A Sustainable Design Repository for Influencing the Eco-Design of New Consumer Products

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Abstract

Engineering designers are constantly seeking ways to be more innovative, decisive, and informed of emerging technologies in the design of consumer products. Design tools, such as functional decomposition, morphology, and Pugh charts help stimulate the design process. However, these tools require designers to have experiential or empirical design knowledge; novice designers, or designers with little experience designing for certain objectives, may struggle to apply these approaches. In contrast to these current tools, using repositories to store product design information can provide additional and extensive design knowledge to the global design community. Using repository data in the design of new products can be especially impactful for *DfX* design objectives, such as product sustainability, about which many engineering designers have limited knowledge. In this paper, we discuss the creation of a sustainable design repository – a collection of product data that includes environmental impact information. Through the initialization of a 47-product repository, we seek to create data-driven design processes that can influence designers to consider environmental sustainability. We found, for example, that in the first year of a product's life, 29-64% of the environmental impact occurs during the product's use phase, and that uncertainty in input data (such as component manufacturing location and disposal method) can significantly contribute to environmental impact variation. The creation of this sustainable design repository highlights the need for the consideration of input uncertainties when conducting environmental impact analysis. Additionally, the repository has also been used in tandem with machine learning to understand design decisions that lead to more sustainable products. This sustainable design repository enables subsequent data-driven design research in that it provides a large dataset on which machine learning approaches can operate.

Keywords: *Sustainable Product Design; Design Repository; Data-Driven Design; Eco-Design*

1. Introduction

Currently, globalization in consumer product design and increased competition is driving innovation, and increasing the demand for accessible design knowledge. Today's designers need readily-accessible and multi-disciplinary information sources to be able to make informed design decisions and to meet design objectives, including cost models, manufacturing data, consumer preference models, environmental impact data, and many more. Currently, there are many tools in the design field that are used to stimulate the design processes and facilitate designers' ability to ideate unique design concepts. Functional Decomposition, Morphology, and Pugh Charts are all used to increase the diversity and novelty of a designer's design ideas (Belaziz et al., 2000; Stone and Wood, 2000; Thakker et al., 2009). However,

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such methods are not typically data-driven, in that they do not employ existing product data from existing or analogous products. Instead, these approaches rely on the cognitive and creative ability of the designer, and can be intractable for novice designers or for designers with little experience in *design-for-X (DFX)* areas of interest, such as design for the environment, risk mitigation, reliability, and other objectives (Ford et al., 2016). We hypothesize that integrating data in the early design phase can enable designers to make more informed design decisions, resulting in reduced redesign throughout the design process.

One solution for providing new information to the designer is the use of design repositories (Guo and Murphy, 2012). Design repositories are a collection of databases that house product design data in the form of a data schema (Bohm et al., 2008). The data schema includes information about component function, bill of materials, and design structure matrices (Bohm et al., 2008). These repositories catalog design solutions for design problems and allow designers to identify solutions that best fit a design need. Design repositories are used as a searchable tool that increases the accessibility of design knowledge. However, these repositories have yet to be widely adopted in industry, largely due to a lack of accessibility and/or awareness about design repositories (Reap et al., 2008).

Current research in design repositories is focused on making design repositories accessible, standardized, and having increased repository utility (Reap et al., 2008). Specifically, researchers have focused on increasing the viability of design repositories by creating a standardized data schema (Hetherington et al., 2014; Ozoemena et al., 2013). One area of interest in current design repository research is automating concept generation with the use of data from the repositories (Keith et al., 1999). Emerging repositories will inform users about available secondary design decisions based on the project constraints (Reap et al., 2008). Specific to the area of sustainable design, it has been shown that environmental impact data has validity in the early design phase of concept generation(Bohm et al., 2010; He et al., 2017). Furthermore, eco-design repositories have been used to track environmental performance through product iterations (Donnelly et al., 2006).

Sustainability is becoming an emerging *DfX* topic of interest in design (Bohm et al., 2010). Connecting Life Cycle Analysis (LCA) indicators to design decisions is a viable way to improve the potential sustainability of a product during the design phase (Wisthoff et al., 2016). Introducing the concept of environmental sustainability and LCA data in the early design is of meaningful interest since 70% of product cost and 80% of environmental impact is embedded into a product during the early design phase (Hertwich and Roux, 2011). In this paper, we explore the idea of connecting the potential design benefits of using design repository data and product environmental sustainability, through the creation of a sustainable design repository (SDR). Our goals in conducting this research are to improve the data-knowledge of current design repositories, enhance the viability of sustainable design in industry by providing specialized knowledge, and provide a vehicle to further research in environmental sustainability relating to design.

