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EXPLORING THE INTEGRATION OF DSM AND LCA TOOLS TO IMPROVE DESIGN FOR SUSTAINABILITY

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ABSTRACT

One of the many challenges that engineering designers face today is a deficiency in practical and value-adding design methodologies that consider sustainability. Typically, design for sustainability (DfS) principles that address environmental and social impacts are not prioritized at the same level as economic, physical, and functional needs. Additionally, many newly-introduced DfS methodologies are fragmented and underdeveloped. Furthermore, many methods are catered towards specific niche product domains or corporate workflows, making the application of these methods across a wide range of problems and products a challenge. By investigating the tools and methods available for DfS and identifying their application and limitations, this study explores the integration of design structure matrices (DSMs) and Life Cycle Assessment (LCA) tools to improve DfS. The expectation is that an integrated DSM and LCA will allow designers to explore how a single design change may propagate through to specific changes in environmental and social impacts. The initial development of a full DSM and LCA is demonstrated through two case studies of a reusable water bottle and a micro-pump, showing which components, materials, and processes have the most significant environmental impacts. The results illustrate the value in applying this approach, which may be suitable across a wide range of existing products in an effort to improve DfS.

INTRODUCTION

The topic of sustainability has become increasingly relevant in various research disciplines over the past 20-25 years. While the Brundtland Report of 1987 created one of the most frequently cited definitions of sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [1], more recent mainstream publications like the 2016 United Nations (UN) 2030 Sustainable Development Goals (SDGs) have pushed sustainability into the broader public [2]. The transformative plan of action presented in the 2016 UN report highlights 17 SDGs covering three categories of sustainability: environmental, social, and economic. While design research may not be able to address all of these goals, it can play a meaningful role in creating products and systems with positive environmental and social footprints. In particular, SDG 12 “Sustainable Consumption and Production” is directly relevant to DfS in that it encourages more sustainable behavior among product developing companies and their customers, including specific policies and international agreements on the management of materials that are toxic to the environment [2].

According to previous research by the Royal Society for the Encouragement of Arts, Manufactures, and Commerce (RSA), most products designed today are still far from being ‘circular ready,’ i.e., they are intended to follow a take-make-dispose model [3]. Design for X (DfX) methods have been developed to assist product developers in considering different life phases of the product (manufacture, cost, etc.). One DfX field is Design for

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Sustainability (DfS), which provides techniques to consider the environmental and social impacts of design decisions. The aim of DfS methods is to provide a holistic approach toward product development that considers the "triple bottom line," where a product is sustainable in terms of environment, economy, and society [4]. While many researchers have identified different tools, methods, and techniques that can be used in DfS [5], designers still need a practical and broadly applicable framework that can comprehensively address sustainability in design problems [6].

Recent sustainable design approaches typically fall into one or two of the following categories: Life Cycle Assessment (LCA), Design for X (DfX), and Sustainable Design Methods and Tools (SDMTs). The contributions and limitations of each of these are summarized in Table 1. LCA is one of the more generally accepted methods and is defined by ISO 14040 series as quantifying environmental impacts of a product across its life cycle [7, 8].

TABLE 1. Contributions and limitations of major sustainable design approaches

	LCA	**DfX**	**SDMTs**
Contributions	Methods for assessing the environmental, and sometimes social, impacts of a product or system; metrics capture the most important impact categories	Approaches to consider specific product life cycle phases during of design; X may be manufacturing, use, end-of-life, or specific activities within these phases	Specific, guided methods and tools for designers to account for environmental and/or social metrics during the design process
Limitations	Intended for post-design evaluation or comparisons, rather than to support design activities	Framed to consider one X/phase at a time; more often focus on economic impacts than environmental or social	600+ SDMTs are published [9], but not widely used; most need more business context

This research explores the integration of design and LCA methods to enable sustainable product design. In particular, we combine the design structure matrix (DSM) with LCA, as a first step toward a holistic approach to sustainable design. The paper begins with a review of the literature in related fields with a focus on DfX, particularly DfS, as well as DSM and LCA. The DSM will be used as the foundation of the analysis, as it is an effective problem decomposition technique that has been used for decades across multiple fields of interest including engineering [10, 11]. A DSM can be an important network modeling tool that represents all the key elements of a given system or product, revealing interactions while displaying the entire architecture in an easy-to-understand format. The simple, compact visual representation of a DSM also reveals system dependencies as well as potential sensitivities in the overall design [12–14]. LCAs, independently, are already used with significant overall success when compared to other tools that address sustainable design. In this paper, a reusable water bottle and a solenoid micro pump [15] are used as case studies to illustrate this integration of DSM and LCA tools. These products are broken down by their individual components and parameters, connections are mapped out in the form of DSMs, and LCA is performed to explore the integration potential and sustainability impacts of the products.

