Exploring Sustainable Design Methods Through The Redesign of a Commuting Vehicle

by
Jack Bellville

A PROJECT

submitted to

Oregon State University

University Honors College

in partial fulfillment of
the requirements for the
degree of

Honors Baccalaureate of Science in Mechanical Engineering
(Honors Associate)

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Abstract approved:

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Bryony DuPont

The process of redesigning products in order to reduce their environmental impact is a challenging task because formalized methods in sustainable product design do not yet exist. There are many tools and methods that designers can use to be more informed of the sustainability of a product, but many are difficult to use, due to lack of life cycle analysis data, or provide an incomplete analysis, due uncertainties that exist in the analysis of the environmental impact data. This case study explores the application of two sustainability analysis tools, including the Eco-Indicator 99 manual and Solidworks Sustainability, in the redesign of a common commuter vehicle. The primary methods that were used to help reduce the environmental impact and improve the sustainability of the redesign included: sustainable material selection, component weight reduction, and reducing the complexity of component systems. The project highlights areas in the sustainable design process that are incomplete or difficult for designers to follow and discuses potential remedies to these challenges.

Key Words: Sustainable product design, sustainability, life cycle analysis, Eco-Indicator 99, Solidworks Sustainability

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

Jack Bellville, Author

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Introduction

As the population of the world rapidly continues to increase, we as human beings are consuming more and more of the Earth's natural resources in order to develop the products we use today. The large consumption of natural resources is contributing to many devastating impacts including deforestation, agricultural runoff, toxic emissions, and overall resource depletion. These detrimental impacts are contributing to major global effects such as climate change, ozone depletion, and ecosystem destruction. If we continue to consume natural resources at such a high rate without developing strategies to reuse or replenish these resources, we as a population will face major challenges in terms of product development and consumption in the near future.

Many products developed today are primarily designed for how they will be used, creating products that appeal to consumers, while overlooking the types of impacts these products are having on the environment. This especially applies to the quickly expanding single-serving market, which encompasses products such as plastic water bottles and many snack food items. Single-serving products are designed and marketed for their convenience, portability, and portion control, to be used once by the consumer. The merits to these products are that they reduce the amount of food and water wasted by the consumer. The downside to this method is that a large percentage of product packaging ends up being thrown away, rather than recycled or reused, by the consumer.

The K-Cup pod technology, developed by Keurig for use in their home coffee machines, is an example of a popular single-serving product, the success of which has led to the vast investment into single-serving technology. Keurig users save electricity by making single-serving hot drinks rather than using constant electricity to keep a traditional coffee pot warm for extended periods of time. Using single-serving pods means that coffee grounds can be used more efficiently to extract the coffee from each bean. However, many single-serving coffee pods are made of several different plastics and are not recyclable in their current state [1]. The inventor of K-Cups regrets that he ever invented them because the expensive technology produces so much waste and bears a heavy cost for both the environment and consumers [2].

The amount of waste that is being produced by the global population is greater than ever. The amount of consumer waste heavily outweighs the amount of recycled items and these rates continue to increase. This steadily increasing generation of waste means that the amount of toxic emissions being released and overall pollution rates are also increasing. While there are many people and organizations that are trying to increase awareness in an effort to help reduce the rate that waste is being generated, this alone is not enough to bring about drastic changes. Figure 1 shows the increasing rate of municipal solid waste (MSW) generated, and Figure 2 shows the rate of recycling MSW is now lower than it previously was as compared to total amount of MSW generated.

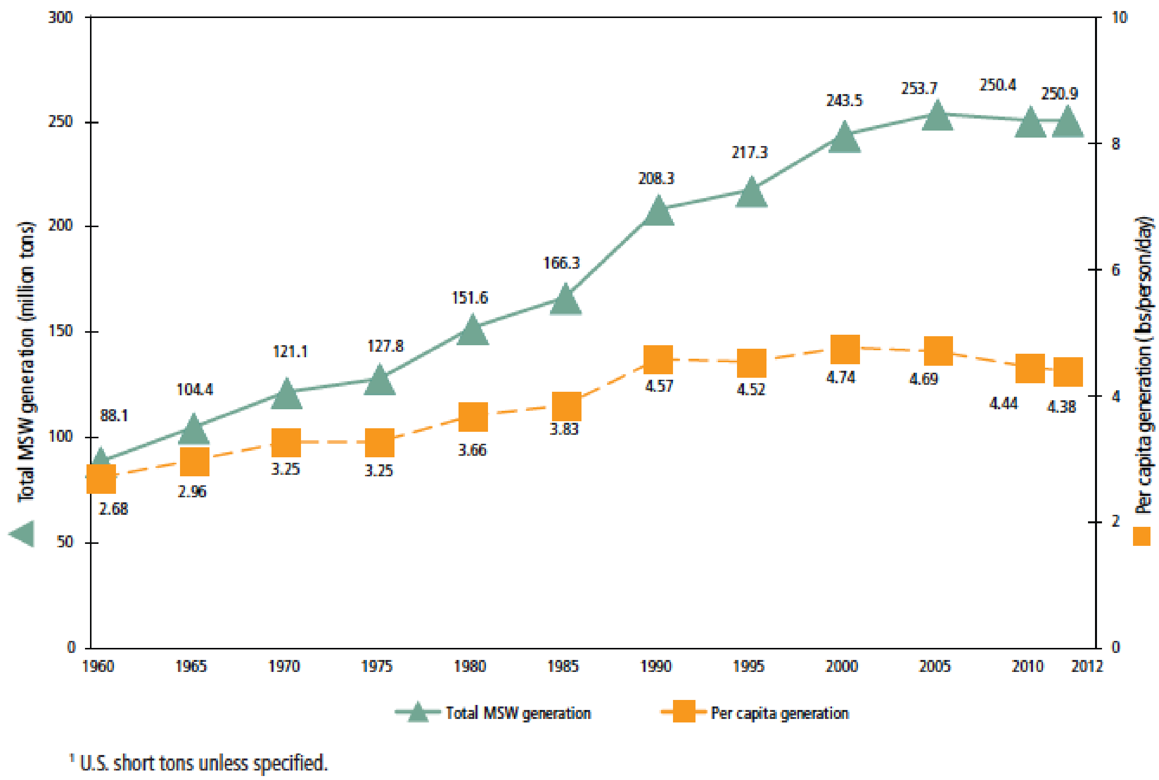

Figure 1: Municipal solid waste (MSW) generation rates, 1960 to 2012 [3]

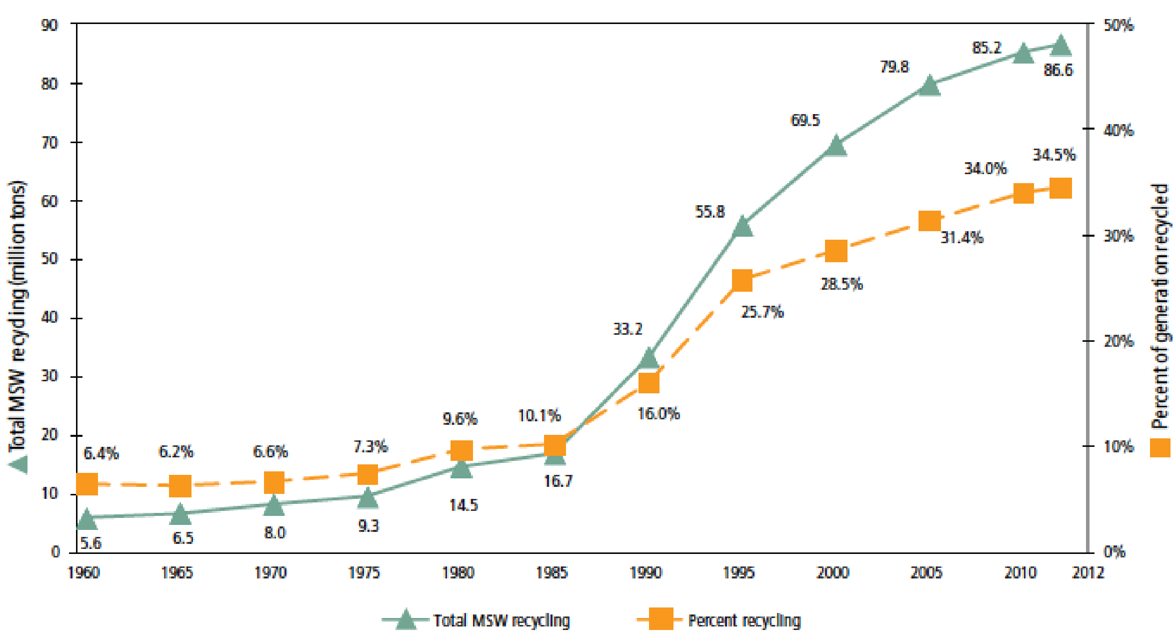

Figure 2: Municipal solid waste (MSW) generation recycling rates, 1960 to 2012 [3]

Despite these statistics, there are solutions to these waste problems and they begin at the conception of products. The design of sustainable products addresses many of these problems and can help diminish the impacts that are developing because of these issues. However, it is challenging to analyze and improve the sustainability of products because formalized methods for performing sustainable design do not yet exist. It is also difficult to be informed of the sustainability of a product using the current methods and tools. This brings up a question of how do we redesign existing products such that they are more sustainable.

Background Research

In order to better understand the product design process and how environmental analysis can be incorporated successfully, it is necessary to determine the factors that influence product design and development. This includes determining stakeholder needs and designer roles, and identifying aspects the product life cycle, while assessing current sustainable product design methods. It is also important to assess the current state of environmental analysis, looking at methods such as life cycle analysis and design for ‘x’, and the tools used by designers to determine environmental impacts of products.

Sustainable Product Design

Sustainability is defined as keeping and maintaining the operation of an existing system, such that the original requirements are satisfied [4]. The scope of sustainability for this project focuses on eco-design; the impact that a product has on the environment and its surroundings during its life cycle. Sustainability is a continually growing area of interest for many companies, universities, and research groups. This increased interest is due to the growing amount of pollution, energy usage, and waste being produced by the population. Consumer behavior is a major area that is sustainable design methods are trying to address. There are many factors that make it challenging for consumers to make sustainably-conscious decisions regarding their purchasing and usage habits. Developing products and systems that can help consumers make these sustainable decisions is critical to the integration of sustainability into people’s lives.

Sustainable product design (SPD), also referred to as and used interchangeably with *eco-design*, is the activity aimed at integrating environmental aspects into product design and development to reduce adverse environmental impacts throughout a products life cycle (PLC) following the International Standardization Organization (ISO) standards 14006:2011 [5]. ISO standards are strategic tools that reduce costs by minimizing waste and errors, and increasing productivity; ensuring that products are safe, reliable, and of good quality [6]. In order to develop sustainable products, certain aspects of a PLC must be considered over the lifetime of a product. These aspects include:

- Reducing materials and energy use of a product
- Reducing emissions
- Reducing the creation and dispersion of toxic materials
- Increasing the use and amount of recyclable materials
- Maximizing the sustainable use of renewable resources
- Minimizing the service intensity for products and services
- Extending the useful life of a product
- Assessing and minimizing the environmental impacts
- Increasing the efficiency of a product in the usage phase
- Using ‘‘Reverse logistics’’ meaning that all efforts are used in order to reuse products and materials [7]
- Creating product features that promote re-manufacturability or de-manufacturability [8].

The development of sustainable products primarily focuses on the potential environmental impacts that may occur during a product's lifetime, whereas a holistic method for sustainable product design that incorporates economic and social aspects has yet to be realized. The environmental trade-offs between different products is quite complex and it is challenging to quantify the trade-off between economic benefits and environmental impacts [9]. In order to understand how aspects of the product PLC can be addressed, and how to prevent the transfer of detrimental impacts from one life cycle stage to another, it is important to have a comprehensive understanding of the environmental, economic, and social effects associated with decisions made during the PLC [8]. This approach to meet the demand for measuring the sustainability of a product is termed Triple Bottom Line (TBL) and is used as a framework for measuring and reporting corporate performance against these three areas [7]. The interactions within and across these areas are critical to the fundamental understanding of sustainable design and manufacturing [10]. Many eco-design methods are solely focused on the environmental dimension of sustainability, while economic and especially social factors are often neglected [11].

The trade-off between economic growth and environmental protection has been a prominent discussion in the last few decades. Until now, governments are still struggling for a balance between environmental legislation and economic growth policy [9, 12]. Social impacts and long term factors are rarely studied. Proper aggregation and weighting methods on economic, societal, and environmental indicators do not exist, especially when they are conflicting with each other [11].