Our Sustainable Design Repository (SDR) includes Life Cycle Analysis information for existing consumer products and their design features. Products that are added to the repository are subject to a standardized input data schema that includes (at minimum): bills of materials, manufacturing locations, disposal methods, and intended use phase quantification. This data schema is used to complete three LCA methods per product included in the SDR: Eco-indicator 99, SolidWorks Sustainability, and ReCiPe (via GaBi). These LCA outputs are recorded in the repository for the respective product.

In this paper, the SDR data schema standard and methodology is applied to an initial study of 47 products. This product set is a proof-of-concept and the starting seed for the SDR. The 47 products represent a wide variety of consumer products and were chosen to test the robustness of the data schema when subjected to varied sources of information. The case study performed on the initial product set also provides a real-time method for identifying inherent problems with missing information for the data schema and LCA methods. This study is used to refine the methods of data input to the SDR, and to develop troubleshooting solutions for future users. Lastly, using the SDR, this paper explores preliminary research in LCA end-result variations due to changes made in input data.

2. Materials and Methods

2.1. Life Cycle Assessment Methods

The design of the SDR provides multi-fidelity LCA information for consumer products. The first step for implementing the SDR is to identify various LCA methods that represent a wide breadth of analysis complexity. Currently, there are many LCA methods available, including CML, TRACI, ReCiPe, Eco-Indicator 99, and ILCD 2011 (Bare et al., 2003; European Union, 2011; Goedkoop and Spriensma, 2000; Guinée et al., 2002; Huijbregts et al., 2016). Implementing these methods can be assisted by the use of software, such as GaBi, OpenLCA, SimaPro, and Solidworks Sustainability (GreenDelta, n.d.; Pre' Consultants, n.d.; SolidWorks, n.d.; Thinkstep, n.d.). In developing the sustainable design repository, we use CML via Solidworks Sustainability, Eco-Indicator 99, and ReCiPe via GaBi. These three methods, in tandem with their implementation software, each provide a unique LCA approach that covers a wide range of use difficulty, convenience, and information. A description and rationale for each of the methods are given as follows.

2.1.1. Eco-Indicator 99

Eco-Indicator 99 (EI99) is the simplest and most novice LCA of the chosen methods; it is the only LCA method that does not require any software to implement. EI99 includes three impact categories: Ecosystem Quality, Human Health, and Resource Use (Goedkoop and Spriensma, 2000). Using a normalization process, the output of the in the EI99 methodology is a single unit-less metric called a milliPoint (mPt). This single metric can be separated in a variety of ways to quantify the impact of specific phases of a product's life cycle. At the discretion of the user, the impact of transportation, manufacturing, use, and disposal can be isolated to identify areas of high impact. The higher the mPt value, the more negatively impactful the product is to the environment. As EI99 is a single-metric LCA method, it is primarily used as a comparative tool between similar products and process alternatives (Goedkoop and Spriensma, 2000).

The SDR uses isolated production, use phase, and disposal indicators as the three metrics of focus. The production metric highlights the production of the materials used and the manufacturing processes. The use phase metric measures the impact of any resource required throughout the duration of time in which the product is used by the consumer. Lastly, the disposal or end-of-life metric records the impacts of the method through which the product is destroyed or repurposed. The mPt indicators for each metric for a given product are recorded into the SDR LCA database.

2.1.2. *CML (SolidWorks Sustainability)*

The CML LCA method—available in SolidWorks' Sustainability analysis—is an LCA method that is designed to be applied during the embodiment design phase. SolidWorks, a commonly used computer-assisted drawing program, includes this sustainability tool that uses a modified CML method to quantify the estimated environmental impact of CAD models (Guinée et al., 2002; SolidWorks, n.d.). The modified CML LCA has four output indicators: carbon footprint, energy consumption, air acidification, and water eutrophication. After a model or assembly is created in SolidWorks, the user can specify the material, manufacturing method and location, use phase, and disposal method for each component. SolidWorks Sustainability (SWS) offers the ability to view the relative impact variation caused by changing any of user-specified inputs listed above.

