Functional Impact Comparison of Innovative and Common Products

Conference Paper · August 2013

DOI: 10.1115/DETC2013-12599

Proceedings of the ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference
IDETC/CIE 2013
August 4-7, 2013, Portland, Oregon, USA

DETC2013-12599

FUNCTIONAL IMPACT COMPARISON OF COMMON AND INNOVATIVE PRODUCTS

Brady Gilchrist*, Douglas L. Van Bossuyt, Irem Y. Tumer
Complex Engineered Systems Design Lab
School of Mechanical, Industrial, and Manufacturing Engineering
Oregon State University
Corvallis, Oregon 97331
Email: gilchrib@onid.orst.edu*, vanbosdo@onid.orst.edu, irem.tumer@oregonstate.edu

Ryan Arlitt, Robert B. Stone
Design Engineering Lab
School of Mechanical, Industrial, and Manufacturing Engineering
Oregon State University
Corvallis, Oregon 97331
Email: arlittr@onid.orst.edu, rob.stone@oregonstate.edu

Karl R. Haapala
Industrial Sustainability Laboratory
School of Mechanical, Industrial, and Manufacturing Engineering
Oregon State University
Corvallis, Oregon 97331
Email: karl.haapala@oregonstate.edu

ABSTRACT

Innovation has been touted as a means toward providing sustainability. Innovations in materials, manufacturing, and product design can lead to a reduction of global environmental impacts while helping to realize the goals of a sustainable society. This research aims to explore whether or not product functionality has an effect on environmental impact and if the flow of energy, materials, and signals (EMS) have an effect on product environmental impact. Innovative and common products are identified and life cycle assessment is performed for each product at the component level. Using function impact matrices, the environmental impacts of the product components are propagated back to the functional level, where their impacts are compared. The innovative products of the comparisons conducted appear to be more environmentally impact; more work must be done to understand whether the result is generalizable. The intended use of this research is during the conceptual design phase when little is known about the final form of a product. With approximate impacts of functions known, designers can better utilize their design efforts to reduce overall product environmental impact.

INTRODUCTION

As new products are designed and existing products are improved upon, it is important to remain vigilant on the environmental impact of those products. "Green washing" has become a serious problem in the sustainable products market, where companies exaggerate or misleadingly present their product's sustainability claims [1]. With a population nearing seven billion and standards of living increasing across the globe, it will be ever more important to maintain a high degree of product responsibility in the coming years.

Sustainable development has been defined as "…development to meet the needs of the present generation without compromising the ability of future generations to meet their own needs" [2]. To align better with this definition and to adopt responsible practices, regulations around the world are requiring manufacturers to be responsible for their products through their entire life cycle [3]. These regulations motivate sustainable product development, which is defined as the process of making products and/or services to be more sustainable throughout their entire life cycle [4]. Even incremental changes in product design can help realize a large reduction in environmental impact. An example of product development with sustainability in mind can be seen in laundry detergents designed for cold water. If all users were to adopt this type of detergent across the U.S., it could cut 3% of the country's overall energy use by avoiding water heating [5]. In addition, cold water detergents are more concentrated, requiring less packaging, and further reducing the environmental impact of the product [5].

Life cycle assessment (LCA) is a standard approach to determine whether or not successive generations of products are more environmentally sustainable than before, by focusing on the relative environmental impacts as measured by such indicators as ecotoxicity, ozone depletion, and land use, among others. To conduct a comprehensive product LCA, it is necessary to have a detailed design, with component geometries and materials chosen. However, during the concept generation phase of design, not much is known about the form of the product and what materials and manufacturing processes will be selected. Without this information, calculating an approximate environmental impact is very difficult. Unfortunately, however, as much as 80% of a product's environmental impact is established during the conceptual phase of design [6]. Thus, there is a disconnect between the product information available in the conceptual design phase and the desired environmental impact information.

Quantifying a product's environmental impact at the functional phase of design is necessary in order to properly leverage the importance of conceptual design on environmental impact. No direct mapping between function and environmental impact exist, however, it is understood that functions lead to form, embodied by components, and environmental impact can be derived from existing components. Using these relationships, the environmental impact of components can be mapped to the functions they perform. This information can then be used when designing a new product by guiding the designer in selecting functions that have low impacts and targeting their design efforts on product functions that have higher impacts.

Comparisons can thus be made at a high level by decomposing actual products and identifying materials and production processes used in creating the products. Life cycle inventories can then be formed and impacts calculated using commercially available LCA software (e.g., SimaPro 7.3) [7]. It is important to note that, due to the dearth of comparable social and economic impact methods for products, sustainability comparisons can be solely on an environmental impact basis.

This paper explores the hypothesis that innovative products are more environmentally sustainable than their common counterparts, and that lower environmental impacts are realized on both the functional and flow level. This work is an extension of prior work reported by Gilchrist et al. [8], with the key difference in this research being that the overall product environmental impacts are distributed to the functions solved within the product. Previous research by the authors only assessed the environmental impact of the product as a whole, not on the basis of its individual components and functions. It is assumed that if designers can create environmentally friendly product concepts at the functional level, then innovative solutions can arise, but there is not evidence that this premise has been previously tested. Additionally, this research examines what functions and flows most affect a design's environmental impact. Once a function's impacts have been identified, a comparison can be made between different functional approaches to accomplish the same user-related functionality (i.e., functions that are associated with accomplishing the needs of a user).

The motivations for performing product LCA studies are introduced below. This then leads to a description of the products to be examined and the methodology employed. Assumptions and limitations of the study are presented next, followed by a discussion of the results. Finally, future work to apply and strengthen the methods and findings of this research is discussed.

RESEARCH CONTRIBUTIONS

This research compares the environmental impact of innovative and common products on both the product-related functional level, as well as the impact of EMS flows. The products used in this research have been identified as innovative by popular media, and are compared with similar products that make no claims of innovativeness (i.e., common products). While there is no concrete definition of innovation, most agree that it involves the application of novel and creative ideas [9].