BACKGROUND

To make engineering decisions that are truly sustainable, we must be able to systematically consider the interactions among human stakeholders, technology, and the natural and built environments. It is important to consider challenges in today's engineering processes for creating a product from initial concept to final production, while also maintaining design objectives that incorporate sustainability. Designers of a product often focus on the details of a design along with functional and performance-related objectives, i.e., making products work as intended physically [16]. Any other decisions like marketing, big picture future choices regarding the company, or government interactions and regulations are usually left to upper management and entities outside the company altogether. This disconnect results in unintended consequences and often a lack of execution when seeking to develop a product that functions properly and is also designed for sustainability.

One of the biggest dilemmas when it comes to implementing sustainability across all products is that there are too many sustainable design methods. Over the past few decades, a growing list of engineering methods have emerged, ranging from simple checklists to sophisticated analytical tools (i.e., LCA methods) available for companies to design more sustainable products [17]. In recent years, surveys have revealed criticism related to the progress over the years regarding sustainability methods. One major reason for this is that many methods seem to be catered towards specific problems or product situations, which makes it difficult to carry over the same process in other product domains. There is also a push to create a holistic approach to integrate existing tools and simplify the overall effort in designing for sustainability.

Still, product designers continue to push for simpler and more effective methods for lowering environmental footprints of their products and addressing DfS concepts [8]. Newer techniques attempting to tackle DfS include the use of mind maps, more detailed guidelines and checklists that have numerous requirements, closed-loop approaches [3], reduction of silos when implementing LCA methods, and improved key performance indicators (KPIs) for newer products.

Design for X

Design for X (DfX) is not a static field, as new categories continue to be created due to changing market needs and business drivers. However, no single DfX sub-category has yet attracted widespread industry adoption [6]. DfX guidance and coordination has struggled in recent years because the ‘X’ can represent any desired particular life cycle phase, idea, or characteristic for a given product or system. DfX categories in the literature include Design for Assembly, Design for Procurement, Design for Manufacture, Design for Recyclability, and others [18, 19]. As a result, overall DfX guidelines merely provide a foundation for addressing generic, life-cycle-oriented information in the first stages of the innovation process [18]. Essentially, DfX approaches tend to be too generic to be used to maximum capacity for any particular product or company.

Today, DfS is still a broad field of research that strives towards large-scale system-level changes to address sustainability within a product or system. DfS includes many ideas from the past and present, including reduce-reuse-recycle, renewable energy consumption, efficiency improvements, repairability, green design, eco-design, customer questionnaires, cradle to grave, cradle to cradle, biomimicry, and base of pyramid systems [5]. The main characteristics of DfS approaches may be categorized within the following innovation levels: product, product-service system, spatio-social, and socio-technical system [5]. These four levels make up the evolutionary framework that defines DfS today; while previous DfS iterations were narrowly focused on green design methods, today’s DfS frameworks address the larger scope of the environmental, social, and economic dimensions of sustainability.

Design Structure Matrix

One important step in understanding a complex design problem is to decompose it into its essential parameters and functions and study the relationships among its components. A design structure matrix (DSM) is used in this framework to assess and demonstrate couplings among the parameters, components, and design decisions of the product. DSM-based methodologies, historically, have several key functions, which include organizing tasks associated with product design processes, breaking down complex relationships for analysis, and influencing the production of automated algorithms or programs to improve product or process inefficiencies [20]. A fully constructed DSM can be broken down and manipulated either manually or through software to reveal connections and sensitivities that other methods may not show as easily. Overall, when compared to other modeling or graphical methods like casual loop diagrams [21], the primary benefit of a DSM is the ability the matrix format has in being highly compact and scalable when organizing and interpreting a product’s overall system architecture [11].