A SolidWorks assembly model is created for product in the SDR, or sourced from websites such as GrabCAD (Stratasys, n.d.). Each product component, within the assembly, is assigned a material, manufacturing method and location, use location, use phase, and life expectancy. For each product, the SDR records the CML output indicators. Additionally, the SWS program calculates the weight of each component via model geometry and material density. The SWS estimated part weights are used to populate the component weights in the product schema if the product is not physically available for part weighing.

2.1.3. *ReCiPe (GaBi)*

ReCiPe via GaBi software is the most robust LCA method used in the SDR. The ReCiPe LCA has 21 output indicators; 18 are mid-point raw indicators and three are normalized end point indicators (Thinkstep, n.d.). The 18 mid-point indicators measure specific LCA outputs such as global warming potential, global toxicity, CFC-11 emission, and radiation emission. The three end points—DALY, Species Depletion and Resources Cost—are normalized from the 18 mid-point indicators, and represent an easy-to-understand indicator alternative compared to the mid-points. DALY is the measure of damage to human health by the summation of the metrics *years of life lost* and *years of life disabled*. DALY is classically applied to quantify the damage inflicted by diseases, but has proven useful in LCAs (Scanlon et al., 2013). The loss of species per year is a measurement of the damage to the eco-system and represents the fraction of species lost over an area and time multiplied by species density. Resource usage is the measure of damage to resource availability quantified by increased resource cost.

GaBi allows the user to create and control manufacturing flows, enabling multiple manufacturing locations and disposal methods to be applied to a single product. The software uses a graphical interface in which the user adds materials, manufacturing methods, and disposal methods to the product plan. These processes are pre-programed into GaBi from a database similar to the *ecoinvent* database (ecoinvent, n.d.; Frischknecht and Rebitzer, 2005). Many of the manufacturing processes that are added to the product plan require secondary resources to be added. These resources include (but are not limited to) electricity, water, lubricants, and thermal energy. The secondary resources allow the user to define the manufacturing location as there are multiple options for each resource based on country of origin; these geographical options extend to the disposal methods as well. The user also has the ability create custom processes to add to the plan. These customized processes can be use phases, disposal methods, manufacturing methods, or transportation methods that may not be available within the GaBi database.

GaBi calculates ReCiPe environmental impact indicators based on component weights, which are found using SolidWorks Sustainability or by manually weighing components. For the creation of the GaBi manufacturing plan, all of parts that share the same material and manufacturing processes are added together to represent one material flow in the product plan; for example, the weights of all of the product components made of injection-molded ABS are summed into one flow. The use phase of each product is determined empirically and is influenced by use statistics and manufacturer-provided data.

2.2. Product Information Set Form and Data Schema

The SDR *data schema* is a defined set of product information that is required to ensure that the LCAs can be performed accurately. The *set form* includes the information from the data schema, but includes additional information such as MSRP, retailer information, and CAD models. The data schema requires product information including bills of materials (component names, materials, manufacturing methods, and component weights), disposal methods, and product use parameters. This information is populated by the physical deconstruction of the product, is sourced from CAD models, and/or is found through publicly-available online information.

In establishing the SDR, each product's manufacturing location information is sourced from product websites or tags on the physical product. When a product is added to the SDR, a specific exemplar product is chosen, and information about this exemplar product, such as a picture, model number, trade name, and manufacturer are added to the SDR set form. An example of the product data schema for an exemplar plastic water bottle is shown in Figure 1.

Accurately defining the use phases of the products in the SDR poses a difficult challenge. The use phase of a product accounts for 50–80% of the total life-cycle environmental impact of a product (Hertwich and Roux, 2011). Any potential inaccuracy in quantifying the use phase can lead to significant variation in the LCA indicators. Survey-based use phases offer a good starting point for defining use phases in the SDR. However, surveys and statistics don't always measure actual consumer behavior, but more often intention (Polizzi di Sorrentino et al., 2016). The use phases used in the SDR are defined by aggregating survey and statistical data, to ensure the applied use phases are realistic and are representative of the average use scenario. For example, the use phase of a coffee maker can be based on data found about the average of cups of coffee consumed over the lifetime of the coffee maker by an average user.