The hypothesis of this work is that the innovative products have lower environmental impacts than common versions of the same product. To test this hypothesis, the products were decomposed both physically, by disassembly to the component level, and functionally, using the functional basis developed by Stone and Wood [10]. The selection of function and flow for a product is also discussed in the context of reducing environmental impact.

This research begins to develop a method of determining if components that perform the same functions have comparable environmental impacts. This is achieved by the introduction of a novel Product Function Impact Matrix (PFIM), a modification and extension of the Product Function Matrix (PFM) [11] generated by the Design Repository [12]. The PFIM populates a matrix of products and the functions of those products in order to calculate average functional impacts of product groups.

BACKGROUND

Companies across the world are starting to realize the value in designing products in a more sustainable way. This is resulting in significant environmental impact reductions, aided by LCA. Understanding the role LCA plays in design and how it can benefit sustainable design is important to the research presented in this paper. Several tools and methods that take advantage of the power of LCA are described below. They range from QFD-based tools to the one used in this research, namely, function impact matrices.

In this section, research related to incorporating innovation and sustainability into product design is first presented. Next, the LCA method is explained, which is then followed by an explanation of how it can be employed in design. This sets the stage to describe the function impact matrix method used in this research, which combines the QFD and LCA methods.

Innovation and Sustainability in Design

Although technology development has stimulated economic growth, it also has resulted in detrimental resource use and waste generation. A variety of solutions are available to achieve sustainability, and both long-term and short-term solutions need to be employed [10, 11]. In the short term, a product can be redesigned to create a solution with lower overall environmental impacts than the prior product generation. Environmentally sustainable long-term solutions will require a paradigm shift in the way designers think about the products that they develop.

An emerging market trend is that of healthy and sustainable products. This ranges from hybrid and electric vehicles to organic and eco-friendly materials used in consumer products [15]. Sauers and Shekar reported that 5-10% of consumers are willing to pay more for environmentally friendly products and services; while another 70-75% are indifferent as long as the product meets their needs [5]. With sustainability becoming more accepted by mainstream consumers, this market will continue to grow. It has been shown by Abele et al. that, when given the choice, a customer will select an environmentally friendly product over its common competitor when supplied with proper information about its environmental impact [16]. As a result, consumers will likely continue to increase their expectations for more environmentally friendly products.

Aside from addressing the voice of the customer, to be competitive in the global market companies must design products to address emerging environmental policies such as the European Waste Electrical and Electronic Equipment (WEEE) and Restriction of Hazardous Substances (RoHS) directives [3, 17]. To help designers comply with these regulations, several novel design methodologies have been developed. Eco-innovation has been defined by the Organization for Economic and Co-operative Development (OECD) as "the creation…of new, or significantly improved, products (goods and services), processes, marketing methods, organizational structures and institutional arrangements which…lead to environmental improvements compared to relative alternatives" [18]. When sustainability is considered earlier in the design process, the potential for reducing the environmental impact of the final product is greatly increased.

As alluded to above, eco-innovation is a type of design process that focuses on innovation and sustainability in design. As the practice is in its infancy and has yet to be implemented on a wide scale, there is little literature available on eco-innovation techniques to aid designers. Most methods are TRIZ-oriented and based on seven eco-innovation elements including material reduction, energy reduction, and product durability [19]–[23]. TRIZ is a design methodology whose Russian acronym can be translated to "Theory of Inventive Problem Solving" and is based on contradictions in parameters that exist during design. Design principles are used to solve those contradictions [25,27-29].

Another approach for eco-innovation in design takes advantage of the Quality Function Deployment (QFD) methodology, created by Sakao, which works to minimize the negative environmental impacts and costs while evaluating functions based on customer importance [24]. First, an LCA is conducted to get a baseline of environmental impacts. Problem areas are then highlighted and used as inputs to the QFDE (Quality Function Deployment for Environment) as environmental customer requirements in part two of the method. From the QFDE, conflicts with engineering requirements are identified and, using TRIZ inventive principles, those contradictions are solved. It was discovered that a component that has a small environmental impact may have a function that largely affects environmental impacts [24].

These approaches for eco-innovation in design show that there is the potential to reduce environmental impact by focusing on function rather than form, which can address limitations of only focusing on materials and manufacturing based environmental impact reduction. Thus, a broader design methodology incorporating functional changes to reduce impact, rather than just material changes could prove to be useful in reducing environmental impacts of new products.

Life Cycle Assessment in Design

When products are redesigned, they typically have improvements in performance, functionality, and quality [25]. As environmental regulations and policies become more restrictive, products will need to be increasingly designed for environmental sustainability to be sold in the marketplace. Comparative LCA studies can be used to determine whether redesigned products improve upon previous versions environmentally. LCA can be used to examine environmental impacts using a number of different methods. Examining the differences in functionality and components needed to solve functions will give insight into how the innovative products differ from their common competitors.

The backbone of this research is a comparative LCA of an innovative product and a common version of the same product. Using a similar approach, Joshi compared the environmental impacts of steel fuel tanks and plastic fuel tanks [26]. It was found that the steel tanks had a greater environmental impact than the plastic ones in almost all categories of impact. Taking a parallel approach, Hartikainen et al. used a comparative LCA study to determine whether the application of a novel new material for superconducting electromagnets had a smaller environmental impact than the currently used copper electromagnets [27]. Although using superconductor wire requires significantly less material, it requires a more energy intensive process to produce. This results in the copper magnets having a lower impact than the superconducting magnet. Product families were established by Collado-Ruiz and Ostad-Ahmad-Ghorabi to set benchmark values of environmental impact to help target future design efforts. Families of product packaging were compared, including bottles, cans, foils, and storage containers [28]. Such comparative LCA studies for products are commonly reported in the literature [29]–[31].

