**
    1. Maraging steel – 250
    2. Alloy steels -- cast -- SAE 4130
    3. Low carbon steel -- cast – annealed
    4. Cast irons -- alloy -- austenitic -- flake graphite -- EN GJLA XNiCuCr15 62
    5. Coated steels – galvanized
    6. Wrought Iron
    7. Make hardening YS260, cold rolled
    8. stainless steel
    9. Precipitation hardened stainless steel
    10. Tool steels, AISI A10
- **Non-Ferrous**
    1. Aluminum
    2. Chromium -- Nickel Alloy
    3. Cobalt -- Commercial Purity -- annealed, soft
    4. Copper – Brass
    5. Lead -- Tin alloy -- ASTM Sn20B (20-80-solder)
    6. Magnesium -- commercial purity -- ASTM 9980A
    7. Nickel Titanium Alloy -- wire, annealed, austenitic
    8. Tin -- Commercial Purity, Grade A
    9. Titanium -- Unalloyed -- Grade 1
    10. Zinc -- Aluminum Alloy -- Kirksite I
- **Thermoplastic**
    1. Polystyrene general-purpose crystal
    2. PLA General Purpose
    3. PP Random Copolymer low flow
    4. PMMA Molding and Extrusion
    5. PMMA Molding and Extrusion
    6. Cellulose Acetate - Molded
    7. 1 kg PET unfilled semi-crystalline
    8. Polyamide/Nylon -- PA1010 -- unfilled
    9. EVOH - unfilled
    10. ABS -- Aluminum Filled -- 40% aluminum flake
- **Thermoset**
    1. PF cellulose filled, impact modified, molding
    2. PF cellulose filled, impact modified, molding
    3. DAP molding, glass filled

4. Polyimide 40% glass filled
5. Polyimide unfilled
6. Epoxy
7. Vinyl Ester - standard
8. Polyester Cast, Rigid
9. Phenol Formaldehyde Unfilled Casting Resin
10. Polyurethane

- **Thermoplastic Elastomer**
  1. TPV Shore A40
  2. TPU
  3. TPS Shore A50
  4. TPO
  5. TPC Shore d40
  6. TPA Shore D25
  7. PVC Flexible standard grade
  8. PVC -- Shore A35
  9. POE -- Ethylene-based, Shore A65
  10. MPR -- Shore A60
- **Thermoset Elastomer**
  1. Polysulphide rubber
  2. Styrene butadiene rubber
  3. Polyurethane Rubber
  4. Polyisoprene rubber
  5. Natural rubber
  6. Nitrile rubbers
  7. Ethyl Vinyl acetate rubber
  8. Chlorinated polyethylene
  9. Butadiene Rubber
  10. ACM Acrylic Rubber
- **Ceramics and Glasses**
  1. Zirconia
  2. Tungsten Carbide
  3. Silicon Carbide
  4. Alumina (85) (410)
  5. Ceramic Tile
  6. Cement (high alumina)
  7. Silica (96%)
  8. 1 kg soda lime glass 070
  9. Borosilicate