DSMs generally fall within one of two categories: time-based or static. According to Kimita et al. [22], static DSMs work better when clustering algorithms are used, which result in a reordering of rows and columns to reveal modules or clusters that are tightly interconnected. Using DSM software, partitioning (sequencing) can reveal an automatic reordering of rows and columns of the DSM. This process groups the components according to some user or product-based objective [11]. Partitioning or sequencing can move higher prioritized components to the top of the overall matrix order through an algorithm of components based on user-defined dependencies or other manually inputted system logic. Depending on the product analyzed, clustering may lead to design efficiencies in the manufacturing process. Other researchers have explored the idea of automatically generating DSMs through the evolution of the product models [23], where computer-aided design (CAD) models are used to extract the data and develop an automatic DSM. Such a process could facilitate the implementation of DSMs into integrated design frameworks.

Life Cycle Assessment

Life cycle assessment (LCA) is a method to evaluate the potential environmental impacts of products by compiling an inventory, assessing the impacts using inputs and outputs, and interpreting the results. Potential environmental impacts of a product throughout its life cycle can be evaluated using LCA [7]. Some LCA techniques handle complex parameters such as part wear or trends in supply and demand as stochastic processes, often represented by a single percentage value [24]. For many parameters, such as the greenhouse gas emissions associated with extracting and processing raw materials into plastic pellets, average market values are used as approximations, as it may be impractical, if not impossible, to use precise values related to a specific product and its raw material sources [25]. Despite database expansions and improvements in recent years, substantial LCA-related information about a product is still required to both statistically differentiate product systems and reduce the need to approximate results.

The wide variety of LCA software tools and the lack of interdependencies between product architectures and process requirements across a specific life cycle make it difficult for designers to utilize LCA tools as intended. LCA outputs produce results that have high uncertainties, data inaccuracies, data gaps, and model variability due to a wide range of source selections available [26].

Researchers have not agreed on a single correct way to conduct an LCA [27]. However, the consensus is that all assumptions, boundary conditions, and unknowns need to be documented as completely and accurately as possible, and that this information is made transparent to all stakeholders involved in a given problem or product. Other research has attempted to address these concerns by reviewing the challenges of simplifying LCA tools in order to produce higher levels of sustainability [28];

however, these do not explicitly solve the problem of integrating LCA into the earlier phases of design. Altogether, LCA results are often too complex for designers not familiar and experienced with environmental assessments [24]. Since improving LCA databases requires significantly more data, regionalization information, and investment from all contributors, improving LCA techniques is a trade-off situation in itself where improving the system could potentially make the system even more difficult to implement and use. These are some of the challenges with LCA that tend to create hurdles among individual stakeholders, while also leading product designers to move towards more precise alternative tools in order to better estimate environmental impacts on particular components or materials for a specific part [29].

Integration

To address the gaps in current DfS practices, this paper proposes an integrated framework combining DSM and LCA tools. In this method, the product is broken down by its components, parameters, variables, and functional subsystems. This top-down approach closely follows modern-day model-based systems engineering (MBSE) concepts where a system (product) is broken down to its concept geometry and packaging, its performance characteristics, and then to its structural and sub-components. This process familiarity may reduce the learning curve needed to broadly implement this overall method.

Further investigations exposed the pros and cons of recent research on DfX tools. These included the purposes of the various DfX categories and examples of their applications. Research revealed recent attempts to combine different methods into new combined methodologies to build environmentally conscious guidelines into product design. Telenko and Seepersad introduced a step-by-step methodology for developing new guidelines in emerging areas of environmental sustainability by integrating reverse engineering concepts with life cycle analysis [30]. In their research, LCA is used mainly to help identify environmental requirements that are then used to generate various environmental guidelines for a given product or class of products.

The DfS literature discusses two key gaps in the current landscape of sustainable design methods and tools. First, users will continue using different methods or tools for a variety of contexts, while at the same time, combining components from different methods regardless of whether they are interrelated [31]. Second is the clear importance to develop DfS tools and methods that can be implemented early in the conceptual design stages [8], as later in the design process substantive changes are often prohibitively costly. This laid the foundation for this paper, addressing the need to develop a widely-applicable approach that leverages existing methods and tools.

METHODOLOGY

Existing sustainable design methodologies are typically grouped in one of the following categories: diagram tools, checklists, guidelines, additional DfX categories, add-on LCA tools, and new CAD-integrated tools [32]. This research proposes the integration of DSMs and LCA tools to improve DfS.

This methodology can reveal the environmental impacts associated with the product's design decisions using LCA software. Then, adjustments can be made to these decisions in the DSM and LCA through multiple iterations to compare the newly adjusted results to the original product baseline. The following subsections will discuss the case studies and the two major steps of this methodology: design decision mapping through DSM and environmental impact assessment through LCA.