Despite the challenges that accompany it, sustainable design is widely gaining industrial interest. Engineers are eager to begin developing sustainable products, but they require a specific, robust methodology to follow that does not yet exist. A survey conducted by the American Society of Mechanical Engineers (ASME) supports the notion that design engineers are motivated to comply with current sustainability standards. The survey finds that organizations are most interested in compliance with regulatory requirements, and are most likely to only consider green methods that are cost competitive [13].

Managing product end of life (EOL) has become a field of rapidly growing interest for product manufacturers. EOL management is the process of converting end-of-life products into re-marketable products, components, or materials. It enables manufacturers to comply with legislation while gaining some economic advantage as well. As a result, more companies have become interested in EOL management, and successful cases have been reported by various industries, including information technology (IT) and consumer electronics, household appliances, industry equipment, and automobiles [14].

Life Cycle Analysis

Life Cycle Analysis (LCA) is a widely used and accepted method of environmental assessment that helps to quantity the potential environmental impacts throughout the PLC and is used to evaluate improvement options in order to select the best design from a set of alternatives. The results obtained from LCA are intuitive and a number of environmental impacts could be quantified and thus visible to the design engineer enabling them to make improvements [15].

Interest in LCA is rapidly growing as more companies begin taking deeper looks at their products' impacts. LCA is widely accepted among manufacturing industries as the most important way to integrate environmental concerns into product development [9].

LCA has been categorized into three different levels of methodologies: Screening LCA, Simplified LCA, and Completed LCA. A Screening LCA is tailored to fit for the early design stage and serves for an initial (quick) overview of the environmental impacts of a product. A Completed LCA is for comparative assertions and other external communication, following the ISO 14040 and 14044 standards. The Screening LCA is a practical approach for designers because they can use it to compare alternative design concepts, since only limited information can be obtained in the early design stages [16].

The technical framework for conducting LCA, according to the ISO directive ISO 14040, involves a systematic process consisting of four main steps. Step one is goal and scope definition: the intention for the use of LCA and the system boundaries are defined, together with the functional unit used for evaluation. To define the scope of LCA, EOL options are considered, as they can extend a product's usable life, utilizing the same material and energy consumption [9].

Step two is life cycle inventory (LCI) calculation: all the necessary input and output data for the processes corresponding to the PLC are collected in terms of the defined functional unit. The emission data for different sub-processes are estimated, combined and presented as the total emissions of environmental parameters, such as the grams of carbon dioxide, methane, or other substances [17].

LCI is a process of quantifying energy and raw material requirements, atmospheric emissions, waterborne emissions, solid wastes, and other releases for the entire life cycle of a product, process, or activity. Life cycle inventory analyses can be used in various ways. They can assist organizations in comparing products or processes and considering environmental factors in material selection. In addition, inventory analyses can be used in policy-making, by helping the government develop regulations regarding resource use and environmental emissions. An inventory analysis produces a list containing the quantities of pollutants released to the environment and the amount of energy and material consumed [18].

The PLC normally comprises five separate stages. The raw materials are first extracted and formed into the usable stock configuration. Next, the parts are manufactured and assembled as specified. The finished product is transported to its point of use destination. The product is utilized in the intended fashion by the end user over the course of its lifetime. When the product is no longer usable or needed by the customer, it is either disposed of or recycled for future use. The EOL stage could lead to any of a number of scenarios depending upon what the product and its components are. Some products are disposed of in a landfill. Some products are designed for reuse by disassembly or modification in a modular fashion. In some cases, the parts of certain material types could be incinerated to form a recycled raw material for future manufacturing of other products. [12]. In a sustainable design process, the associated quantities of each environmental emission are obtained from established LCI data for the life cycle stages of each material component.

Step three is life cycle impact assessment (LCIA): the inventory data on input (material and resources) and output (waste and emissions) are translated into information related to the impacts, such as global warming or ozone depletion, that the operation of the process causes on the environment, human health, and resources.

The LCIA phase of an LCA is the evaluation of potential human health and environmental impacts of the environmental resources and releases identified during the LCI. Impact assessment should address ecological and human health effects as well as resource depletion. A LCIA attempts to establish a linkage between the product or process and its potential environmental impacts. The results of an LCIA show the relative differences in potential environmental impacts for each option. For example, an LCIA could determine which product causes more global warming potential. Life cycle interpretation is a systematic technique to identify, quantify, check, and evaluate information from the results of the LCI and the LCIA, and communicate them effectively [18].

Current LCA tools and techniques calculate the life cycle impact without considering sources of uncertainties within the data. These sources of uncertainty are usually generated by empirically inaccurate parameters in LCI data originally caused by imprecise, outdated measurements or lack of data and/or by the LCIA model caused by utilizing simplified factors, which do not consider the spatial and temporal characteristics [14]. How these uncertainties affect implementing sustainable design remains unsolved. Identifying uncertainty in sustainable design involves two critical tasks: to quantify the imprecision in LCI data in the proper metric forms; and to develop robust design methods based on these metrics [11].

Step four is Interpretation: the results from the previous steps are presented for analysis with respect to the goals of the study. In order to quantify the results, the sensitivity and uncertainty of the calculated impacts should also be considered in this step [17]. Accurate interpretation of the data is critical in the realization of a sustainable product. In evaluating the overall performance, accumulated errors that have been developed throughout the processes may present themselves, and it is challenging to prevent these errors. This accumulation of error often makes it difficult to distinguish clearly which element is the root cause of the impact. Therefore, iterative analysis together with a comprehensive analysis of the underlying errors and uncertainties is required to provide a more scientific interpretation [9].

The LCA process can be used to determine the potential environmental impacts from a product, process, or service. The goal definition and scoping of the LCA project will determine the time and resources needed. The defined goal and scope will guide the entire analysis process to ensure that the most useful results are obtained. Every decision made throughout the goal and scoping phase impacts how the study will be conducted, or the relevance of the final results [18].

The purpose of conducting an LCA is to better inform decision makers by providing a life cycle perspective of environmental and human health impacts associated with a product or process. However, LCA does not take into account technical performance, cost, or political and social acceptance. Therefore, it is recommended that LCA be used in conjunction with these other parameters [18].

Adding LCA to the decision-making process provides an understanding of the human health and environmental impacts that traditionally is not considered when selecting a product or process. This valuable information provides a way to account for the full impacts of decisions, especially those that occur outside of the site that are directly influenced by the selection of a product or process [18].

Various methods of sustainable product design suggest implementing LCA early in the design process, while some suggest applying different phases of LCA throughout the stages of the design process. It is difficult and costly to apply an accurate LCA early in the design process when design decisions are still being formalized [13]. LCA requires detailed information about the PLC, which may not be available during the early design stages [19]. The early stage of product development is the “fuzzy front end” where there is not enough specified information to support the goal and scope definitions. A complete LCA scope can be very complex and contains a wide range of information about materials, energy and properties [9]. The difficulties of LCA make it much better suited to be used as a retrospective analysis tool, used late in the design process, when most of the data has been collected, to better analyze the impacts of a design [19].

Role of the Stakeholder

In addition to a low environmental impact, sustainable products must also designed to satisfy stakeholders’ preferences, such as affordability and functionality, throughout the PLC [20]. Stakeholders, also known as life cycle participants, include manufacturers, users, distributors, service engineers and end of life asset managers. In order for the designer to obtain a better understanding of the importance or weight associated with each design requirement, stakeholders can be categorized into major and minor stakeholders. Major or key stakeholders have a direct influence on the environmental impact of a product and include designers, manufacturers and users. Minor stakeholders have minimal influence on the product's environmental impact and include the general public [21].

The manner in which a product is used largely affects how the product performs. As one of the major stakeholders, the user has a direct impact on the performance products. Sustainably-designed products that are overused or misused by the consumer will not achieve the level of sustainability that they were designed to meet. This behavior of the consumer is difficult to predict and a major challenge to address in sustainable product design. Designers need to develop products that can help change this behavior by encouraging and enabling users to behave in more resource-efficient ways [22]. This change can be minor from the selection of a more sustainable material, or major by reducing energy used and waste generated, both of which improve the sustainability of a product [23].

Consumer satisfaction is an important aspect in the design of sustainable products. In order to be considered successful, a sustainable product must perform as well or better as a traditional, non-sustainable product. If the consumer is not satisfied with the product, it will be unsuccessful in the market and an economic failure [7]. Product designers often face difficulty in that many sustainable products have received limited commercial success. Nearly 90% of all technically sound products will not be successful on the market for various reasons, regardless of their relative sustainability [7]. This is a counter to market research that reveals many consumers desire environmentally sustainable products. Researchers have proposed that consumers may not trust marketing of sustainable products, or are unaware of a product's sustainable features during purchasing evaluations [24].

Role of the Designer

To implement SPD effectively and achieve maximum sustainability, it is crucial to continually look for ways to minimize the environmental impact of the product. This is most efficiently resolved in the early design phases because the further in the design process, the more difficult and costly it will be to implement changes to the design. Design considerations are most effective when brought into a design process as early as possible, when design flexibility is greater and the impact of any design change is mitigated [14]. In terms of sustainability, 80-90% of the final environmental impact of a product is determined by design decisions made during the early design stage [20]. Design choices, especially decisions made during the early design stage, can have an impact on up to 70% of costs including material and resource consumption committed [14]. Given these facts, methods that aid in making design decisions that relate sustainability and cost must be developed for the early design phase, as designers have oversight of the products throughout their entire life cycle. The greater demands and expectations placed on new products require the designer to take a greater role in specifying and controlling the new product, from its inception to EOL [25].

The designer has the most input and control over the product design process and subsequent life cycle phases because only the designer has the overview of the whole design and manufacturing process [25]. However, there are many challenges that the designer faces in achieving a sustainable solution. The major difficulties lie in collected LCI data and the lack of reliable materials and processes databases. Other challenges include the overlap of the traditional product analysis with sustainability analysis, the lack of detailed methods for designing sustainable products, and uncertainties in design [8]. Regardless of the product, uncertainty effects can fail product functionality from the early design stages to the end of use life cycle [20]. Uncertainty in sustainable design involves quantifying the imprecision in LCI data in the proper metric forms and developing robust design methods based on these metrics [11].

Due to the fact that formalized methods for conducting sustainable design do not yet exist, LCA along with other methods and tools are often used in combination to try and reduce the environmental impact of a final design. This approach to sustainable design makes it difficult to develop consistent and reliable solutions and because there is no concrete methodology to follow, and designers new to sustainable design are faced with many roadblocks. The term “fuzzy front end’ is used to describe the initial stages of conceptual design generation that can hinder designers from generating valuable design solutions because the overarching scope of sustainability limits the space a designer can work in [9].

Design for ‘X’

Numerous methods, such as certain Design for ‘X’ (DFX) methods, have been proposed to address the sustainability-oriented challenges that designers face [26]. DFX and ‘3Rs’ (reduce, reuse, recycle) are good approaches to add additional value to products. DFX can include many design objectives, including Design for Environment, Design for Sustainability, Design for Disassembly, Design for Upgradability, and Design for Manufacturing and Assembly. These strategies can set LCA goals for lowering environmental impacts and help to extend the system boundaries with the concerns of prolonged lifespan [14].

Design for environment (DFE) is a practice by which environmental considerations are integrated into product and process design procedures. DFE practices are used to develop environmentally compatible products and processes while maintaining product, price, performance, and quality standards [14]. DFE considers design issues from an environmental viewpoint as an overall evaluation and includes a set of principles that provides guidelines and references for manufacturers and designers. To maximize product sustainability, it is more desirable to integrate environmentally conscious manufacturing efforts with design for the environment DFE [26].

There are few quantitative tools that exist to use for DFE during conceptual design due to many issues including the cost of LCA and the lack of LCI data that is applicable during early design. Other issues include the accurate representation of uncertainty, the inclusion of life cycle calculations and social impacts for sustainable decision-making, and the allocation of environmental flows to the appropriate process [27]. There are many limitations associated with various sustainable design tools and no sustainable design tool is able to handle all aspects of sustainable product realization [14].

Design for Sustainability (DFS) has emerged as a powerful approach to take broader sustainability related issues into consideration in the early product design stages. These sustainability issues are involved in three aspects: economy, society, and environment. However, qualifying these issues into design factors is very challenging [26].

Design for Disassembly (DFD) is different from the '3Rs'. It considers ease of disassembly at the design stage. DFD is a design strategy that considers the future need to disassemble a product to be repaired, refurbished, or recycled. DFD increases the effectiveness of a product both during and after its life. [9].