To conduct an LCA, a life cycle inventory (LCI) is compiled to account for material and energy flows of each process across the product life cycle. In the case of the products studied in the research reported herein, not everything was known about the specific materials used and manufacturing processes necessary to produce the products. To assist in developing the LCI for the products considered, the Design Repository housed at Oregon State University was used to gather component data [32]. The Design Repository is used to capture and reuse design data about components, functions, failure modes, and other product information [33]. Within the Design Repository products are broken down into assemblies, and by individual components within the assemblies. Information is recorded for component material, mass, dimensions, and manufacturing processes [32].

In this study, the Design Repository is used to catalog components of each product. Materials are entered through a drop down menu with a specific set of materials. Metal alloys are generalized as "metal." In this study, metals are assumed to be steel. A similar approach was taken by Deng et al. by assuming the various types of metal in the study were common steel [34]. Similarly, components made of various types of plastic were assumed to be polypropylene, and rubber or synthetic rubber components were assumed to be styrene butadiene. In addition to component data, the Design Repository has functional models of every product in the study. This functional information indicates which functions are performed by which components, as well as the general energy, material, and signal (EMS) flow paths through the system.

LCA is typically used throughout the design process [35], but the uncertainty that exists in the early design stages increases the difficulty of performing accurate LCA. However, it has been shown that it is possible to obtain representative LCI data using information stored within The Design Repository. Bohm et al. estimated the environmental impact of virtual concepts in early design using such data for existing products and found comparable predicted environmental impacts for virtual concepts and actual products [6]. Another approach to assessing environmental impact in the conceptual design phase is with the use of modified design structure matrices (DSMs). Rocco et al. used DSMs to record the interaction of the concept with the outside environment and between its functions [36].

Function and Environmental Impact

With every design there is functional intent behind the selection of components. The designer is focused on *what* needs to be accomplished, not *how* [37]. Functional design is a way to abstract the design problem in such a way as to increase understanding of the problem and create an opportunity for creative solutions [37].

Work done by Devanathan et al. has shown the feasibility of associating environmental impact with its given function with the use of a Function Impact Matrix (FIM) [38]–[40]. There is no way to directly calculate environmental impacts of the functions in a product. Impacts can be found for components, and components solve functions. Therefore, one can deduce that a function leads to a component, and component information is what is needed to calculate an environmental impact. LCA is inherently product design oriented, and working with the early stages of design and a functional model, environmental impact information is difficult to incorporate. The result of Devanathan et al.'s work is the Function Impact Matrix (FIM), which is used to distribute environmental impact to functions of the product.

The FIM combines LCA with several aspects of QFD. The function component matrix is a binary matrix that shows the connections between components in the product and the functions they solve [41]. A FIM is created by combining a function component matrix with the environmental impact data calculated from each component, and then distributing that impact data over the functions of the product. Devanathan et al. used the FIM to isolate dominantly impactful functions and target them for redesign to reduce environmental impact. With their case study, they showed that environmental impacts could be reduced without compromising product functionality.

METHOD

Several steps must be performed in order to determine functional environmental impacts for innovative and common products. First, the products used in the study are introduced and their selection explained. Next, the products must be decomposed physically to the component level as well as conceptually at the functional level. After product decomposition, LCI data can be taken for each component. Then, using FIMs, the environmental impact of the component's various functions can be calculated. With this data gathered, functions as well as flows for innovative and common products can be compared.

Product Population

As mentioned previously, this study examined the environmental impacts of innovative and common products. All of the innovative products that are examined in this study are selected based on their inclusion in various lists of the most innovative products of recent years. The lists used in this research are the *Popular Science* "Best of What's New Award" from various years [42, 43], the *TIME Magazine* "50 Best Inventions Award" [44], the *Good Housekeeping* "Very Innovative Products Award" [45], and the *IDSA* "International Design Excellence Award" [46, 47]. The selection process by these magazines is based on the opinions of industry experts rather than a rigorous, objective method since innovation is something that is inherently difficult to quantify.

Selection methods are inherently subjective and vary for each award. *Popular Science*, for example, uses a panel of expert judges in the categories of innovations being selected e.g., computing, engineering, gadgets, home technology, health, and green technology. Some of the judging criteria include significance of design, quality of design, and originality [43]. The products that have been identified as innovative in this research are listed in Table 1, along with the source that identified each product as innovative and the common products to which the innovative products are being compared.

While the black box, or user-related, functionality of the products being compared is the same, in some cases the basic technology is vastly different. For example, while the Dyson Air Multiplier™ and the Holmes® Fan have the common black box function to provide user cooling through air flow, each uses a different principle to direct the air flow. The Dyson unit uses an impeller to channel the air flow around a ring, and then exports fast moving air, while the Holmes® fan is a conventional fan that uses an electric motor and rotating blades to export fast moving air. Both fans can be seen in Fig. 1. A summary of the innovative features of all of the products in the study, and their black box functions, can be seen in Table 2.

Other products being compared are similar in their architecture and operating principles. For example, the RIDGID JobMax™ is compared to two other similar handheld multi-tools – one that is battery powered and one that plugs into a wall socket, as seen in Fig. 2.

Table 1. SELECTED INNOVATIVE AND CORRESPONDING COMMON PRODUCTS FOR COMPARISON.

Innovative Product	**Source**	**Comparable Common Product**
Dyson Air MultiplierTM	*Time Magazine*- 50 Best Inventions of 2009 [44], *Good Housekeeping*- Very Innovative Products 2011 [45]	Holmes® Fan
Milwaukee M12™ Copper Tubing Cutter	*Popular Science*, Best of What's New 2009 [48]	RIDGID Tube Cutter
Clorox® ReadyMop®	*IDSA- IDEA Awards 2003* [47]	Libman Wonder® Mop, Libman Microfiber Floor Mop
Milwaukee M12™ Palm Nailer	*Popular Science*, Best of What's New 2010 [42]	Grip Right Mini Palm Air Nailer
KidSmart Vocal Smoke Detector	*IDSA*- IDEA Awards 2006 [46]	First Alert Basic Smoke Alarm
RIDGID JobMax™	*Popular Science*, Best of What's New 2010 [42]	Craftsman®Nextec Multi Tool, Dremel® Multi-MaxTM

Figure 1: INNOVATIVE DYSON AIR MULTIPLIER™ (LEFT) IS COMPARED TO THE COMMON HOLMES® FAN (RIGHT).