Case Studies

Two case studies were selected to illustrate the mechanism of the integrated framework. First, a reusable water bottle, shown in Figure 1(a), which has different types of materials, such as plastic and stainless steel, and is a consumer-based product. An environmental impacts analysis performed on this 21-ounce water bottle can provide insights into the proposed framework's application and limitations when applied to a simple consumer product. This product consists of three components, cap, seal (o-ring), and bottle. The LCA considers the material extraction, manufacturing, packaging, energy and fuel used, transportation, customer use phase, and end of life phases.

Second, a solenoid-operated micro-pump, shown in Figure 1(b), was chosen to examine the proposed framework for a slightly more complex, customized business-to-business product. This micro-pump consists of twenty components, and it is used in industries and laboratories where a precise, repeatable, and discrete fluid volume is required [15]. Environmental impacts of the micro-pump include raw material impacts on land use, manufacturing processes that may impact global warming,

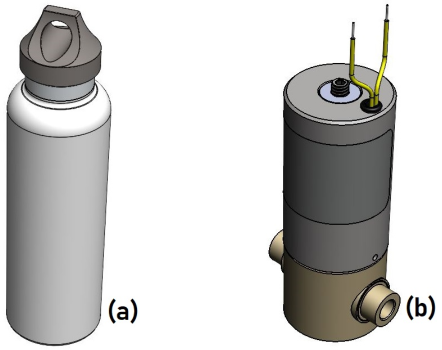


FIGURE 1. Case study products: (a) Reusable water bottle [33], and (b) Solenoid operated micro-pump [15]

non-recyclable materials, potential byproduct toxicities, overall energy consumption in both manufacturing and product use, and product life potential landfill impacts. In addition, the micro-pump design choices influence material and energy use through the manufacturing process and the need for specific engineering processes for increased reliability and precision within the product.

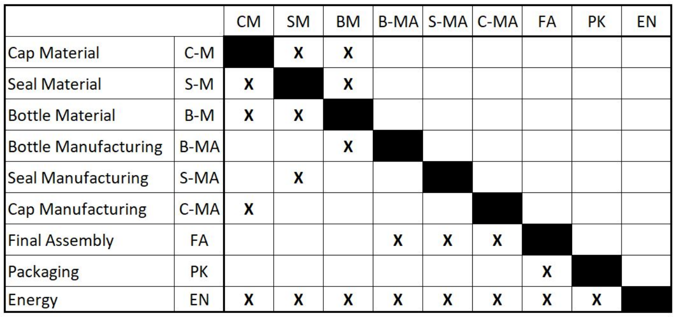
Step 1: Design Decision Mapping Using DSM

The DSM creation begins with the identification of design decisions and their relationships using engineering data, including two-dimensional drawings, CAD models, and bills of materials (BOMs). For the reusable water bottle, available online data were used to identify the details of these design decisions [33]. The manufacturer provided detailed information and engineering data on the micro-pump [15].

The products were first decomposed into components, and then further decomposed to identify specific design decisions related to each component. Other design parameters were collected by exploring the product's assembly and the interactions between components, performance parameters, and end-of-life decisions. Performance parameters include anticipated effects on customer satisfaction and end-of-life decisions such as waste to landfill, recycling, or reuse. All parameters were categorized based on dimensional, material, manufacturing, and performance design decisions. Each parameter was characterized in the DSM with the following details: components/systems, design decisions, symbols (as a representation method), measurement units, whether the parameter is considered to be an input or output, the nominal value of the parameter, and minimum and maximum values. Output characteristics were categorized as functional (i.e., what the product must do) or non-functional (i.e., measurable characteristics).

Next, a square DSM matrix was created with the parameters listed on both the columns and the rows. For the water bottle, this was a 30-by-30 matrix, with a sample section shown in Figure 2. The dependencies between each pair of parameters were manually entered as an "X" when the parameter in the column depends on the parameter in the row symbol. The rationales behind these dependencies are based on many factors, such as interdependencies between the components or their locations within the assembly. For example, the materials associated with the cap, seal, and bottle are dependent on one another because their compatibility is considered throughout the design. The manufacturing process of each component also depends on the material, and the energy parameter includes all the electricity used for material extraction, manufacturing, assembly, and packaging of the water bottle.