PRODUCT: Nalgene Bottle # 2

Name: 32 ounce Wide mouth

Make: Nalgene

Manf. USA

Model: 32 ounce Wide mouth

Picture:

Info: Nalgene Store
Tritan Copolyester

Discription:
Nalgene's Flagship bottle. Constructed out of three pieces: Lid, Strap/Collar, and Bottle. Made from Tritan Copolyester. BPA-Free

Price: $11

BOM reference(s): Water bottle LCA
Nalgene Materials
Small LCA

Bill of Materials:

	Item	Quanity	Material	Manufacturing Process	Weight	
1	Lid	1	HDPE	Injection Molding	16.72	
2	Strap/Collar	1	LDPE	Injection Molding	2.91	
3	Bottle	1	Tritan Copolyester	Injection Molding	161.1	
				Total	180.73	g

Figure 1 Example of SDR product data schema

2.3. Database for Recording Information

The SDR is a collection of databases of product information. The primary product information database includes the data schema and the set form. Use phase quantification is the subject of concurrent research in tandem with the SDR; as such, the use phase of each product is the only data schema input that has a stand-alone database. The LCA output indicator database includes all of the correlated product LCA data, including any additional LCAs completed for a product when looking at variation in material, use phase, manufacturing location, or other uncertain product input data.

Variation in input data can contribute to inaccurate environmental impact metrics if there is uncertainty present in completing the product data schema. The preliminary research included in this paper focuses on variations caused by changes in use phase, manufacturing location, and disposal methods. Use-phase variation is of interest as it can account for a large percentage of environmental impact of a product. Manufacturing location input data is generally higher-confidence information (as most products readily display where it was manufactured). Disposal method input data is lower-confidence information, as these methods are assumed not for the individual product, but based on consumer product disposal patterns in North America.

3. Problem Formulation

3.1. Initialization of the Sustainable Design Repository

A 47-product case study is analyzed to initialize the SDR. While the primary purpose of this case study is to provide a robust dataset from which data-driven design processes can be created, the secondary purpose of this case study is to identify any refinements necessary to improve the quality of the SDR set form and data schema. This is done by identifying product information input areas that are subject to creating large variations in the indicator data. Input data that causes large variations will be subject to a more rigorous validating process to preserve LCA integrity.

The chosen case study products represent a variety of different criteria, primarily perceived complexity, number of components, and how many sustainable design guidelines apply to each product. These guidelines are taken from the GREEn Quiz, an online design tool that provides a preliminary analysis of environmental sustainability of a product concept (Wisthoff and DuPont, 2016). Table 1 lists the 47 products used in the initiation of the SDR.

TABLE 1. Sustainable Design Repository Product List

#	Product	#	Product	#	Product
1	Cast Iron Skillet	**17**	“Big Wheel” Toy	**33**	Razor Scooter
2	Soda Can	**18**	Bicycle	**34**	R/C Car
3	Plastic Bottle	**19**	Spring Drive	**35**	Electric Shaver
4	Scissors	**20**	Apple Peeler Corer	**36**	Lawn Mower
5	Kayak	**21**	Mechanical Calculator	**37**	Electric Guitar
6	Disposable-Battery Toothbrush	**22**	Hand Gun	**38**	Insulated Water Bottle
7	Bookshelf	**23**	Hand Dryer	**39**	Chat Headset
8	Vacuum	**24**	Single Serve Coffee Maker	**40**	Pocket Knife
9	Office Chair	**25**	Oil Lamp	**41**	Sunglasses
10	Coffer Maker	**26**	3D Printer	**42**	Glass-Aluminum Desk
11	Stapler	**27**	Tattoo Gun	**43**	Skateboard
12	Lamp	**28**	Toaster	**44**	Keyboard
13	Game Boy	**29**	Blender	**45**	Computer Mouse
14	Electric Chainsaw	**30**	Motorcycle Helmet	**46**	Smoke Alarm
15	Drill- Battery pack	**31**	Mechanical Pencil	**47**	Game Controller
16	Drill- Corded	**32**	Electric Tea Kettle		

For the given 47 products, existing exemplar products were identified and added to the primary database, along with the product model number, image, name, price, and a short description. The description adds useful information about the product that may not be specified on the data schema, e.g., how the device is powered, or the functionality of the product. Most of the product manufacturing locations were sourced from the product manufacturer’s website or origin stickers on the product. For other products, we sourced manufacturing locations from the manufacturing company’s production facilities that are listed on company websites.