All of the products used in the comparison study are contained within the Design Repository, which also contains the pertinent information to perform a screening-level life cycle assessment of the products. There are many products that are similar to the common ones selected for the study. These products may use different materials or have different specifications, which could potentially change the outcome of the study. The purpose of this work is to identify the level of sustainability for innovative products by focusing on several examples; expansion of the product set is left to future work. Common products selected are intended as benchmarks to gage the relative level of environmental impacts.

Figure 2. THE INNOVATIVE RIDGID JobMax™ (BOTTOM) IS COMPARED TO THE Dremel® Multi-Max™ (MIDDLE) AND Craftsman® Nextec Multi-Tool (TOP).

Table 2: INNOVATIVE FEATURES THAT RESULT IN PRODUCT IDENTIFICATION AS INNOVATIVE.

Innovative Product	Innovative Feature(s)	Black-Box Function
Dyson Air Multiplier™	Bladeless fan. Air pulled in through the base and pushed out using an impeller around a circular airfoil [44], [45].	Move air to cool user.
Milwaukee M12™ Copper Tubing Cutter	First cordless pipe cutter. Jaws hold pipe while cutter rotates at 500 rpm. Increases plumber efficiency [48].	Cut copper tube
Clorox® ReadyMop®	Disposable cloth technology on mop head, onboard cleaning solution with one touch dispensing [47].	Mop floors
Milwaukee M12™ Palm Nailer	Powerful, cordless, lithium-ion battery powered, palm hammer. Ability to hammer nails in tight spaces [42].	Nail nails
KidSmart Vocal Smoke Detector	Uses a parents recorded voice to wake children and provide evacuation instructions [46].	Sense for smoke
RIDGID JobMax™	Ability to drill, tighten/loosen bolts, and drive nails in tight spaces due to interchangeable tool heads [42].	Drill/nail/ tighten/loosen bolts

Step 1: Product Decomposition

The first step in the methodology reported herein is to decompose products into individual components. The Design Repository [12] provides an opportunity to store new product deconstructions and utilize existing product breakdowns. The functional basis developed by Stone and Wood was used to describe product function in a verb-noun (function-flow) format [10]. Flows are energy, material, or signals that are inputs and outputs to functions. Functions, on the other hand, are operations performed on the associated flows [10]. Functions for every component are included in the data recorded in the Design Repository [12]. For example, the "impeller" in the Dyson Air Multiplier™ solves the functions "transfer gas" and "convert mechanical energy to pneumatic energy."

Step 2: Component LCI

The second step determines the LCIs of every component of each product. The products must have the same black box use-phase functionality in order to justify product selection for pairwise comparison. For example, the black box functionality of both the Dyson Air Multiplier™ and the Holmes® Fan are to move air. The functional unit used for comparison is the black box function of each product pair performed over a fixed time period.

Several assumptions are made based on the usage cycle of each product as well as any components that will need replacement throughout the life of the product. Considering that it is unknown how the consumer will dispose of the product, an end-of-life disposal scenario of landfilling is assumed. The packaging materials and shipment of the final product however are not considered. For the purposes of this research, it is assumed that variations in these product stages produce negligible impacts compared to cradle-to-grave impacts for the product pairs. SimaPro [7] was used for the environmental impact assessment.

Use phase impacts are based on an estimated lifetime of each product and the duty cycle each exhibits. Based on previous literature, the lifespan of an electric motor can vary between three years for heavy use to eight years for light use [49]. Considering the electric motor is one of the most critical components to the functionality of each electric product, it will limit the products lifetime. With this assumption in place, the lifetime energy use of all of the electronic products can be found. The power tools in the set (RIDGID JobMax™, Craftsman® Nextec Multi-tool, Dremel® Multi-Max™, Milwaukee M12™ Copper Tubing Cutter, Milwaukee M12™ Palm Nailer, and Grip Rite Mini Palm Air Nailer) are all assumed to be used for an average of one hour per week for a total of six years. The six year assumption is based on the fact that they will see variable loads and potentially high stresses during use, resulting in an intermediate lifetime.

The smoke detectors in the set are assumed to have a useful life of ten years, based on suggestions from the manufacturer, with batteries being replaced every year. The floor mop product variants are expected to require replacement mop heads at different intervals. Some of the mop heads are designed for multiple uses, while the others are disposable.

The desk fans are expected to be used for two hours per day for a total lifetime of eight years. This is considered light use because the motors in the fan will reach full speed and maintain that speed, resulting in constant stresses. The other products with electrical components see more variable loads, increasing the stress on their components.

To calculate the cradle-to-grave (material extraction through end-of-life treatment) environmental impacts, ReCiPe 2008 is used [50]. This methodology classifies eighteen impact categories at the midpoint level (ozone depletion, human toxicity, water depletion, etc.) and aggregates them into three endpoint indicators (damage to human health, damage to ecosystem diversity, and damage to resource availability). There are three different weighting and normalization methods based on short term impacts through long-term impacts (heirarchist, egalitarian, and individualist). These weightings can aggregate the endpoint indicators into a single metric for evaluation. The weighting perspective used in this research is the hierarchist perspective, which is balanced between short-term and long-term impacts. Because of the coarseness of the final evaluation in this research, specific midpoint indicators are not useful. As the design's detail increases, more specific impact indicators can be used.

Step 3: Function Impact Matrices

Using function impact matrices (FIMs), the component's environmental impacts can be assigned to the product functions they solve. To generate function impact matrices, each component's contribution to each function needs to be distributed to the various functions they solve. Devanathan et al. [38] suggest assigning percentages to component-function mappings to reflect the extent to which each component contributes to accomplishing each specific function. However, there exists no generally accepted method to reliably distribute these percentages. A repeatable method is critical for avoiding the unnecessary addition of further uncertainty at this highly abstract stage of design. Therefore, this work uses a simple heuristic: the contribution of each component is distributed evenly to the functions it solves. This increases the repeatability of the approach and reduces the amount of variability in the study.