The micro-pump has a more complex system of components and mechanisms, which requires a more specific identification method. Parameters of the product were extracted by dividing the product into components, sub-assemblies, and final product



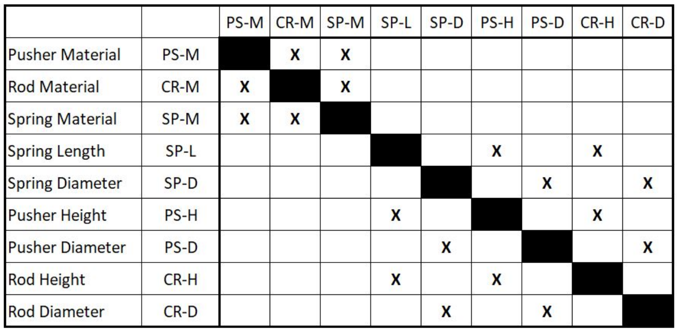
		CM	SM	BM	B-MA	S-MA	C-MA	FA	PK	EN
Cap Material	C-M	■	X	X						
Seal Material	S-M	X	■	X						
Bottle Material	B-M	X	X	■						
Bottle Manufacturing	B-MA			X	■					
Seal Manufacturing	S-MA		X			■				
Cap Manufacturing	C-MA	X					■			
Final Assembly	FA				X	X	X	■		
Packaging	PK							X	■	
Energy	EN	X	X	X	X	X	X	X	X	■

FIGURE 2. Sample section of reusable water bottle DSM

assembly. This method helps categorize the design parameters according to specific components while also identifying the dependencies between the component's design decisions. Using a CAD model and drawings while considering the functions of the components, design decisions were divided into mechanical, electrical, fluid, pump body (structure), performance specifications, and manufacturing categories. A sample section of 84-by-84 micro-pump DSM is shown in Figure 3, highlighting the mechanical sub-systems. For example, the fifth parameter shown is the spring diameter, which is a dependency for the pusher diameter and connecting rod diameter.

The versatility of DSM structures allows for different applications towards product architecture DSM models. Many DSMs define product component interactions in a symmetric way [11]. However, for the purposes of defining the sequence of design decisions that can eventually feed into LCA tools and lead to actionable conclusions, the DSM is structured to have asymmetric interactions where it is defined whether component B (column) depends on component A (row), but not necessarily vice versa. This is shown in the excerpt of Figure 2, which shows parameters that have one-way dependencies. In Figure 3, the parameters shown all impact one another bi-directionally.

Once the manual dependencies were marked in the DSM,



		PS-M	CR-M	SP-M	SP-L	SP-D	PS-H	PS-D	CR-H	CR-D
Pusher Material	PS-M	■	X	X						
Rod Material	CR-M	X	■	X						
Spring Material	SP-M	X	X	■						
Spring Length	SP-L				■		X		X	
Spring Diameter	SP-D					■		X		X
Pusher Height	PS-H				X		■		X	
Pusher Diameter	PS-D					X		■		X
Rod Height	CR-H				X		X		■	
Rod Diameter	CR-D					X		X		■

FIGURE 3. Sample section of micro-pump DSM

they were entered into an open-source DSM Excel macro program that automates several common DSM operations, including partitioning, tearing, and banding [34]. The main purpose for using this software in this project is to generate a dependency report. It can also reveal a new grouping of design decisions to improve the efficiency of the design process, based on the dependencies. The partitioning algorithm ranks parameters from the fewest to the most dependencies. This rearrangement provides a big picture view of the total dependencies in the system, identifying critical and non-critical parameters. In this first step of the proposed integrated framework, design decisions were identified and their dependencies were mapped using the DSM tool.

Step 2: LCA Modeling

LCA modeling often requires detailed product information that is not always available during the conceptual stages of product design [30]. However, the DSM step is meant to prepare designers to leverage the benefits of utilizing LCA tools while reducing the difficulty, uncertainties, and error margins built into the overall system. Therefore, prior to performing an LCA it is important to know the precise materials used in all components, a complete understanding of the manufacturing process, including heavy machinery and resources used during production. According to Millet et al. [35], the value of LCA tools is that they answer short-term questions by the design team while creating long-term dynamics that favor environmental impacts in the overall design.