Design for upgradability (DFU) enables products to be used for longer than their conventional counterparts. However, one of the difficulties of design for upgradability involves the prediction of future trends such as technological development and market movements; therefore upgradable products must be robust against such future uncertainties [28].

Design for manufacturing and assembly (DFMA) has emerged as a framework to address the imperative need of accommodating manufacturing and assembly considerations within the design. The product manufacturing process is the main stage in the life cycle that consumes resources directly and produces environmental pollution as well as being the main factor that affects the result of enterprise performance in terms of sustainable development. Traditional manufacturing processes are generally designed for high performance and low cost, while little attention is paid to environmental issues. Efforts to minimize the environmental impacts of manufacturing processes can roughly be classified into three categories: process improvement and optimization, new process development, and process planning. Although efforts in improving the environmental performance of manufacturing processes can lead to significant reductions in environmental impacts, these efforts alone may not be sufficient for sustainable product realization [14].

Tools and Methodologies

Accurately analyzing the sustainability of products and processes is very challenging because the analysis methods and tools that exist for sustainable design are generally lowfidelity. Various analysis methods have been proposed and developed for sustainable product design, however there is little consistency in the impacts that these tools assess. Most sustainable design methods developed in the past failed to address the interdependencies among different stages in a PLC. This deficiency may result in biased estimation and ill-informed decisions. Other feature-based sustainable design methods suffer from oversimplification by failing to fully consider the other phases of a PLC. Current eco-design tools vary in data presentation and design process implementation. Over the past ten years, numerous eco-design tools have been proposed and developed. ISO-TR 14062 suggests the use of some 30 various tools. These tools generally fall into one of the three categories: tools based on checklists, tools based on LCA, and tools based on quality function deployment (QFD) [14]. An emerging need is to develop a systematic method that integrates the scopes of product, process, system, and ecosystem, while balancing conflicting product development perspectives [11].

Eco-Indicator 99 (EI99) is a type of screening LCA method; it is specially developed for product design purposes and outputs a single score number to reflect the environmental impacts in material extraction, production, transportation, usage and disposal stages. Compared to the completed LCA method, it simplifies the procedure of modeling and collecting data for LCI. EI99 sees environmental impacts as damages to three categories: human health, ecosystem quality and resources, as the consequences of the process activities related to the life cycle of a product. It uses a model to calculate the value of damage to each of the three categories. The higher the indicator value, the greater the environmental impact [26].

Once the goal and scope of an LCA have been determined and environmental data has been collected, an inventory result is calculated. This inventory result is usually a long list of emissions, consumed resources, and other items. The interpretation of this list is difficult. ReCiPe is an LCIA procedure designed to help with this interpretation. The primary objective of ReCiPe is to transform the long list of LCI results into a limited number of indicator scores. These indicator scores express the relative severity on an environmental impact category. ReCiPe uses an environmental mechanism as the basis for the modeling that can be seen as a series of effects that together can create a certain level of damage to for instance, human health or ecosystems. ReCiPe determines indicators at two levels: eighteen midpoint indicators and three endpoint indicators. Each method (midpoint, endpoint) contains factors according to the three cultural perspectives: individualist, hierarchist, and egalitarian. These perspectives represent a set of choices on issues like time or expectations, so that proper management or future technology can avoid future damages. Unlike EI99, ReCiPe does not include potential impacts from future extractions in the impact assessment, but assumes such impacts have been included in the inventory analysis. The user can thus choose between uncertainty in the indicators, and uncertainty on the correct interpretation of indicators [29].

Computer aided design (CAD) tools play an essential role in modern product design. Implementing sustainable design in CAD software would be advantageous and a more natural approach for design engineers in their daily work. The issue is that these tools lack material and process data, which is necessary to accurately analyze the environmental impacts associated with products. Conventional CAD technologies are based on feature modeling and LCA involves extra information relating to processes, machines, purchasing and suppliers, which CAD systems do not support and linking design features with LCI data may be an infeasible approach [11].

Utilizing LCA software in sustainable design can be helpful in analyzing the impacts of various products and processes. There is various LCA software on the market today such as BOUSTED, SimaPro, Umberto, and GaBi, which provide different degrees of sustainability analysis and can eliminate time spent deriving sustainability metrics manually [17]. While LCA software can be extremely helpful, it is not directly linked to process synthesis-design tools that can generate sustainable design alternatives. Thus, there is still a need for simple LCA software that can be integrated with process design tools in order to perform multi-objective process evaluation [17].

There are various methods and tools other than LCA and eco-design assisting designers in evaluating aspects of sustainable design that conventional product development tools usually tend to ignore. These tools focus on design aspects such as environmental impacts, defining potential problems, suggesting improvement strategies, and exploring optimal decision-making. These methods include Environmentally Responsible Product Assessment (ERPA) and checklists or matrix approaches [30].

A matrix approach is one of the most common abridged methods of analysis and usually involves assigning priority weighting and scores to a list of environmental considerations. Qualitative and quantitative data inserted within the matrix may be scored using an appropriate scoring system suited to the particular purpose. Qualitative data depends on the experience and knowledge of the user and will involve developing ‘rules of thumb’ based on practical experience. The outcome of the scores will highlight areas in the PLC with the greatest environmental impacts, and help pinpoint priorities for further design effort in decreasing these impacts. Abridged LCA using predominantly qualitative data can typically identify 80% of the useful actions that could be taken. [18]

Other tools can have sustainability-related criteria added to their regular functionality, but are not inherently designed to do sustainable design. These tools include: Failure Mode Effect Analysis (FMEA), Quality Function Deployment for Environment (QFDE), and the Theory of Inventive Problems Solving (TRIZ). However while suggesting improvement strategies, these environmental tools put mostly aside cost and quality parameters [31].

Method

The purpose of this research is to explore the application of existing sustainable design tools on a particular product to better understand the current state of the SPD process. In an effort to develop a product that is potentially desirable, a target market was chosen – those who are already making sustainability-conscious decisions, such as commuting without gas- or electric-powered vehicles. It was decided that for this project it would be the most beneficial to choose a popular bike, which catered to cyclists who primarily used their bicycle for short commutes, such as to and from work, rather than those who purchased a bicycle for competition in extreme sports or professional touring. A new human-powered commuting vehicle design would then be developed based on this customer basis and the environmental assessment of the bicycle. An important question was which brand and style of bicycle to choose. To answer this, it was important to collect information about customer purchases in order to make a decision based on data, rather than make a decision based on personal preference. This would provide a more accurate analysis of commuter needs and prevent any underlying biases based on the decision of the brand. Ultimately, a survey based on consumer purchases was necessary to determine the brand and style of bicycle to purchase in order to develop a baseline environmental assessment for the new commuter vehicle design.

The survey developed for this study involved speaking to representatives at a wide assortment of bicycle shops across the United States in order to determine which type of bicycle to purchase. It was necessary to make sure that this survey complied with the Institutional Review Board (IRB), because of the involvement with human subjects. After an IRB survey evaluation at Oregon State University, it was concluded that if the respondents based their answer solely off bicycle sales (and not their own experience or opinion), then no IRB approval would be needed. Needing no approval eliminated many of the steps and constraints that would have been necessary if the survey had required approval from the IRB.

There needed to be a way to determine which bicycle shops to survey in order to obtain results that would be conclusive of the entire United States (accounting for climate, local commuting culture, and other unknown factors). A simple way to locate popular bicycle shops in different states is to use the 'Maps' feature of the popular Google search engine [32]. This was a cost-free and easy way to gain information on popular bicycle shops including their phone numbers, which was necessary to conduct this survey. The Maps feature of Google organizes shops based on customer reviews to display popularity. This knowledge was necessary to develop an algorithm that would randomly choose 10 states and 5 shops from each state, for a total of 50 shops to be surveyed. It was hypothesized that 50 shops would provide enough information necessary to be able to determine the most popular commuter bicycle in the United States.

Once the randomly ordered states and shops had been chosen, the survey was conducted. It was necessary that people being surveyed based their answers on shop sales, rather than their assumption of popular bicycles, in order to comply with the Institutional Review Board. It was also pertinent that the bicycle shops surveyed sold an assortment of bicycle brands, rather than specializing in a particular brand, so that accurate data would be collected. If a bicycle shop was unable to answer the survey questions, or if the shop specialized in a specific brand of bicycle, then the next shop on list would be surveyed. This continued until 5 complete answers were obtained from each of the 10 states.

The results of the survey yielded many different bicycle brands to consider for the bicycle that would be used for a baseline environmental impact assessment. Based on the results of the survey, there were twelve brands and twenty-five different models of bicycles that were considered. Jamis, Trek, Giant, Cannondale, Specialized, Survello, Purefix, Raleigh, Novara, Diamondback, Marin, and Kona were the twelve bicycle brands that were determined to be the most popular bicycle brands in the United States. The bicycle model that was determined to be the most popular, for short commutes, in the United States was a model in the Trek FX 7 series. This specific series of bicycles has multiple models, and it was necessary to decide which of these to purchase. It was decided that the base model, Trek FX 7.0, would yield results that could be applied accurately to the majority of people in the United States who were looking for a low cost bicycle that could be used for short commutes. This decision was made because the basis for this analysis was to obtain a bicycle that would reflect the majority of commuters in the United States. There is a large discrepancy in the materials and manufacturing methods that are used to develop high-end, expensive, and customized bicycles in comparison to a low cost, mass-produced bicycle, so the environmental impact results would differ immensely based on the model chosen. Environmental impact results obtained from a mass produced bicycle will be more useful to analyze and improvements in the sustainability of this design will yield a overall larger reduction in environmental impacts because of the large scale production of these models.

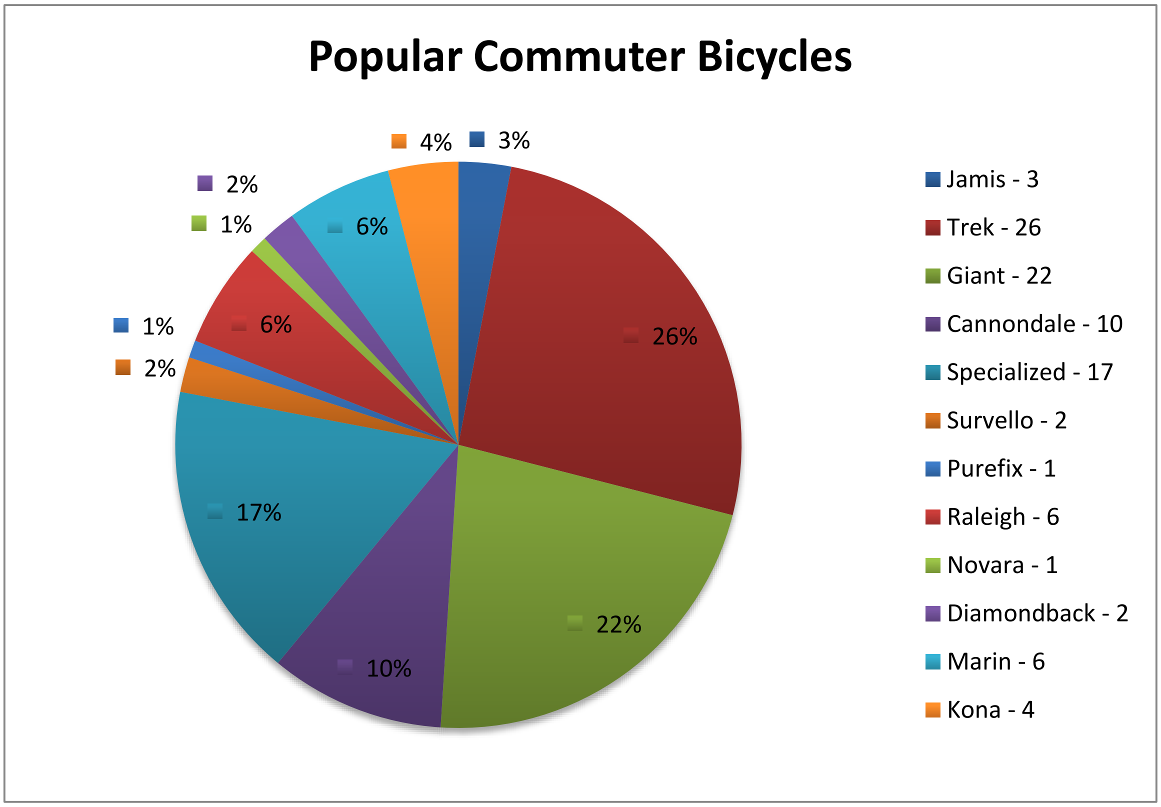

Figure 3: Common commuter bicycle results obtained from a nationwide survey

In order to obtain an accurate analysis of the type of impacts the Trek FX had on the environment using environmental impacts tools and methods, it was necessary to reverse engineer and analyze the Trek FX on a part-by-part basis. The techniques that were used to analyze the parts included manual analysis using the EI99 manual and CAD analysis using Solidworks Sustainability. It was important to use both of these analysis techniques because they provide varying levels of sustainability analysis. The EI99 supplies important information needed to determine impacts that are created during the "cradle to grave" or life cycle of the product. CAD analysis, on the other hand, is important because it provides important information on environmental impacts, as well as information that can be used to help diminish many of these impacts through the incorporation of different materials that provide comparable performance.