The size of the full FIM is too large to present, hence part of the FIM for the Dyson Air Multiplier™ can be seen in Table 3. The total impact of each component is listed under the "Impact" column and the individual contribution to each function is in the associated cell. As described earlier, the impact of components that solve more than one function, for example "base motor," gets distributed evenly to each function (i.e., import electrical energy, convert electrical to mechanical, and export mechanical energy).

Table 3. PART OF THE DYSON AIR MULTIPLIER™ FUNCTION IMPACT MATRIX.

Dyson Air Multiplier	Impact	Export mech. energy	Import mech. energy	Convert electrical to mech. energy	Import electrical energy
angle slider	**0.0257**				
base	**0.0210**	0.0105	0.0105		
base motor	**0.0194**	0.0065		0.0065	0.0065
circuit board	**1.2404**				
control plate	**0.0088**				

This process is repeated for all of the products in the study, by distributing environmental impact based on the functions each component solves. By summing the impact contributions of each component associated with that function, it is possible to calculate the impact of that function.

Step 4: Function –Flow Impacts

Finally, similar functions from the common and innovative products can be compared and analyzed to determine whether or not function has an effect on environmental impact. In addition, the impact of the flow of material, signal, and energy are analyzed based on adding the impact of all functions associated with each flow in the system. For example, there are five flows associated with the Dyson Air Multiplier™ and Holmes® Fan: electrical energy, mechanical energy, control signals, human material and energy, and gas (air).

ASSUMPTIONS AND LIMITATIONS

There are several assumptions and limitations about the data used in the study. First, the material assumption introduced earlier applies to all products in the study. Plastic, metal, and rubber are all assumed to be the same type for each component in the study. Second, certain components were comprised of multiple materials, but were incapable of being further disassembled without destroying the component. An example of this is the outer case of several devices. These housings for hand-held devices were primarily plastic, but also contained a type of synthetic rubber for the handgrip. The actual mass of each material in the component was unknown for these instances, so an approximation was used.

Additionally, when material types for a component were not reported in the Design Repository, they were assumed to be the same as the materials reported for similar components in the repository sample set. When mass data for a component was not contained in the Design Repository, that component was omitted from the analysis. These components were typically screws and small fasteners that had negligible mass.

It is likely that the products were not designed with environmental sustainability in mind. If they were, different materials may have been chosen, or special processing techniques could have been used, which is not captured in this analysis. There are also differences in the durability of the product pairs. For example, a product made primarily of plastic components is more likely to require replacement of components before the life of the product is over. Conversely, a product with metal components is likely to be more robust and last longer. Actual impacts will also depend on whether or not the customer will replace the components, or simply purchase a new product. It is assumed that the products in the study are small and inexpensive enough, such that when a component of the product breaks, the product will be thrown away and a replacement will be purchased. It would be extremely difficult and time consuming to disassemble the products and recycle or reuse its constituent materials. For a proper evaluation of the impact of the durability and replacement differences of each product, failure data along with repair and replacement rates is necessary, but is outside the scope of this current study.

RESULTS AND DISCUSSION

Results of the functional LCA show that for all of the products, innovative and common, there are four or less product-related functions that dominate the environmental impact before the use phase of the product life cycle is considered. All of the products in the study contain function impacts that, when combined, contribute at least 44% of each products' overall environmental impact. The product with the lowest number of product-related functions is the Libman

Microfiber Floor Mop with 15. As a result, at least 44% of the environmental impact can be attributed to less than 27% of its functions. In all of the products that use electricity, functions associated with electricity dominate product environmental impact. An example of impact clustering can be seen in Fig. 3 with the Dyson Air Multiplier™. The "Other" category accounts for the impact of 21 other product-related functions.

When the use phase is taken into account, it plays a large role, contributing at least 27% of the impact, in three innovative products and four common products. The innovative products with significant use phase impacts are the KidSmart Vocal Smoke Detector, Dyson Air Multiplier™, and the Milwaukee M12™ Palm Nailer. The high impact use phase common products are the First Alert Basic Smoke Alarm, Holmes® Fan, Craftsman® Nextec Multi Tool, and Dremel® Multi-Max™.

In almost every product comparison, the innovative product had a larger total number of total component functions. The only exception was the First Alert Basic Smoke Alarm. Rather than the actual product design, this anomaly could potentially be a result of how information is entered into the repository and the variability due to subjectivity of data entry. More likely, a larger number of functions can be attributed to more functional complexity. More functions give rise to more components, and ultimately, higher environmental impact.

When considering overall product environmental impact, innovative products outperform common products in two cases: the Dyson Air Multiplier™ and Clorox® ReadyMop® (Fig. 4). The RIDGID JobMax™ outperforms one of its common competitor products. One final aspect that was considered for each product was the impact of each EMS flow through the system. Only two of the innovative products had higher impacts across all flows being compared: the Milwaukee M12™ Palm Nailer and Milwaukee M12™ Copper Tube Cutter.

The RIDGID JobMax™ had one flow with a lower impact than its comparison products. The final four product comparisons had two or more flows with lower impacts. Figure 5 shows the EMS flow impacts for the two desk fans, and indicates that the innovative product has several dominant flows with lower impacts.