The use phase of the products was determined empirically; in most cases, the product use phase was primarily centered on the use of electricity. Product details regarding the actual electrical consumption specifications were found through product websites or component datasheets. Other use phases that include materials (such as metals, paper, water, or plastics) were found using statistic-driven techniques in tandem with the functional unit. For example, a coffee maker’s use phase was based on average cups of coffee consumed, and related use materials such as the filter were assumed to fill the need of the cups of coffee consumed. For this study, the functional unit is one year of “average” use.

The component information for the bill of materials was sourced from websites such as the *CMU Design Decisions Wiki* (Carnegie Mellon Design Decisions Laboratory, n.d.), physical disassembly, and empirically for simple products (such as the soda can). In addition to these sources, some of the bills of materials were created from deconstructing pre-existing detailed product CAD models. CAD models were completed manually and sourced from GrabCAD (Stratasys, n.d.). Part material and manufacturing processes were identified using information from *Manufacturing Processes for Design Professionals* and empirical evidence (Thompson, 2007). If a physical product was not available, the component weights were estimated using SolidWorks part geometry and material density. The three LCAs were performed for each product using the completed data schema/set form.

3.2. Case Studies

3.2.1. *Use Phase Variation*

Using the SDR, a series of comparisons were performed that are designed to measure LCA variation caused by data schema inputs. Three inputs: manufacturing location, disposal method, and use phase, were identified to have a high propensity to cause variation.

For the use phase comparison, three sample products were chosen to highlight varying use phases and unique consumables. The three products and their use phase properties are as follows:

1. Keurig – Three-input use phase (water, electricity, and polypropylene cups)
2. Stapler – Single-input use phase (steel staples)
3. Drill (Battery-powered) – Single-input use phase (electricity)

Each product was subjected to four LCA trials using ReCiPe. The trials were defined by a use phase of 1.0 year, 2.0 years, 0.5 years, and 0.0 years; all other data schema input parameters remained the same. The 0.0-year use-phase trial represents the impact of a product based solely on manufacturing and disposal. The impact caused by a product's use phase was found by subtracting 0.0-year trial data from the each of the three trials. The percentage of impact contribution by use phase was calculated by dividing the use phase LCAs by the full product LCA. This was conducted for all 15 ReCiPe output indicators, then averaged to give the overall percent of contribution from use phase to impact.

3.2.2. *Manufacturing and Disposal Variation*

In addition to the three use phase variation products, three more sample products were added. These products represented products that were primarily manufactured out of one material, such that we could isolate the impact due to manufacturing and disposal variation. The three added products are:

1. Cast Iron Pan – Cast Iron (representing the material family of steels)
2. Soda Can – Aluminum
3. Nalgene Bottle – Plastics

For the manufacturing comparison, only the product's manufacturing location data was manipulated. In this case, the secondary GaBi resources including thermal energy, electricity, water, and lubricants were set to come from the experimental manufacturing location. The actual manufacturing methods locations could not be changed as GaBi's database almost exclusively works with European manufacturing processes. However, changing just secondary resource inputs has an impact on the variation in the ReCiPe LCAs. The three areas for the geographical comparison were China, USA, and Europe. For each product, the absolute difference between the outputs metrics was found for USA versus China and USA versus Europe. The percent change was calculated for each metric, and the overall variation per product was found by averaging the percentage differences for each metric.

The Disposal method comparison followed the same methodology of the manufacturing location experiment. However, there were only two disposal methods that were readily available through the GaBi program; incineration and landfilling. Only disposal method was changed, no other input metrics from the data schema were change including manufacturing location.

3.3. Assumptions

The data included in the SDR are subjected to a variety of assumptions. LCAs, by nature, are subject to great uncertainty (Bisinella et al., 2016; Steen, 1997). Since this research is focused on using LCA tools, it is important to make consistent and universal assumptions to preserve integrity. These assumptions are as limited and general as possible to increase the future research potential of the SDR. The product *data schema/set form* is where the majority of the assumptions are made.

Manufacturing and use-phase locations are limited to the USA, China, and Europe. LCA databases provide resource generation, manufacturing, and disposal data based on the geographical location that these processes take place; the majority being USA, China, and Europe. These three locations offer a large range of manufacturing regulations, and are where the majority of consumer products are manufactured (Giffi et al., 2016). Transportation of consumer goods is omitted from the LCAs. Transportation methods and distances require information on actual locations of use and manufacturing, which are generally unavailable; assuming transportation scenarios would add significant uncertainty to the LCAs. However, it is recognized that different transportation methods and varied product weights can contribute to variation in calculated environment impact. The use location is assumed to be the USA, as all of the products sourced for the case study are readily available in the USA. To be consistent with the assumed location of the use phase, disposal methods are assumed to be located in the USA.