An important thing to do, throughout the process of reverse engineering, was to document all of the components of the Trek FX in detail in a bill of materials (BOM) that could be used for reference during later phases of component analysis. The BOM, for the Trek FX, documents important and useful information including the weight, name, type of material of each component, as well as create a numbering system for the parts so they can easily be identified. It was important to create an accurate and detailed BOM so that there would be a reference for important information relating to the analysis of environmental impacts, namely weight and material type, which could be utilized in subsequent stages of this project. The BOM, for the Trek FX 7.0, is one of the most important and informational supporting documents because it is utilized often in the progression of this project and can be located in Appendix A.

After completing the Bill of Materials, the next step was to develop CAD models for components of the Trek FX. CAD models were a necessity for this project in order to obtain accurate environmental analyses, as well as be a useful reference for the design of the new human-powered commuting vehicle. The CAD models were developed in Solidworks and analyzed using the sustainability feature within this program. The importance of a CAD model of each component was determined based on whether methods to redesign that particular component would be pursued. Components including the braking system and gear shifting system were not modeled because it was hypothesized that these components would be difficult to develop new designs for, based on their complexity, or that similar systems would be used in the new design. In the process of building these CAD models, learning multiple modeling techniques was necessary in order to accurately create these models. For example, a comprehensive understanding of the lofting feature was necessary to recreate portions of the Trek FX components that could not be created using extrusions of simple geometries. The frame was a component of the Trek FX that required frequent lofts to develop and accurate model. The pattern feature, circular pattern specifically, was a necessary skill to master in order to create models for the sprocket, and wheels, along with several other components of the Trek FX. In a brief analysis of the Trek FX, there were eighteen components that were ultimately not modeled because there would be little chance of improving the impact of these parts for the new vehicle design including: the derailleurs, shifting and brake cables, and other small components that are included in the braking and shifting mechanisms.

This information was ultimately gathered in order to use the EI99 manual to analyze and determine a final impact value for the Trek FX based on the summation of the impacts of all the components and use Solidworks Sustainability in order to further analyze the original components against the components used in the new design. The goal of this project is to design a human-powered commuting vehicle that has a total EI99 value that is lower than that of the Trek FX, utilizing techniques including material selection, weight reduction, and design simplification.

The design of the human-powered commuting vehicle is focused on lowering the EI99 point value of the components, thus reducing the overall environmental impact. The EI99 manual is used to place a value to the environmental impacts of a product, based on its life cycle. As there are many design options available for a certain product, the Ei99 is used to determine the option that has the lowest environmental impact, based on a point value given to each overall design. The EI99 manual was created for companies to design more environmentally-conscious products, but its use was not intended for government standards or for consumer information (i.e. product A is better than product B). The EI99 value can be calculated in three steps: (1) complete an inventory of all relevant emissions, resources extractions, and land-use in all processes that form the life cycle of a product, (2) calculate the damages these flows cause to Human Health, Ecosystems Quality, and Resources and (3) weigh these three damage categories. The basis for the EI99 manual is also used in the GaBi educational software [33].

This study used the EI99 manual in order to analyze the environmental impact of the Trek FX on a part-by-part basis. This method of generating environmental impact values for the different components is a useful way to analyze products, because it takes into account the life cycle of the components and in most cases, can be used to identify major impact parts of an assembly that would be suitable for a new design. The EI99 analyzes several phases of the PLC include material extraction, transportation, use, and disposal of the material. It should be noted that the use phase was not included in the analysis of this product because there are negligible impacts generated directly from the Trek FX during the use phase, assuming that no parts are replaced.

There were several challenges and in developing accurate environmental impacts analyses for certain components. EI99 evaluations are dependent upon the weight of the material and because these were very lightweight parts, they would likely have a very low environmental impact. Thus the low-weight components of the Trek FX, less than one gram, were taken to weigh one gram, to simplify the analysis. Another challenge was that impact values for the EI99 manual had to be approximated for certain components of the Trek FX because there were several materials and disposal processes not included in the manual that were necessary based on the Trek FX's design. The material values approximated included brass, tin, and several polymers. The material disposal processes absent from the manual included all wood processes, several polymers, and rubber. The absence of these processes was a major roadblock because wood was a major consideration for the design of the new frame, many of the polymers were critical to the analysis of the original design and the development of the new design, and rubber is not biodegradable and cannot be recycled so it was hypothesized that rubber would have a large impact in the analysis of the disposal phase of the Trek FX. The EI99 manual offers an explanation to the absence of some these materials - "Building materials that are to be regarded as chemically inert have no other environmental impact than that they occupy an area in a landfill" [32]. A general figure for landfilling a certain volume has been given, but this value is only valid under certain assumptions of the material. However, these assumptions are unclear in that they are based on material height rather than volume and do not apply to rubber or polymers.

After analyzing the Trek FX on a part-by-part basis and obtaining the results, determining and evaluating the major environmental impact components of the Trek FX was the next step. The higher environmental impacts were directly correlated to the parts of the Trek FX that had larger weights. This is in part due to that the EI99 manual evaluates environmental impacts of materials on a weight basis. There were fifteen components that had major contributions to the impact of the Trek FX. The largest of these contributions came from the frame, front fork, sprocket, wheels, and tires. Another important point is that most of these heavy components are manufactured from materials that have relatively high impact values. EI99 values for the original design can be found in Appendix B.

This information can be used to develop a more eco-friendly design using multiple strategies. The known materials of the components on the Trek FX can be used to choose materials with similar or comparable material properties that have a lower environmental impact. The weights of these parts also have a large effect on their environmental impacts. Designing product structures that make more efficient use of their materials, thus reducing their weights, can reduce these impacts. These two methods can be used together to create components that are both lighter and use more sustainable materials and manufacturing methods. Incorporating the use of recycled materials into the new design would also be an effective and simple way to lower the impact of the components.

Results

In order to better understand how the sustainable design process works and how it can be used to redesign existing products, a case study of the design of a human-powered commuting vehicle was conducted. In order to develop this eco-friendly design, other requirements needed to be addressed to meet the needs of the customer. The necessity to meet these various requirements in development of a sustainable human-powered commuting vehicle, lends valuable insight into the product design process and how eco-design can be incorporated, thus allowing this case study to be applicable in areas of industry and research.

The goal of this project was to develop a human-powered commuting vehicle design that had a lower environmental impact than a Trek FX 7.0, a popular commuter bicycle determined by a nationwide survey, based on an EI99 analysis and further evaluation using Solidworks Sustainability. In order to develop a more eco-friendly design, it was necessary to develop new designs for many of components of the Trek FX utilizing sustainable strategies to lower their environmental impacts. The major sustainability strategies used in the design of the new components included light weighting, material selection, and reduction of parts. The Trek FX is made up of various components that these strategies can be applied to, however there are many other components where these strategies cannot easily be applied because their size and material structure is crucial to the longevity of the system. Based on this, redesign efforts were focused on applying these strategies to components that had larger EI99 scores in order to achieve greater reduction of various environmental impacts. The components with the highest environmental impacts were the frame, handlebars, wheels, tires, sprocket, and front fork.

The frame, being the component that contributed the highest environmental impact to the bicycle, was the primary component on the new design that sustainable design strategies were focused. The frame of the Trek FX is one-piece and made from 6061-aluminum. Aluminum is very lightweight, thus strategies focused on reducing the weight and number of parts of this component were not be feasible in development of a new design. The strategy for developing a more eco-friendly frame was to utilize a different, more sustainable material while optimizing weight and considering the needs of the user. This was a challenge to accomplish because there are various materials that would be well-suited in the development of a new frame, however based on the material selected, various design styles would need to be implemented that differ greatly from each other.

The thought was then to create a frame style and choose the most sustainable material based on that design, however the issue in this case is that the optimal design would not necessarily be achieved without using iteration methods. These methods require extra time that was not available during the design phase of this human-powered commuting vehicle. There are no tools available that can be used to aid in this dilemma, and because of our customer driven requirements for an innovative frame design, it was necessary to use our empirical knowledge of sustainable, yet strong materials, to develop the design. Based on our knowledge of material selection, and the information of material impacts provided in the EI99 manual, sustainably-sourced wood was chosen as the primary material for the new frame design. Once the material was picked, the frame was designed to use a method of combining several plies of wood and bend them to the desired shape. Based on the new design, ash wood was picked as the primary material for the frame because the consistent grain structure that will remain once bent.

The final design of the frame was able to achieve an EI99 point production value score of 362.653 mPt compared to the original Trek FX frame of 1533.6 mPt. It should be noted that the EI99 method did not provide recycling, incineration, and landfill impact values for ash wood, so these areas could not be compared to the aluminum frame of the Trek FX. The landfill value for wood was estimated based on the volume of component as opposed to the weight based values used for all other impact calculations. The disposal indicator value for the new frame was 3.08 mPt compared to the aluminum frame value of 2.52 mPt. This disposal value indicates that the new wood frame will release more emissions and have a greater impact on the environment that the aluminum frame, if these components are disposed of in a landfill. This is mainly due to the amount of material that was used in the construction of the frame, including the large amount of excess material. This amount of excess material can be reduced significantly by incorporating manufacturing methods that allow for more efficient use of materials.

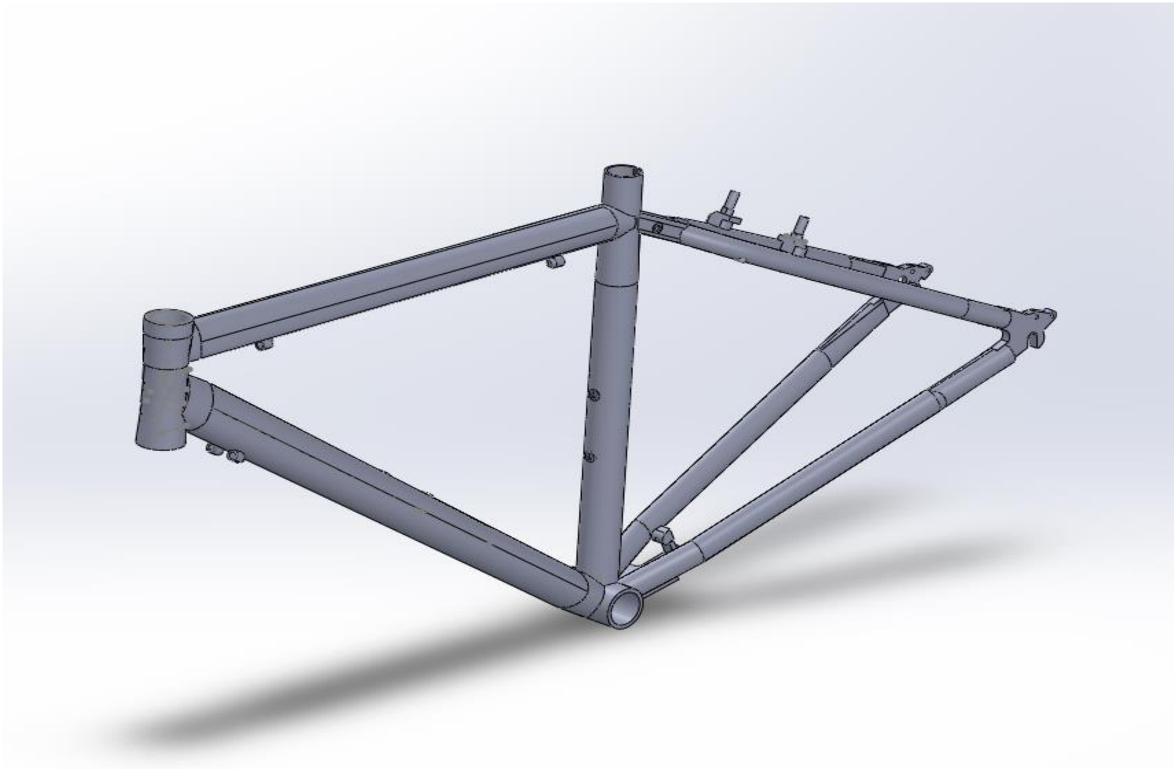

Figure 4: CAD model of the Trek FX frame used for Solidworks Sustainability analysis

Figure 5: CAD model of human-powered commuting vehicle frame for Solidworks analysis

The handlebars of the Trek FX are made of steel, which is a very strong and has a relatively low EI99 indicator value compared to other metals. However, as bicycle handlebars do not have large forces applied to them during their use, this allows for the implementation of various material and design possibilities. Incorporating the customer-driven requirement of aesthetic appeal, the new handlebar design utilizes wood in an effort to increase the aesthetics of the new vehicle. The handlebars were not built when this paper was written, so their weight is estimated based on similar material components in the new design. In the comparison of these two designs, this estimation would affect the accuracy of the analysis only if their indicator values are relatively close. The new handlebar design has an estimated EI99 production impact score of 9.3 mPt while the Trek FX handlebars have a score of 48.07 mPt. The same issues that were faced in determining disposal values for the frame were faced when determining these values for the handlebars. The estimated landfill value for wood handlebar design was 0.21 mPt compared to 0.612 mPt for the steel handlebar. Based on this large difference in impact values, it was determined that this estimation of weight will not significantly affect the sustainability comparison of these designs.