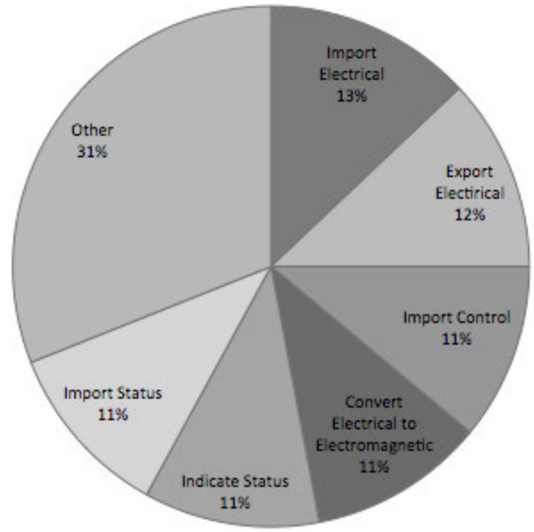

Figure 3. RELATIVE FUNCTIONAL ENVIRONMENTAL IMPACT FOR THE DYSON AIR MULTIPLIER™.

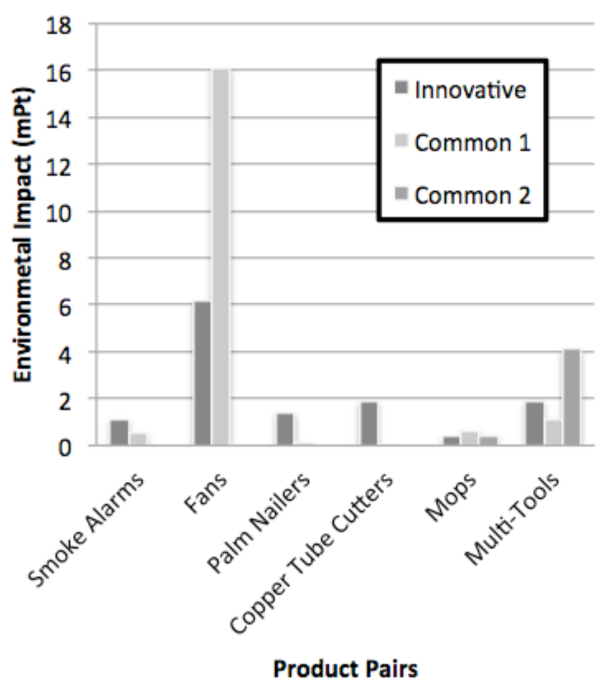

Figure 4. ENVIRONMENTAL IMPACT COMPARISON FOR INNOVATIVE AND COMMON PRODUCTS (ReCiPe 2008 HIERARCHIST ARCHETYPE).

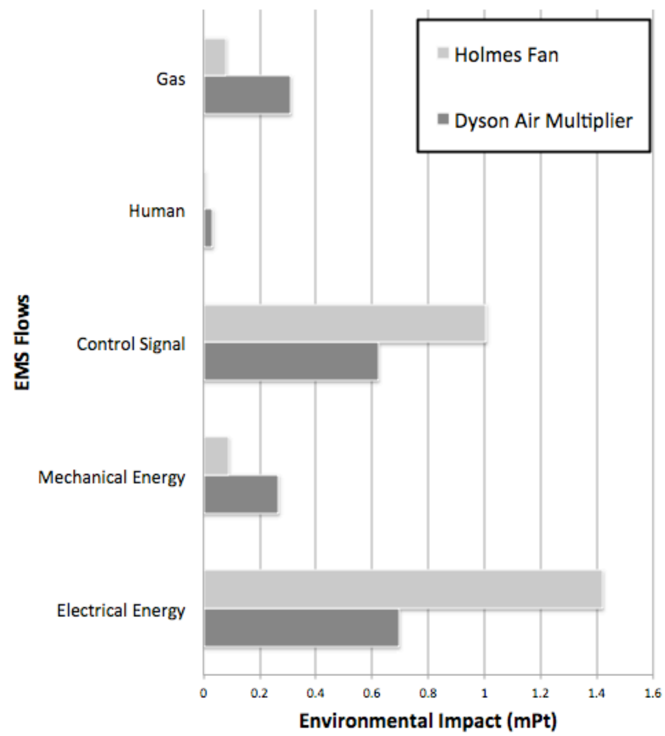

Figure 5. ENVIRONMENTAL IMPACTS ASSOCIATED WITH THE EMS FLOWS FOR TWO DESK FANS (ReCiPe 2008 HIERARCHIST ARCHETYPE).

CONCLUSIONS

The results of this analysis strengthen the findings in previous work [8]. There appears to be an inverse relationship between innovation and sustainability, not only on a basis of materials and manufacturing process environmental impacts, but also, innovative products tend to have higher environmental impacts at the function and flow level. It is unknown whether or not these results are generalizable to different pairs of innovative and common products, as the results and conclusions of this research apply only to this specific product set.

It was found that the innovative products have a higher environmental impact than common versions of the same product across their flows. Two of the innovative products had higher impacts across all flows, two had higher impacts across 80% of flows, and the remaining two had higher impacts across 75% and 25% of their flows. If this conclusion holds true for different product sets in different domains, it can be used to explore different flow options and functional architectures for a product. This warrants further investigation to determine whether the findings of this research can be extended.

Innovative products, in all but one case, have a larger total number of functions than common products. This could simply be a result of inconsistencies within the Design Repository or innovative products may be more functionally complex than common products. More functions can give rise to more components, resulting in a larger environmental impact.

The individual FIMs that were generated can be combined into an overall PFIM. As the environmental impact of more products in the Design Repository is added, the PFIM will be populated with more functional impacts. From this matrix, average impacts can be calculated for each function. This can then be used in the conceptual design phase to calculate the estimated environmental impact of a concept and select concepts to be pursued accordingly. This is a potential application of the tool that could result from populating a large PFIM with the functional impact of many products.

As consumers begin to demand more environmentally sustainable products, such tools will continue to need to be developed to support design and manufacturing efforts. Results of this research are intended to highlight the need for more emphasis on sustainability in early design. Eco-design and Eco-innovation tools are available, but the reported work intends to bring sustainability considerations earlier in design.

This work has also demonstrated that designers must consider the potential impacts of innovative products on the environment, as they can result in functional expansion, as well as simultaneous increases in components and the materials and energy needed to implement them within a product.