Information about the specific disposal methods of unique products is widely unknown. To limit the assumptions made in the SDR, disposal methods fell into one assumption: all of the SDR products are disposed of in a US landfill. This is based on the fact that the US population throws away most of its waste instead of recycling or incinerating (EPA, 2016). Lastly, due to the limitations of the LCA databases some materials and manufacturing methods are assumed to be their closest relative; substitutions are noted in the BOM.

4. Results and Discussion

The data gathered shows how important it is to consider the accuracy of input data. Table 2 presents the percentage of impact caused by use phase over time across the three products that exemplify unique use phases. Table 3 displays the results of the variation tests for manufacturing and disposal of six products manufactured with various material types.

TABLE 2. Case Study: Use Phase Variation of a Keurig Coffee Maker, Stapler, and Drill

Product (yr)	% Impact from Use Phase	Product (yr)	% Impact from Use Phase	Product (yr)	% Impact from Use Phase
Keurig (0)	-	**Stapler (0)**	-	**Drill (0)**	-
Keurig (0.5)	48.47	**Stapler (0.5)**	21.09	**Drill (0.5)**	18.51
Keurig (1)	63.56	**Stapler (1)**	33.79	**Drill (1)**	29.43
Keurig (2)	75.81	**Stapler (2)**	46.33	**Drill (2)**	42.54

The data show the stapler and the drill have a use phase impact contribution of less than 50% for the first two years of use. The Keurig coffee maker, with a material and electrical use phase, exceeds 50% use phase impact contribution within the first year of use. Each year of the product's life produces ~13% increase in environmental impact attributed to use phase versus manufacturing and disposal. The variety in the data highlights a specific need to affirm the one-year functional unit used in the case study to quantify use phase, as the majority of the products in the SDR are used for more than one year. Quantifying use phase for the total life cycle of a product necessitates new variables, including an evolving use phase year to year, product obsolescence timelines, and more in-depth user data. The current selection of the one-year use phase enables a controlled comparison of products that otherwise have variation in use lifetimes. The current data schema—including measuring use for only one year—allows for manufacturing and disposal to be represented without being overshadowed by use phase life cycle impacts for product that have longer lifespans. Knowing the extent to which the use phase contributes to the impact during the one-year functional unit can offer insight on trends that can be expected for the future of the product.

The type of consumable that is prevalent during the use phase dictates the area of increased environmental impact for the product. Pure electrical, and plastic, use-phase consumables contribute to an increased impact caused by CFC emissions, water use, and radiation. However, plastic consumables have more radiation emission impact and less water impact compared to solely electrical use phases. Use phases that have primarily metal consumables contribute high amounts of eco-toxicity, particulate matter emission, and SO_2 (terrestrial acidification). Using ReCiPe's normalized end-point indicators, metal consumables have a more significant impact on humans, while electricity and plastic consumables increase the overall impact on the environment.

TABLE 3. Case Study: Manufacturing and Disposal Variation

	Manufacturing		Disposal
Product	%Variation US vs. EU	%Variation US vs. China	%Variation Disposal
Keurig	10.33	34.66	51.85
Stapler	7.32	54.92	72.78
Drill	10.65	64.54	85.19
Nalgene Bottle	10.76	35.65	85.36
Soda Can	0.81	4.73	114.72
Cast Iron Pan	24.67	42.86	123.69

Table 3 shows that the variation between US and Europe when only considering location of manufacturing is 10.76%. In contrast, the same manufacturing location study conducted on the US and China has an overall indicator variation of 39.56%. The data also show that the EU had the least impactful manufacturing phase, followed by the US and then China. It is theorized that the greater contribution to impact caused by manufacturing in China is due to local regulation and clean energy initiatives in western countries. However, the data does highlight that China produces significantly less CFC and radiation impact compared to the US and EU. In fact, for the cast iron pan, the CFC and radiation indicators are omitted in the overall variation calculation as the percentage of difference of those two metrics were orders of magnitude larger than the majority of the indicators variation seen.

Chinese manufacturing has a reduction of impacts caused by CFC emission, radiation emission, and freshwater eutrophication. US manufacturing has reduced terrestrial acidification, marine eutrophication, water depletion, particulate matter formation, and photochemical oxidant formation impacts. European manufacturing has a reduction in global warming potential, oil depletion, and overall end point indicators. Table 3 presents that the differences in these metrics varies depending on the product. For example, soda cans have minimal variation compared to the other products. This is likely attributed to the weight of the products and the complexity of manufacturing.