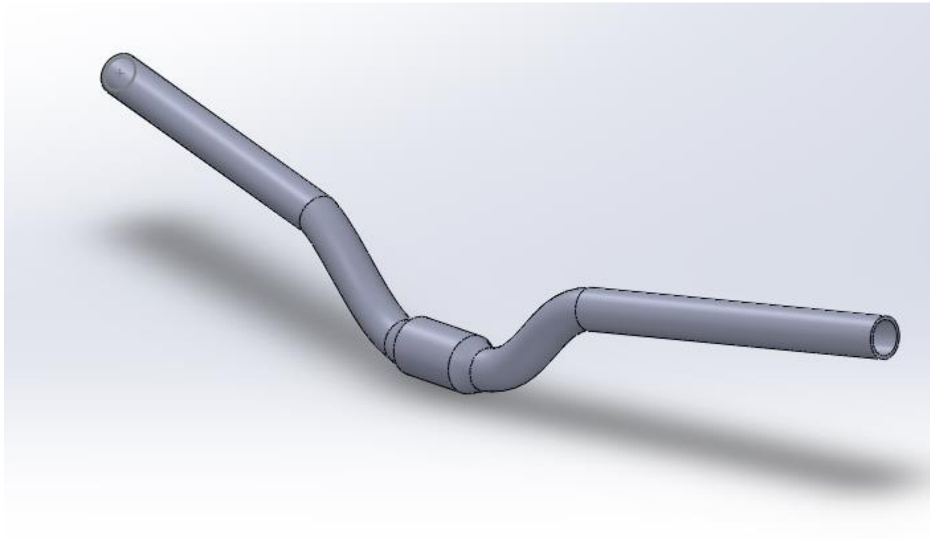

Figure 6: CAD model of handlebars used for Solidworks Sustainability analysis

The wheels of the Trek FX were 26-inch diameter aluminum wheels. In order to achieve a lower environmental impact the strategy implemented was reducing the weight by using 20-inch diameter wheels and using steel wheels rather than aluminum. Smaller wheels will have a reduced weight compared to larger wheels, and based on the customer-driven requirements, it was reasoned that this size would provide comparable durability and maneuverability to larger wheels. The major change in the environmental impact though, comes from the modification of the material from aluminum to steel. The smaller 20-inch wheels have an EI99 production score of 132 mPt while the larger 26-inch wheels have a score of 769.08 mPt. The recycling, incineration, and landfill data for the new design is -84, -38.4, and 1.68 mPt respectively, compared to data for the old design that had respective values of -709.92, -108.46, and 1.384 mPt.

Figure 7: CAD model of wheels used for Solidworks Sustainability analysis

The tires of the Trek FX were made from rubber, a material with a very high environmental impact because it cannot be recycled like many other materials. The tires also require inner tubes, also made from rubber. While there are merits of this tire and tube combination, including being very lightweight, easily serviceable, and low cost, they are easily punctured and require frequent service during their usage, adding to the amount of landfill waste that is developed. To improve this component, airless tires that are made from recyclable polyurethane were incorporated, so replacement of inner tubes would not be an issue with this new design and the environmental impact would be much lower with this recyclable material. The EI99 production score of the new tires was 307.734 mPt and the score of the rubber tires was 523 mPt combined with the inner tube with a score of 162 mPt this created a combined score of 685 mPt. The landfill data is the only other impact value that can be compared to the new tire design, because recycling and incineration data is not available for rubber. The landfill value for the new design is 2.784 mPt compared to 0.6598 mPt for the tire and 0.281 mPt for the inner tube. The new tire design is manufactured from polyurethane and would be recycled as a primary method of disposal. While this value cannot be compared to rubber, as rubber cannot be recycled, it is worth mentioning the various methods of disposal possible for the new tire design. The weight of airless tires is a major factor in their environmental impact, because the EI99 uses a weight-based method of environmental assessment for measuring sustainability. There are lightweight design options for airless tires on the market that could further reduce this impact, but because they are a new technology their price was much too high for the budget of this project.

Figure 8: CAD model of tires used for Solidworks Sustainability analysis

The crankset of the new design incorporated the same aluminum material that was used for the on the Trek FX, but incorporated methods of weight reduction and part reduction based on the size and number of sprockets of the old design. Eliminating two of the cranks from the design reduced the weight of the crankset. The crankset design of the Trek FX incorporated three sprockets in order to effectively use its gear shifting system. This shifting system was eliminated from the new design so that the newly designed crankset only required one sprocket. This new shifting system incorporated an internal hub on the back wheel and will be an automatic method of gear changing as opposed to the manual shifting system on the Trek FX. The new crankset design has an EI99 production score of 64.46 mPt while the Trek FX crankset has a score of 75.5 mPt. The recycling, incineration, and landfill data for the new design is -178.54, -18.75, and 0.82 mPt respectively compared to the Trek FX crankset values of -212.2, -43.09, and 1.04 mPt respectively.

Figure 9: CAD model of original sprocket used for Solidworks Sustainability analysis

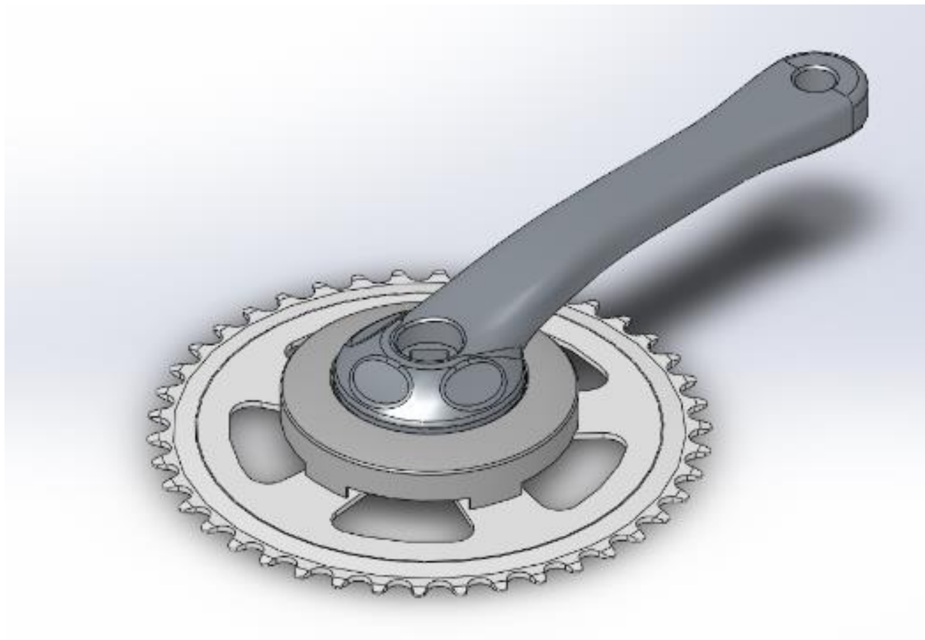

Figure 10: CAD model of sprocket design used for Solidworks Sustainability analysis

There was only a slight modification to the front fork for the new design. It was necessary to increase the length of the front fork in order to accommodate the new recumbent design, however the blades of the front fork were shortened in order to fit the size of the new 20-inch wheels. It was also necessary to continue to use steel as the material for the front fork because of the absorbent and structural properties that steel has in creating a comfortable ride for the user. The new front fork design has an EI99 impact score of 107.8 mPt compared to the Trek FX fork score of 143.11 mPt. The recycling, incineration, and landfill data for the new design are -68.6, -31.36, and 1.372 mPt respectively compared to data for the old design with values of -91.07, -41.63, and 1.82 mPt respectively. By light weighting this component, its sustainability was improved. This was the only high impact component that was not able to achieve a significant impact reduction in the new design.

Figure 11: CAD model of original front fork design

There were certain components for which environmental impacts were not determined in the analysis of the Trek FX design. These components including the brake system and the shifting system and other small components that based on their complexity and size, would have been challenging to develop new designs for and even more difficult to analyze correctly to obtain accurate results with strategies used. These components had little or no change to their style of design. This was beneficial in that the difference in the environmental impact scores of these components be negligible in the overall design. The only non-analyzed set of components that incorporated a completely new design was the gear-shifting system. On the new design, it was decided to utilize a SRAM automatic internal hub as the method for changing gears. This was in part to the customer requirements and the hypothesis that many of the gear ratios that are possible on common commuter bicycles are used infrequently, if at all, and reducing the number of possible gear ratios would not affect usability for the rider. The SRAM internal hub has great customer ratings with many of the positives reviews highlighting the elimination of shifting cables and limited service necessary when compared to traditional shifting systems. There are benefits and drawbacks to this decision based on a sustainability analysis. The benefits include eliminating steel shifting cables and the time required to service the system. Drawbacks to this decision included the greater weight and material complexity, which inherently has a higher environmental impact compared to the original shifting system.

A complete BOM (Appendix C) and EI99 evaluation (Appendix D) of the new design were created in order to compare the impacts of the two designs. The total weight of the human-powered commuting vehicle is an estimated 18147.35 grams; compared to a weight of 10010.505 grams for the Trek FX. This is primarily due to the use of wood for the newly designed frame, which is more than four times as heavy as aluminum Trek FX bicycle frame. Using these methods, a total sustainability impact of 2490.8 mPt for the production of the new design of could be achieved, compared to a total production impact of 4698.5 mPt for the original Trek FX 7.0 bicycle. The recycling, incineration, and landfill data for the new design is -1057.885, -326.3, and 19.63 mPt respectively compared disposal values of -3513.128, -620.638, and 16.305 mPt for the Trek FX. The production impact for the new design is much lower than that of the Trek FX, even though the new design is much heavier. Determining an overall impact value for the two designs is difficult because it is necessary to make certain assumptions about the method of disposal each component of the two designs. Analyzing each of these three disposal categories separately and assuming all off the components are disposed using these methods, the new design is able to achieve overall lower incineration and landfill impact, however the new design and the Trek FX bicycle are able to achieve similar overall impacts if all of their components are recycled, 1432.1 mPt and 1185.4 mPt respectively. This is due, in large part, to the frames of the two designs and the fact that wood does not have a recycled or incineration impact value to calculate. However, this is not an accurate representation of consumer disposal habits. In order to accurately determine disposal values for these designs, data on consumer disposal habits of bicycle components would need to be collected.

Solidworks Sustainability was further used to analyze and compare the sustainability of the high impact components. To perform an analysis using Solidworks Sustainability, CAD models were developed. Models for the frame, wheels, tires, and handlebars, of the old and new design proposed designs, were compared and analyzed in order to obtain a better understanding of what the different strategies implemented would accomplish in terms of improving the overall sustainability. Solidworks Sustainability comparison results are shown below.

As shown in Figure 12, Solidworks Sustainability analysis show that the new frame design was able to achieve drastic reductions in the overall environmental emissions compared to the original frame. This is due to the fact that the new frame design is built from ash wood instead of aluminum. The Solidworks Sustainability analysis for the new frame analyzed oak wood instead of ash wood due to the lack of ash wood material data and was also based on solid wood rather than wood laminate. This analysis also shows that utilizing wood as the primary material can significantly increase the financial impact of the new design as compared to aluminum.