FUTURE WORK

To further develop this research, it is proposed that environmental impact data be added to components in the Design Repository. The component material and physical parameter data necessary to add this type of information is already available for many components in the repository. Propagating this information to the functions that each of those components solves, which could be done automatically, is the next logical step. This will provide a large database of components that solve a particular function, and a more accurate representation of each function's environmental impact could be calculated. This information could be used in the early stages of design when designers are working with only a functional model of the design. Knowing the environmental impact of the functions selected could drive designers to use different, less conventional means of accomplishing their intended design, resulting in lower impact, innovative products.

Another area of future work is in revisiting the assumption of evenly distributed functionality between components. While this simplifying assumption was made in the absence of a repeatable function allocation method, it was observed that certain common types of connections between components, functions, and flows could be leveraged to perform function impact mapping. For example, most designers would agree that the most important function of an electric motor is to convert electrical energy to rotational energy, and other functions such as guiding electrical energy are negligible compared to this conversion. Identification of these types of heuristics based on available product data may lead to repeatable and automatic generation of more accurate FIMs.

A limitation of this research is the determination of what is considered an innovative product. The products used in this study were all chosen based on popular media or organizations using expert opinions and judging criteria. If a more impartial method for scoring the "innovativeness" of these products is developed, their label of "innovative" can be further justified and/or other products identified. Innovativeness itself is difficult quantify, although there are attributes of products that lead to innovativeness. The authors are pursuing quantification of product innovativeness based on a latent variable model, which will measure innovativeness based on product attributes.

By undertaking additional innovative-to-common comparisons based on the approach demonstrated herein, an improved justification for the innovativeness of the products used, and implementation of sustainability indicators beyond environmental impact, any existing links between innovation and sustainability can be exposed and exploited to stimulate a greater emphasis on sustainability in innovation design.

ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation under Grant No. CMMI-0928076 and CMMI-0927745 from the Engineering Design and Innovation Program. Any opinions or findings of this work are the responsibility of the authors, and do not necessarily reflect the views of the sponsors.

REFERENCES

[1] E. Gillespie, "Stemming the tide of 'greenwash'," *Consumer Policy Review*, vol. 18, no. 3, pp. 79–84, Jun. 2008.

[2] H. Brundtland, "Report of the World Commission on Environment and Development," United Nations, Dec. 1987.

[3] "Directive 2002/96/EC: Waste Electronic and Electrical Equipment." European Union, Feb-2003.

[4] D. Maxwell and R. Van der Vorst, "Developing sustainable products and services," *Journal of Cleaner Production*, vol. 11, no. 8, pp. 883–895, 2003.

[5] L. Sauers and M. Shekhar, "Sustainability Innovation in the Consumer Products Industry," *Chemical Engineering Process*, vol. 105, no. 1, pp. 36–40, Jan. 2009.

[6] M. R. Bohm, K. R. Haapala, K. Poppa, R. B. Stone, and I. Y. Tumer, "Integrating Life Cycle Assessment Into the Conceptual Phase of Design Using a Design Repository," *J. Mech. Des.*, vol. 132, no. 9, pp. 091005–12, 2010.

[7] "About SimaPro," *PRe Sustainability*. [Online]. Available: √http://www.pre-sustainability.com/simapro-lca-software. [Accessed: 18-Dec-2012].

[8] B. Gilchrist, I. Y. Tumer, R. B. Stone, Q. Gao, and K. R. Haapala, "Comparison of Environmental Impacts of Innovative and Common Products," in *Proceedings of the ASME 2012 International Design Engineering Technical Conferences & Computers and Information in Engineering Conferences*, Chicago, Illinois, 2012.

[9] S. K. Oman and I. Y. Tumer, "Assessing Creativity and Innovation at the Concept Generation Stage in Engineering Design: A Classroom Experiment," presented at the International Design Engineering Technical Conferences, 2010.

[10] R. B. Stone and K. L. Wood, "Development of a functional basis for design," *Journal of Mechanical Design*, vol. 122, p. 359, 2000.

[11] D. A. McAdams, R. B. Stone, and K. L. Wood, "Functional interdependence and product similarity based on customer needs," *Research in Engineering Design*, vol. 11, no. 1, pp. 1–19, 1999.

[12] "Design Repository," *Design Engineering Lab*. [Online]. Available: repository.designengineeringlab.org. [Accessed: 16-Oct-2011].

[13] E. Manzini, "Strategic design for sustainability: towards a new mix of products and services," in *Environmentally Conscious Design and Inverse Manufacturing, 1999. Proceedings. EcoDesign'99: First International Symposium On*, 1999, pp. 434–437.

[14] J. Cramer, "Towards Innovative, Eco-Efficient Product Design Strategy," *Journal of Sustainable Product Design*, vol. 1, no. 1, pp. 7–16, 1997.

[15] J. Fiksel, *Design for Environment: A Guide to Sustainable Product Development*, Second. McGraw Hill, 2009.

[16] E. Abele, R. Anderl, and H. Birkhofer, *Environmentally-Friendly Product Development: Methods and Tools*. Springer, 2005.

[17] "Directive 2002/95/EC: Restriction of Hazardous Substances." European Union, Feb-2003.

[18] A. Arundel and R. Kemp, *Measuring eco-innovation*. UNU-MERIT, 2009.

[19] H. T. Chang and J. L. Chen, "Eco-innovative examples for 40 TRIZ inventive principles," *The TRIZ Journal*, pp. 1–16, 2003.

[20] H. T. Chang and J. L. Chen, "An Eco-innovative design method based on design-around approach," in *Environmentally Conscious Design and Inverse Manufacturing. EcoDesign'03. 2003 3rd International Symposium on*, 2003, pp. 575–582.

[21] E. Jones and D. Harrison, "Investigating the use of TRIZ in Eco-innovation," 2000.

[22] J. Lewis Chen and C. C. Liu, "An eco-innovative design approach incorporating the TRIZ method without contradiction analysis," *The Journal of Sustainable Product Design*, vol. 1, no. 4, pp. 263–272, 2001.