Lastly, the variation in disposal method showed less obvious trends than the manufacturing location study. Products that are made predominantly of metals have a large variation in environmental impact between incineration and landfilling. This is due to the increased energy cost required to process metals for incineration. Using incineration instead of landfill disposal reduces freshwater eutrophication, oil consumption, marine eutrophication, and particulate matter formation. Using Landfill disposal instead of incineration reduces radiation emissions. The average variation between all product for disposal methods was 106.72%. When comparing the LCA output variation caused by the manufacturing location and disposal methods, it is clear that uncertainty of disposal methods can have a larger impact on the accuracy of an environmental impact analysis. Therefore, disposal method selection is recommended to be subject of further evaluation when being defined for each product added to the SDR.

5. Conclusions

The goal of this research is to create a design repository that features product information and life cycle analysis data to provide a platform for research in sustainable design. Specifically, this paper focuses on the primary development of the Sustainable Design Repository, and the environmental impact variation caused by uncertain product input data. Through this work, we were able to create the first iteration of the SDR and identify the LCA variation caused by three areas of product input data. There are still areas of input data that have yet to be explored. As such, the overall understanding of the variation, caused by uncertainty in all areas of input data, has yet to be discovered. However, we have confidence that the current areas of variation explored in this paper are representative of areas that would cause the most variation in the LCAs. In the SDRs' current state and with the identification of variation caused by input data, the SDR has already become useful in aiding sustainable design research.

Case study one focuses on the variation caused by the use of a consumer product. Uncertainty on how a consumer will use a product can lead to improper identification of the use model of a product. Case study one identifies the contribution to LCA impact indicators caused solely by using the product. The results of case study one showed that use can be responsible for 29-64% of the impact of product in just the first year of use. These results confirm that there can and will be large variation caused by uncertainty of use phase models. Knowing this, the SDR's set form and requirements for use phase information were changed to be more rigorous and representative of the population: use phase must be informed by vetted statistical data related to the use of a product.

Case study two focuses on the variation caused by the manufacturing location of the product and the disposal of the product. Unlike case study 1, this case study looks at the overall variation caused by changes in manufacturing location and disposal methods without isolating the impacts caused by either manufacturing location or disposal method. The results showed that variation in impact caused by manufacturing location (with the USA as the bases of comparison) was approximately 11% for European manufacturing and approximately 40% for Chinese manufacturing. For disposal methods there was a 107% variation between landfilling and incineration. The results of case study two show that there is limited variation caused by manufacturing location, and substantial variation caused by disposal methods. The SDR product information requirements were changed considering these results. Manufacturing location is designated by manufactured location or "made in" stamps on the product. However, if the manufacturing location is not one of the three available for LCA, it is assumed to be manufactured in the closest listed manufacturing location. Since the disposal method is hard to quantify and causes large variation, all SDR products are be assumed to be landfilled in the USA.

Though the research into understanding variation has strengthened the utility of the SDR, there are assumptions in the current data schema that have potential shortcomings. The fact that the product weights can be estimated by SolidWork, makes room for user error when creating the models for each product. Examples of these errors can be: over-simplification of the bill of material and improper assumptions of density (given by SolidWorks) when calculating weight. Furthermore, the SDR does not consider that products may be manufactured in multiple locations; especially if standardized components are purchased and used during product assembly. Both of these shortcomings were identified early during the development of the SDR and are responsible for the lack of ultra-complex products added to the SDR. However, given that the SDR is designed to be useful in product design research, we strove to make the SDR accessible to researchers with limited resources, and with a specific set of global assumptions. The SDR is meant to be used in research that is exploring sustainable consumer product design. As such, the SDR is not representative of faultless LCA data, but rather useful data that can be used to related design features to the potential impacts they cause.

The current SDR (populated by an initial set of 47 products) provides a solid foundation for the continuation of the SDR development; along with applying enough useful information to promote research concerning design, and potential environmental impact of consumer products. Recently, the SDR has been used to show that machine learning can be effectively used to estimate the environmental impact of a design given a list of product attributes (Wisthoff et al., 2016). The work presented in this paper has identified shortcomings that have been and can be resolved with future research and continual development of the SDR.

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