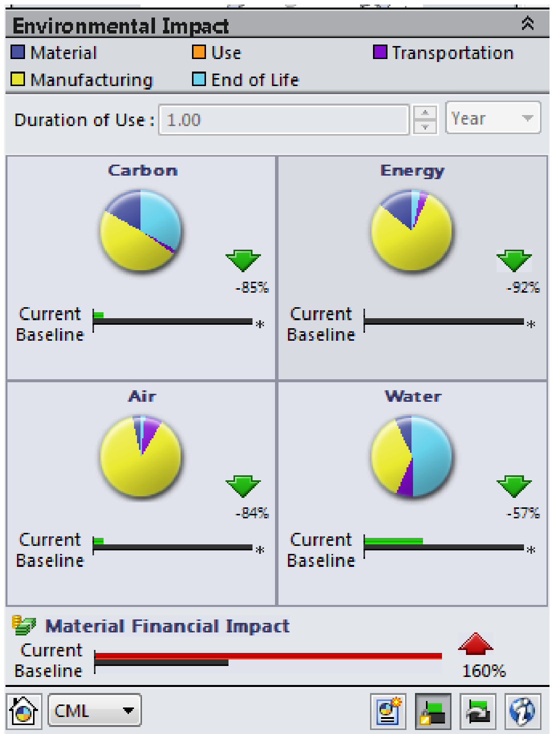

Figure 12: Solidworks Sustainability comparison of frames

As shown in Figure 13, Solidworks Sustainability analysis show that the new handlebar design was able to achieve drastic reductions in the overall environmental emissions compared to the original handlebars. This is due to the fact that the new handlebar design is built from ash wood instead of steel. The Solidworks Sustainability analysis for the new handlebars analyzed oak wood instead of ash wood due to the lack of ash wood material data. This analysis also shows that utilizing wood as the primary material can reduce the financial impact of the new design as compared to steel.

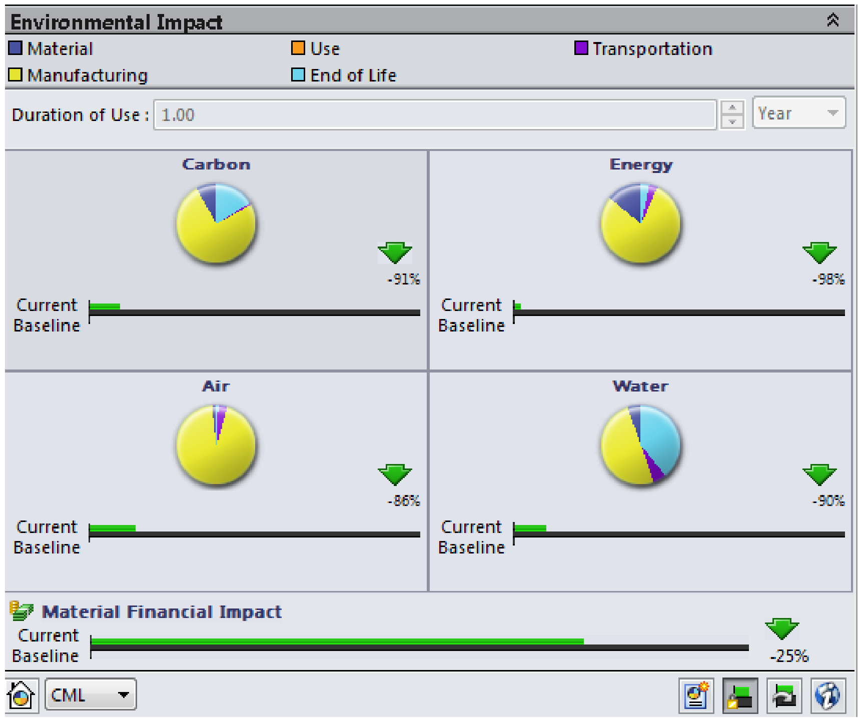

Figure 13: Solidworks Sustainability comparison of handlebars

As shown in Figure 14, Solidworks Sustainability analysis show that the new wheel design was able to achieve drastic reductions in the overall environmental emissions compared to the original wheels. This is due to the fact that the new wheel design is built from steel instead of aluminum. This analysis also shows that utilizing steel as the primary material can drastically reduce the financial impact of the new design as compared to aluminum.

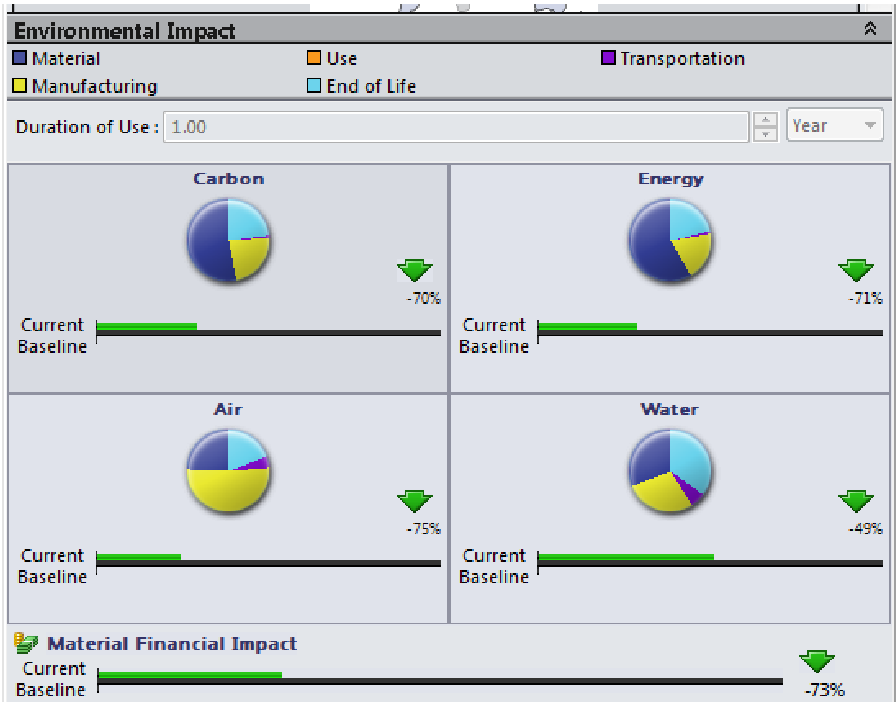

Figure 14: Solidworks Sustainability comparison of wheels

As shown in Figure 15, Solidworks Sustainability analysis show that the new tire design was able to achieve drastic reductions in many of the environmental emissions compared to the original tires however, the energy input required and financial impact for this new design is drastically increased. This is due to the fact that the new tire design is built from polyurethane instead of rubber. The Solidworks Sustainability analysis for the new tires analyzed polyethylene instead of polyurethane due to the lack of polyurethane material data. Improving the accuracy of this analysis would require the inclusion of polyurethane data into Solidworks Sustainability.

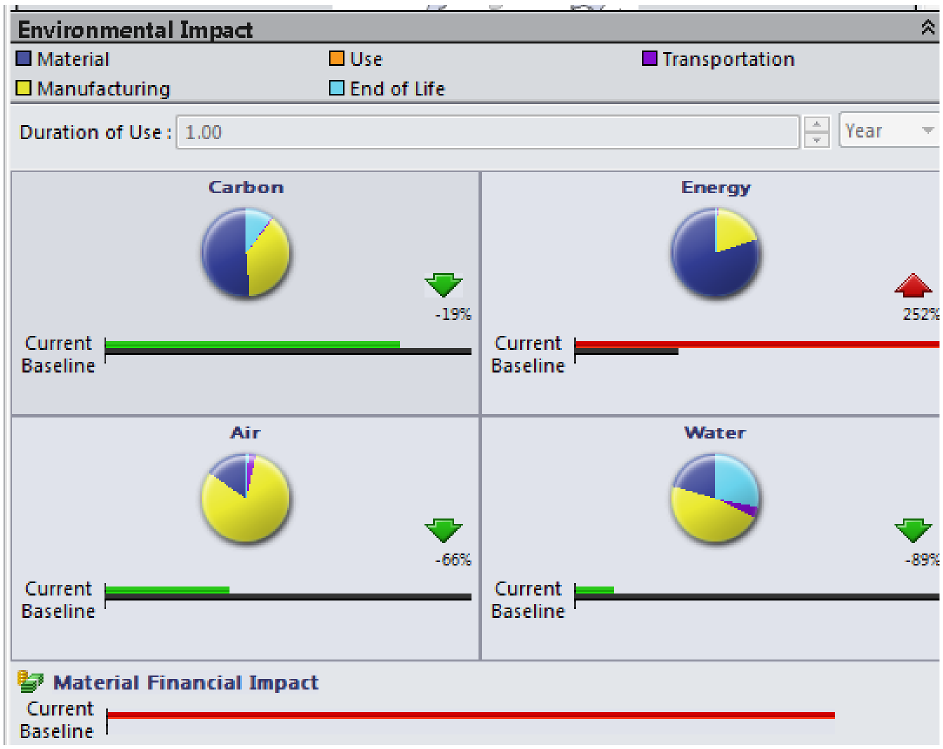

Figure 15: Solidworks Sustainability comparison of tires

As shown in Figure 16, Solidworks Sustainability analysis show that the new crankset design was able to achieve drastic reductions in the overall environmental emissions compared to the original crankset. This is due to the fact that the new crankset design is significantly lighter than the original crankset design. This analysis also shows that reducing the weight of the new design is also able to significantly reduce the financial impact.

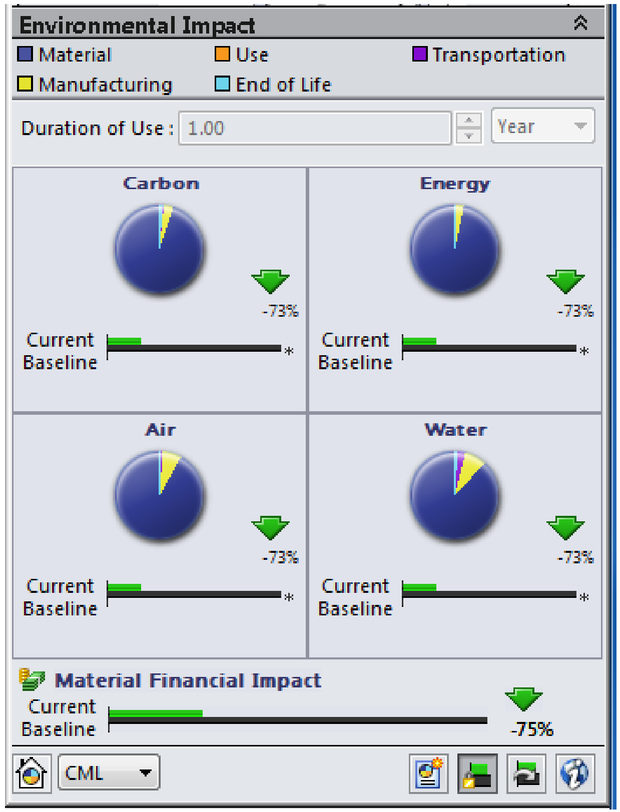

Figure 16: Solidworks Sustainability comparison of cranksets

Based on the analysis performed in Solidworks Sustainability, the components for each design were able to achieve some type of reduction in their environmental impacts; this reiterated the results obtained from the EI99, but with more information on the lowered impacts and in slightly greater detail.

There were many challenges faced using Solidworks Sustainability in analyzing the components accurately. One of the major problems was that not all of the component materials were available for analysis, so in these cases materials with similar environmental properties were used to analyze these components. The new tires are made of polyurethane, which is not an available material to be used for analysis in the Solidworks Sustainability software, so polyethylene was used as the reference material in order to get a relative idea of the impact of the new tires (Figure 17). The wood used for the frame and the handlebars of the new design was made of ash. This material was also not available, so an analysis was conducted using oak as the reference material in order to obtain a relative impact value.