[23] S.-B. Yen and J. L. Chen, "An Eco-Innovative tool by Integrating FMEA and TRIZ methods," *Environmentally Conscious Design and Inverse Manufacturing*, pp. 678 – 683, 2005.

[24] T. Sakao, "A QFD-centered design methodology for environmentally conscious product design,"

International Journal of Production Research, vol. 45, no. 18–19, pp. 4143–4162, Sep. 2007.
[25] K. Otto and K. Wood, "A reverse engineering and redesign methodology for product evolution," in *Proceedings of the 1996 ASME Design Theory and Methodology Conference*, 1996, vol. 96.
[26] S. Joshi, "Product Environmental Life-Cycle Assessment Using Input-Output Techniques," *Journal of Industrial Ecology*, vol. 3, no. 2–3, pp. 95–120, 1999.
[27] T. Hartikainen, A. Korpela, J. Lehtonen, and R. Mikkonen, "A Comparative Life-Cycle Assessment Between NbTi and Copper Magnets," *IEEE Transactions on Applied Superconductivity*, vol. 14, no. 2, pp. 1882–1885, Jun. 2004.
[28] D. Collado-Ruiz and H. Ostad-Ahmad-Ghorabi, "Comparing LCA results out of competing products: developing reference ranges from a product family approach," *Journal of Cleaner Production*, vol. 18, no. 4, pp. 355–364, Nov. 2009.
[29] D. Eastlick, M. V. Sahakian, and K. R. Haapala, "Sustainable Manufacturing Analysis for Titanium Components," in *International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, Washington DC, 2011.
[30] S. Fukushige, E. Kunii, K. Yamamoto, and Y. Umeda, "A Design Support System for Scenario-Based Lifecycle Design," in *International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, Washington DC.
[31] K. R. Haapala, S. K. Tiwari, and B. K. Paul, "An Environmental Analysis of Nanoparticle-Assisted Diffusion Brazing," in *ASME International Manufacturing Science and Engineering Conference, West Lafayette, Indiana*, 2009.
[32] "Design Engineering Lab," *Design Repository*, 16-Oct-2011. [Online]. Available: http://designengineeringlab.org/. [Accessed: 16-Oct-2011].
[33] M. R. Bohm, R. B. Stone, T. W. Simpson, and E. D. Steva, "Introduction of a data schema: the inner workings of a design repository," *Proc. ASME IDETC/CIE*, 2006.
[34] C. Deng, Z. Li, X. Shao, and C. Zhang, "Integration and optimization of LCA and LCC to eco-balance for mechanical product design," in *Intelligent Control and Automation, 2008. WCICA 2008. 7th World Congress on*, 2008, pp. 1085–1090.
[35] B. S. Blanchard and W. J. Fabrycky, *Systems engineering and Analysis*, 4th ed. Englewood Cliffs, New Jersey: Prentice Hall, 1990.
[36] C. Rocco, S. Rizzuti, and L. De Napoli, "A Procedure for Early Environmental Assessment of Industrial Products," in *Proceedings of the IMProVe*, Venice, Italy, 2011.
[37] D. G. Ullman, *The Mechanical Design Process*, 4th ed. McGraw Hill, 2010.
[38] S. Devanathan, D. Ramanujan, W. Z. Bernstein, F. Zhao, and K. Ramani, "Integration of Sustainability Into Early Design Through the Function Impact Matrix," *Journal of Mechanical Design*, vol. 132, p. 081004, 2010.
[39] S. Devanathan, P. Koushik, F. Zhao, and K. Ramani, "Integration of sustainability into early design through working knowledge model and visual tools," 2009.
[40] W. Z. Bernstein, D. Ramanujan, S. Devanathan, F. Zhao, J. Sutherland, and K. Ramani, "Function Impact Matrix for Sustainable Concept Generation: A Designer's Perspective," in *Proceedings of the 15th ASME Design for Manufacturing and the Lifecycle Conference*, 2010, vol. 6, pp. 377–383.
[41] M. R. Bohm, R. B. Stone, and S. Szykman, "Enhancing virtual product representations for advanced design repository systems," *Journal of Computing and Information Science in Engineering*, vol. 5, no. 4, p. 360, 2005.
[42] "Best of What's New 2010," 2009. [Online]. Available: http://www.popsci.com/bown/2010. [Accessed: 18-Jan-2012].
[43] "2011 Best of What's New," *PopSci.com*, 2011. [Online]. Available: https://www.popsci.com/bown2011/html/index/judging. [Accessed: 03-Jan-2012].
[44] "The 50 Best Inventions of 2009," *TIME Specials*. [Online]. Available: http://www.time.com/time/specials/packages/article/0,28804,1934027_1934003_1933966,00.html.
[45] "Third Annual VIP (Very Innovative Products) Awards," *Good Housekeeping*, 2012. [Online]. Available: http://www.goodhousekeeping.com/product-reviews/innovative-products-awards-2011. [Accessed: 18-Jan-2012].
[46] "IDEA 2006 Gallery," *IDSA*. [Online]. Available: http://www.idsa.org/content/panel/idea-2006-gallery. [Accessed: 18-Jan-2012].
[47] "Clorox ReadyMopTM," *IDSA*, 22-May-2010. [Online]. Available: http://www.idsa.org/content/content1/clorox-readymoptm. [Accessed: 26-Mar-2013].
[48] "Popular Science," *Best of What's New 2009*, 16-Oct-2011. [Online]. Available: http://www.popsci.com/bown/2009/. [Accessed: 16-Oct-2011].
[49] M. Klausner, W. M. Grimm, and C. Hendrickson, "Reuse of electric motors in consumer products," *Journal of Industrial Ecology*, vol. 2, no. 2, pp. 89–102, 1998.
[50] M. Goedkoop, R. Heijungs, M. Huijbregts, A. De Schryver, J. Struijs, and R. Van Zelm, "ReCiPe 2008." Ministry of Housing, Spatial Planning and the Environment (VROM), 06-Jan-2009.