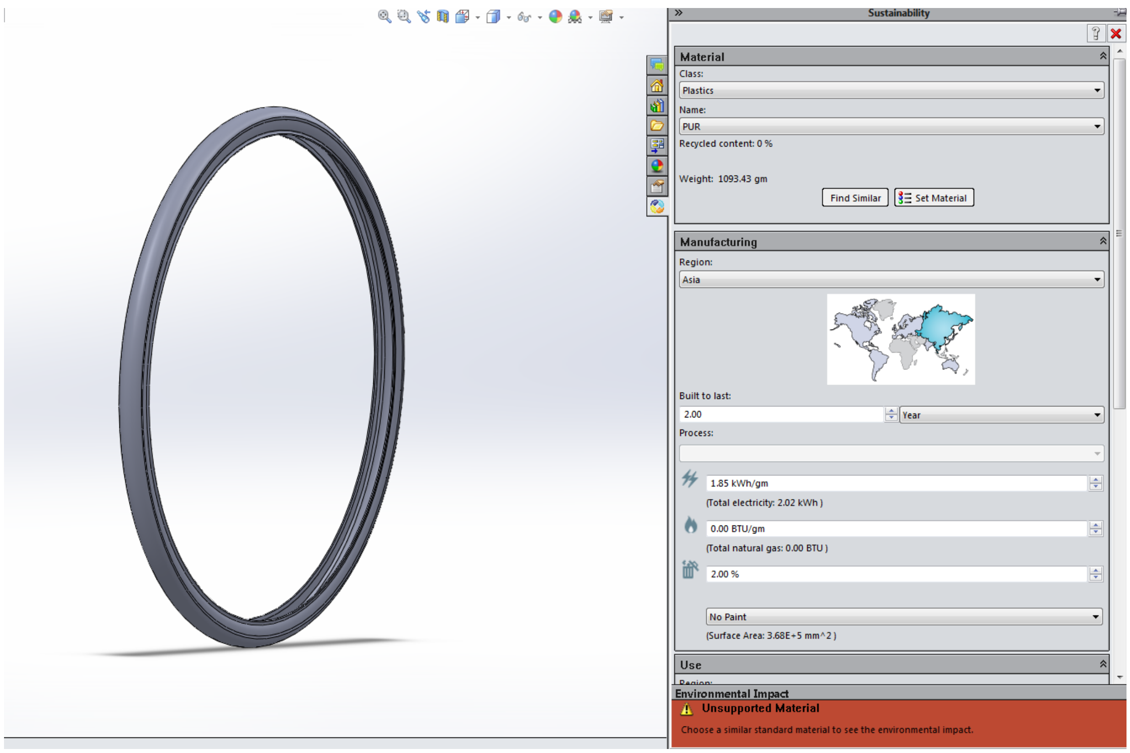

Figure 17: Displaying the unsupported polyurethane material in Solidworks Sustainability

Including the challenges described above, there were also many difficulties that were encountered in the development of the new design. The early phases of concept generation were particularly difficult because of the tradeoffs that exist between design concept and material selection. This “fuzzy front end” - as mentioned in the literature review – was facilitated by focusing on material selection and using that to direct concept generation.

However this is not a simple and reliable method and would be difficult to use accurately in other redesign situations due to its complexity and uncertainty.

Another major challenge was accurately analyzing the materials of the original Trek FX because the material data was limited and there was a certain level of estimation that was necessary in obtaining useable impact values for each of the components. While this method was helpful in determining rough values, there was a level of uncertainty that is difficult to calculate and makes it difficult to accurately analyze the sustainability.

Another difficulty is that there are a very limited number of analysis tools that can be used easily by designers in analyzing and determining sustainability impact values. While a general understanding of the relative environmental impacts for these components was determined, it is not complete and it is difficult to determine where many of these uncertainties lie because there are few analysis tools to compare to each other.

Conclusion

Sustainable product design is important because as the population grows, the amount of waste being produced also increases and designing “green”, or eco-friendly, products can help reduce or alleviate this waste generation. By incorporating different methods of DFX, green products can be designed to address different areas using different design methods.

It is challenging to take existing products and redesign them to be more sustainable because there is not an easy way to determine and calculate the tradeoffs that occur between design structure and material selection. Optimizing the sustainability of a product is difficult without iteration, which takes time that may not be available to complete accurately and can also be a very costly procedure. While there are many different tools available for the use of sustainability analysis, they all vary in their accuracy and do not use a common impact value for environmental assessment. For these reasons, it is difficult to use sustainable design methods in their current form to accurately analyze and help improve the environmental impacts of products.

This work explored two different methods of sustainability analysis in an overarching customer driven design process, in which the goal was to develop a human-powered commuting vehicle that had a lower environmental impact score than a traditional commuter bicycle. The two methods of sustainability analysis explored were the Eco-Indicator 99 manual and Solidworks Sustainability analysis. These two methods were used to analyze the impacts of the components of the designs because of their popularity, ease of use, and design procedures that were used in the development of a new design. These methods were used to develop a human-powered commuting vehicle that had a lower environmental impact through several strategies including material selection, weight reduction, and component reduction.

This project proved that using sustainable design methods and tools in the redesign of an existing product is an effective way to lower environmental impact of that product. However, these methods and tools are not applicable to an assortment of common materials and they are difficult to incorporate into the product design process, where stakeholder requirements must also be met.

There is more that needs to be done in the development of accurate and effective sustainable analysis tools and methods. The current tools lack important material and LCI data that is crucial to the understanding of sustainability and are incomplete and do not provide simple and consistent impact analysis that designers can use effectively in the development of environmentally friendly products.

Further research into the process of developing eco-friendly products will continue, in an effort to create a simple and accurate method to analyze the environmental impact of products and help designers make informed decisions to determine improvement strategies.

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Appendix A: Bill of Materials for Trek FX 7.0

Part #	Name	Material	Quantity
1	Frame	6061 Aluminum	1
2	Socket Head Cap Screw	Stainless Steel	4
3	Socket Head Cap Screw + Washer	Stainless Steel	1
4	Frame Plug	Plastic	6
5	Derailleur Hanger	Stainless Steel	1
6	Derailleur Hanger Socket Head Binding Post Male	Stainless Steel	1
7	Cable Track	Plastic	1
8	Cable Track Pan Head Phillips Machine Screw	Steel	1
9	Saddle Clamp Top	Steel	1
10	Saddle Clamp Bottom	Steel	1
11	Button-Head Socket Cap Screw	Steel	2
12	Countersunk Washer	Steel	2
13	Barrel Nut	Steel	2
14	Seat Post	Aluminum	1
15	Seat Post Clamp	6061 Aluminum	1
16	Button-Head Socket Cap Screw + Washer	Stainless Steel	1
Part #	**Name**	**Material**	**Quantity**

17	Saddle Staple Guard Back	Plastic	1
18	Saddle Staple Guard Front	Plastic	1
19	Pointed Socket Head Screw for Plastic	Steel	10
20	Foam Cushion	Foam	1
21	Staple	Steel	
22	Synthetic Cover	Plastic	1
23	Seat Frame	Plastic + Steel	1
24	Seat Frame Bars	Steel	2
25	Handlebar	Steel	1
26	Hand Grip	Kraton Rubber	2
27	Hand Grip End Plug	Plastic	2
28	Stem	Steel	1
29	Stem Faceplate	Steel	1
30	Socket Head Cap Screw	Steel	2
31	Split Lock Washer for Socket Head Cap Screw	Steel	2
32	Stem Socket Head Cap Screw	Steel	1
33	Split Lock Washer for Stem Socket Head Cap Screw	Steel	1
34	Wedge	Steel	1
Part #	**Name**	**Material**	**Quantity**

35	Big O-Ring	Steel	2
36	Small O-Ring	Steel	1
37	Lock Nut	Steel	1
38	Top Adjustable Cup	Steel	1
39	Front Fork	Steel	1
40	3 Sprocket and Pedal Arm	Steel + Forged Aluminum Alloy	1
41	Lone Pedal Arm	Forged Aluminum Alloy	1
42	Bottom Bracket Socket Axle Bolt with Plastic Collar	Stainless Steel	2
43	Sprocket Chain Guard	Plastic	1
44	Flat Head Phillips Screw	Stainless Steel	4
45	Locknut	Steel	1
46	Bearing Case	Steel	2
47	Ball Bearings and Cage	Stainless Steel	2
48	Rubber O-ring	Rubber	2
49	Rubber Grommet	Rubber	2
50	Pedal Attachments and Case	Steel and Plastic	1
51	Outer Link Plate	Alloy Steel	116
52	Inner Link Plate	Alloy Steel	116
53	Roller	Alloy Steel	116
Part #	**Name**	**Material**	**Quantity**
54	Pin	Alloy Steel	116

55	Pedal	Nylon	2
56	Reflector + Bolts	Plastic + Stainless Steel	2
57	Hex Nut With Tooth Lock Washer	Stainless Steel	4
58	Pedal Shaft	Steel	2
59	Pedal Cap	Nylon	2
60	Tire	Synthetic Rubber	2
61	Inner Tube	Butyl Rubber	2
62	Inner Tube Cap	Plastic	2
63	Wheel Reflector	Plastic	2
64	Rim Strip	Rubber	2
65	Front Wheel	6061 Al Rim	1
66	Hex Nut	Steel	4
67	Spring	Steel	4
68	Front Skewer Rod	Steel	1
69	Back Skewer Rod	Steel	1
70	Threaded Cap	Steel	2
71	Quick Release Lever	Steel	2
72	End Cap	Steel	2
73	Back Wheel	6061 Al Rim	1
74	Cassette	Steel	1
75	Cassette Chain Guard	Plastic	1
Part #	**Name**	**Material**	**Quantity**
76	Brake Arm	Forged Aluminum	2

77	Brake Arm w/ Quick Release Hinge	Forged Aluminum	2
78	Button-Head Socket Cap Screw	Stainless Steel	2
79	Button-Head Socket Cap Screw + washer	Stainless Steel	2
80	Button-Head Socket Cap Screw + washer	Stainless Steel	2
81	Brass Washer	Brass	4
82	Plastic Washer/Guard	Nylon	4
83	Tension Spring	Steel	4
84	Plastic Washer	Plastic	4
85	Pan Head Phillips Machine Screw	Steel	4
86	Brake Tension Manipulator	Steel	4
87	Brake Pad + threaded rod	Rubber + Stainless Steel	4
88	Socket Nut	Stainless Steel	4
89	Self-Aligning Washer Male Half	Steel	8
90	Self-Aligning Washer Female Half + Washer	Steel + Stainless Steel	4
91	Self-Aligning Washer Female Half	Zinc	4
92	Serrated Washer	Stainless Steel	4
Part #	**Name**	**Material**	**Quantity**
93	Front Derailleur	Not Analyzed	1

94	Back Derailleur	Not Analyzed	1
95	Front Brake lever and Shifter	Not Analyzed	1
96	Back Brake lever and Shifter	Not Analyzed	1
97	Shifting cable	Steel	1
98	Brake Cable	Steel	2
99	Brake Cable Solder End	Tin	2
100	Shifting Cable Housing	Plastic + Steel	1
101	Shifting Cable Solder End	Tin	1
102	Brake Cable Housing	Plastic + Steel	2
103	Front Cable Noodle	Stainless Steel	1
104	Noodle Cable Sheath	Plastic	2
105	Cable Spring	Stainless Steel	1
106	Cable Spring Mount Button	Brass	1
107	Front Cable Housing End Cap	Plastic	1
108	Back Cable Housing End Cap	Aluminum	1
109	Back Cable Noodle	Stainless Steel	1
110	Cable Boot	Rubber	2
111	Cable End Caps	Aluminum	4
Part #	**Name**	**Material**	**Quantity**
112	Cable Frame Protector	Synthetic Rubber	3

113	Front reflector	Plastic	1
114	Pan Head Phillips Machine Screw + Washer	Steel	1
115	Handlebar Clamp	Plastic + Steel	1
116	Back Reflector	Plastic	1
117	Seat Post Clamp	Plastic + Steel	1
118	Reflector Mount	Plastic	1
119	Pan Head Phillips Machine Screw	Steel	1
120	Pan Head Phillips Machine Screw	Steel	1
121	Hex Washer Head Screw	Stainless Steel	1
122	Hex Nut	Steel	1

Appendix B: Eco-Indicator 99 Results for Trek FX 7.0

Part #	Weight (g)	Production (mPt)	Recycling (mPt)	Incinerated (mPt)	Landfill (mPt)	Volume (m^3)
1	1800	1533.6	-1296	-198	2.52	N/A
2	3	0.33	-0.21	-0.096	0.0042	N/A
3	3	0.33	-0.21	-0.096	0.0042	N/A
4	0.25	0.16275	0	0.000275	0.0009	N/A
5	16	1.76	-1.12	-0.512	0.0224	N/A
6	4	0.44	-0.28	-0.128	0.0056	N/A
7	4	2.604	0	0.0044	0.0144	N/A
8	1	0.11	-0.07	-0.032	0.0014	N/A
9	20	2.2	-1.4	-0.64	0.028	N/A
10	39	4.29	-2.73	-1.248	0.0546	N/A
11	8	0.88	-0.56	-0.256	0.0112	N/A
12	0.5	0.055	-0.035	-0.016	0.0007	N/A
13	7	0.77	-0.49	-0.224	0.0098	N/A
14	232	197.664	-167.04	-25.52	0.3248	N/A
15	15	12.78000071	-10.8	-1.65	0.021	N/A
16	6	0.66	-0.42	-0.192	0.0084	N/A
17	13	8.463	0	0.0143	0.0468	N/A
18	3	1.953	0	0.0033	0.0108	N/A
19	1.3	0.143	-0.091	-0.0416	0.00182	N/A
20	95	46.208	0	0.1045	0.9215	N/A
21	0.125	0.01375	-0.00875	-0.004	0.000175	N/A
22	40	20.12	0	0.044	0.388	N/A
23	161	104.811	0	0.1771	0.5796	N/A
24	50	5.5	-3.5	-1.6	0.07	N/A
25	437	48.07003496	-30.59	-13.984	0.6118	N/A
26	65	24.765	0	0	0.1035507	7.39648E-05
27	1	0.651	0	0.0011	0.0036	N/A
28	362	39.82	-25.34	-11.584	0.5068	N/A
29	28	3.08	-1.96	-0.896	0.0392	N/A
30	8	0.88	-0.56	-0.256	0.0112	N/A
31	0.5	0.055	-0.035	-0.016	0.0007	N/A
32	58	6.38	-4.06	-1.856	0.0812	N/A
33	0.5	0.055	-0.035	-0.016	0.0007	N/A
34	46	5.06	-0.35	-1.472	0.0644	N/A
35	4	0.44	-0.42	-0.128	0.0056	N/A
Part #	Weight (g)	Production (mPt)	Recycling (mPt)	Incinerated (mPt)	Landfill (mPt)	Volume (m^3)
36	4	0.44	-0.49	-0.128	0.0056	N/A

37	20	2.2	-0.56	-0.64	0.028	N/A
38	40	4.4	-2.8	-1.28	0.056	N/A
39	1301	143.11	-91.07	-41.632	1.8214	N/A
40	501	55.11	-35.07	-16.032	0.7014	N/A
41	246	20.418	-177.12	-27.06	0.3444	N/A
42	14	1.54	-0.98	-0.448	0.0196	N/A
43	78	50.778	0	0.0858	0.2808	N/A
44	0.5	0.055	-0.035	-0.016	0.0007	N/A
45	11	1.21	-0.77	-0.352	0.0154	N/A
46	42	4.62	-2.94	-1.344	0.0588	N/A
47	12	1.32	-0.84	-0.384	0.0168	N/A
48	1	0.381	0	0	0.0014	0.000001
49	1	0.381	0	0	0.0014	0.000001
50	188	122.388	-13.16	-6.016	0.2632	N/A
51	1	0.11	-0.07	-0.032	0.0014	N/A
52	1	0.11	-0.07	-0.032	0.0014	N/A
53	0.5	0.055	-0.035	-0.016	0.0007	N/A
54	1	0.11	-0.07	-0.032	0.0014	N/A
55	169	110.019	0	0.1859	0.6084	N/A
56	14	8.974	-0.98	-0.448	0.0196	N/A
57	1	0.11	-0.07	-0.032	0.0014	N/A
58	20	2.2	-1.4	-0.64	0.028	N/A
59	1	0.651	0	0.0011	0.0036	N/A
60	523	199.263	0	0	0.6598283	0.000471306
61	162	61.722	0	0	0.2018419	0.000144173
62	1	0.651	0	0.0011	0.0036	N/A
63	17	6.647	-4.08	-0.0901	0.0697	N/A
64	40	15.24	0	0	0.0685161	4.89401E-05
65	986	769.0800463	-709.92	-108.46	1.3804	N/A
66	2	0.22	-0.14	-0.064	0.0028	N/A
67	0.5	0.055	-0.035	-0.016	0.0007	N/A
68	31	3.41	-2.17	-0.992	0.0434	N/A
69	38	4.18	-2.66	-1.216	0.0532	N/A
70	22	2.42	-1.54	-0.704	0.0308	N/A
71	12	1.32	-0.84	-0.384	0.0168	N/A
72	28	3.08	-1.96	-0.896	0.0392	N/A
73	1117	871.2600525	-804.24	-122.87	1.5638	N/A
74	563	61.93	-39.41	-18.016	0.7882	N/A
75	34	18.054	-8.16	-0.0956862	0.1394	N/A
Part #	**Weight (g)**	**Production (mPt)**	**Recycling (mPt)**	**Incinerated (mPt)**	**Landfill (mPt)**	**Volume (m^3)**
76	33	2.739	-23.76	-3.63	0.0462	N/A

77	33	2.739	-23.76	-3.63	0.0462	N/A
78	5	0.55	-0.35	-0.16	0.007	N/A
79	8	0.88	-0.56	-0.256	0.0112	N/A
80	7	0.77	-0.49	-0.224	0.0098	N/A
81	11.24	21.4687372	-0.6744	-0.060696	0.0175344	N/A
82	1	0.651	0	0.0011	0.0036	N/A
83	4	0.44	-0.28	-0.128	0.0056	N/A
84	1	0.651	0	0.0011	0.0036	N/A
85	1	0.11	-0.07	-0.032	0.0014	N/A
86	4	0.44	-0.28	-0.128	0.0056	N/A
87	24	1.45	-18.24	-2.89	0.0356	N/A
88	3	0.33	-0.21	-0.096	0.0042	N/A
89	0.5	0.055	-0.035	-0.016	0.0007	N/A
90	1	0.11	-0.07	-0.032	0.0014	N/A
91	1	0.11	-0.07	-0.032	0.0014	N/A
92	1	0.11	-0.07	-0.032	0.0014	N/A
93	N/A	N/A	N/A	N/A	N/A	N/A
94	N/A	N/A	N/A	N/A	N/A	N/A
95	N/A	N/A	N/A	N/A	N/A	N/A
96	N/A	N/A	N/A	N/A	N/A	N/A
97	2.226	0.24486	-0.15582	-0.071232	0.0031164	N/A
98	2.5	0.275	-0.175	-0.08	0.0035	N/A
99	2	0	-0.02	-0.01	0.0034	N/A
100	9.114	5.741900203	-0.63798	-0.2816226	0.04557	N/A
101	0.75	0	-0.02	-0.01	0.0034	N/A
102	17	10.7101496	-1.19	-0.5253	0.085	N/A
103	3	0.33	-0.21	-0.096	0.0042	N/A
104	1	0.651	0	0.0011	0.0036	N/A
105	1	0.11	-0.07	-0.032	0.0014	N/A
106	0.5	0.955015	-0.03	-0.0027	0.00078	N/A
107	2	1.302	0	0.0022	0.0072	N/A
108	2	1.704	-1.44	-0.22	0.0028	N/A
109	2	0.22	-0.14	-0.064	0.0028	N/A
110	3	1.143	0	0	0.0014	0.000001
111	1	0.852	-0.72	-0.11	0.0014	N/A
112	1	0.381	0	0	0.0014	0.000001
113	10	3.91	-2.4	-0.053	0.041	N/A
114	5	0.55	-0.35	-0.16	0.007	N/A
115	4	2.52	0	0.0044	0.0144	N/A
Part #	**Weight (g)**	**Production (mPt)**	**Recycling (mPt)**	**Incinerated (mPt)**	**Landfill (mPt)**	**Volume (m^3)**
116	10	3.91	-2.4	-0.053	0.041	N/A

117	6	3.78	0	0.0066	0.0216	N/A
118	3	1.953	0	0.0033	0.0108	N/A
119	2	0.22	-0.14	-0.064	0.0028	N/A
120	2	0.22	-0.14	-0.064	0.0028	N/A
121	2	0.22	-0.14	-0.064	0.0028	N/A
122	1	0.11	-0.07	-0.032	0.0014	N/A
Total (mPt)	10010.505	4698.492297	-3513.128	-620.6382618	16.305433	N/A

Appendix C: Bill of Materials for the New Design

Part #	Part Name	Purchase or Build	Material	Price Each	Quantity
1	Fork	Purchase	Steel	$59.95	1
2	Head Tube	Build	Steel	$20.83	1
3	3/8 all-thread	Purchase	Steel	$18.97	
4	Headset	Build	Steel	$5.24	1
5	Stem	Purchase	Steel	$135.00	1
6	Extension	Build	Ash Wood	$107	1
7	Handlebar	Build	Ash Wood	$0	1
8	Chain	Purchase	Steel	$62.27	1
9	Seat Post Guide	Build	Steel	$20.69	1
10	Crankset	Purchase	Aluminum	$45.99	1
11	Pedals	Purchase	Nylon	$14.49	1
12	Tires	Purchase	Polyurethane	$39.25	2
13	Wheel	Purchase	Steel	$32.99	2
14	Top Frame Member	Build	Ash Wood	$0	1
15	Bottom Frame Member	Build	Ash Wood	$0	1
16	Seat Post	Build	Steel	$20	1
17	Bottom Bracket Casing	Build	Steel	$6.75	1
18	Rear Brackets	Build	Steel	$41.61	1
19	Screws	Purchase	Steel	$8.85	1
20	Nuts	Purchase	Stainless Steel	$8.24	1
21	Seat	Build	Foam	$17.84	1
22	Seat Back Frame	Build	Aluminum	$53.33	1
23	Seat Back Fabric	Build	Hemp Canvas	$17.87	1
24	Transmission	Purchase	SRAM Automatic 2-Speed Hub	$87	1
Part #	**Part Name**	**Purchase or Build**	**Material**	**Price Each**	**Quantity**
25	Reflective	Purchase	Plastic	$10.85	1

	Tape (Red)				
26	Reflective Discs	Purchase	Plastic	$4.99	1
27	Reflective Tape (White)	Purchase	Plastic	$14.64	1
28	Bottom Bracket	Purchase	Bottom Bracket	$12.49	1
29	Brake	Purchase	Single rear brake kit	$35	1

Appendix D: Eco-Indicator for the New Design

Component	Weight (g)	Production (mPt)	Recycling (mPt)	Incineration (mPt)	Landfill (mPt)	Volume (m^3)
Frame (Top and Bottom)	8845.204	362.653364	0	0	3.08	0.011
Seat post outside	992.2335	109.145764	-69.456345	-31.751472	1.3891269	N/A
Seat post inside	756.5	83.2150605	-52.955	-24.208	1.0591	N/A
Head tube	382.71825	42.0990381	-26.7902775	-12.246984	0.53580555	N/A
Front fork	980	107.800078	-68.6	-31.36	1.372	N/A
Bottom Bracket Casing	113.398	12.4737891	-7.93786	-3.628736	0.1587572	N/A
Wheel	1200	132.000096	-84	-38.4	1.68	N/A
Tire	714	307.734	-171.36	1.9992	2.7846	N/A
Dropout	787.5	86.625063	-55.125	-25.2	1.1025	N/A
Bracket	150	16.500012	-10.5	-4.8	0.21	N/A
Handlebar	226.796	9.298636	0	0	0.077681293	0.0002774
Handlebar Clamp	248	193.440012	-178.56	-110	0.3472	N/A
Stem	146	16.0600117	-10.22	-4.672	0.2044	N/A
Seat	760	369.664	-182.4	2.128	2.964	N/A
Crankset with pedal arms	586	64.46	-178.54	-18.752	0.8204	N/A
Nut and bolts	452	411.32	-31.64	-14.464	0.6328	N/A
Pedal	179	116.529	-42.96	0.1969	0.6444	N/A
Handlebar Extension	280	11.48	0	0	0.07986244	0.0002852
Chain	348	38.2800278	-24.36	-11.136	0.4872	N/A
Internal Hub	0	0	0	0	0	N/A
Reflective Tape (Red)	0	0	0	0	0	N/A
Reflective Discs	0	0	0	0	0	N/A
Reflective Tape (White)	0	0	0	0	0	N/A
Bottom Bracket	0	0	0	0	0	N/A
Brake	0	0	0	0	0	N/A
Seat Back Frame	0	0	0	0	0	N/A
Seat Back Fabric	0	0	0	0	0	N/A
Total (mPt)	18147.35	2490.77795	-1057.884483	-326.29509	19.62983338	N/A