A clearly-defined functional unit is required for the LCA process. A functional unit is a measurement unit or quantified description of the product's function. It serves as a critical reference for any variations to the original product's parameters. Furthermore, a top-down approach (i.e., breaking down of systems into sub-systems and primary components) to the product is recommended when performing the LCA modeling while ensuring that the product's overall purpose to its customers is not being compromised by designing for sustainability. Nevertheless, real-world products rarely achieve all ideals, and compromise is sometimes necessary [6]. For the water bottle, the functional unit for a proper LCA could be something like "100 liters of water transported." This would then be the denominator of the LCA outputs, which may express, for example, the amount of carbon emissions per 100 liters of water transported. However, this functional unit requires a deep understanding of how the water bottle's design influences its lifespan and use patterns, which are outside the scope of this paper. Similar challenges are present with the micro-pump, and even more so as precision is more important than the quantity dispersed by a micro-pump. Therefore, in this paper, the functional unit is chosen to be one product.

LCA modeling is performed using the available data about the case studies and their flows, manufacturing processes, and product type. Flows are all products, materials, or energy inputs and outputs of processes in the product system; these are broken down into elementary flows, product flows, and waste flows. Elementary flows, by definition, are materials or energy of the environment that enters the process directly from the environment without previous human transformation or leaves the process to be released into the environment. In contrast, product flows are materials or energy exchanged between the processes of the product system, while waste flows are materials or energy leaving the system entirely. A unit process is the smallest element considered in the life cycle inventory analysis for which input and output data are quantified in terms of LCA tools. In addition, product types were inputs that are defined as goods, services, software, hardware, or processed materials that can be purchased from another entity [7].

LCA modeling of both case studies were performed using the openLCA 1.10 software, which took in the collected data in the design decision tables developed during the DSM phase. Environmental Footprints (EF) is a freely available life cycle assessment database selected for this analysis. This database was used by the Product Environmental Footprint (PEF) initiative of the European Commission's Single Market for Green Products, to develop a common methodology on the quantitative assessment of environmental impacts of products [36]. The EF database suits the purpose of this analysis, as it contains a higher number of processes and flows compared to other freely available databases.

The inputs to the LCA were entered in openLCA according to the details, nominal values, units and other specifications identified earlier in the design decision table. It should be noted that best available material substitutes within the EF database were used for many of the plastics and metal alloys in the openLCA model. Some unknown parameters such as electricity used for manufacturing were estimated using online available data. Once the inputs and outputs were entered along with any additional data such as machinery used, power requirements, or other resources needed for production, a product system tree was generated. In openLCA, a product system contains all processes under review and is illustrated as a network of processes to produce the unit product.

The life cycle impact assessment (LCIA) method selected for LCA is an essential part of the framework to enable the meaningful representation of environmental impacts while integrating DSM and LCA. There are several LCIA databases available within the openLCA software. ReCiPe is a popular LCIA method that has been used since 2008 to transform long lists of life cycle inventory results into 18 midpoint indicators, and then it aggregates those midpoints into three main endpoints. These endpoints are damage to human health, damage to ecosystems, and damage to resource availability [37]. Each endpoint is measured in terms of its specific unit that can represent the value of environmental impacts. the damage to human health is measured as disability-adjusted life years (DALYs), the unit for damage to ecosystems is the local species loss integrated over time (species/year), and the damage to resource availability has a unit of U.S. dollars (USD), which represents the extra costs involved for future mineral and fossil resource extraction. ReCiPe offers three cultural perspective factors: I, H, and E. The individualist perspective (I) is a short-term, optimism view that technology can avoid many problems in future. The alternatives are the hierarchist (H) which is based on scientific consensus with regard to the time frame and the egalitarian (E) perspective with a long-term view based on precautionary thinking. In this LCA analysis the individualist perspective was selected because it can reveal the impacts considering the relatively short-term goals of product designers and companies.

RESULTS

The impact assessment results obtained from the 18 midpoint impact indicators were listed in order of decreasing impact as measured by the endpoint categories. The highest flow contributions to these midpoints were then listed to demonstrate each category's design decisions. It should be noted that considering the functional unit selected for this LCA analysis is the production of one reusable water bottle or micro-pump, the absolute results are small values. The results obtained from these LCAs, presented in the following subsections, revealed the magnitude that each process flow extracted from the design decisions can impact the environment within the three endpoint categories.

The LCA results for the reusable water bottle are summarized in Table 2. The table shows three endpoint categories and the highest midpoint category contributors to each. Mineral resource scarcity is the highest contributor to the resource availability endpoint. For both of the other two endpoints of damage to human health and the ecosystem, ozone formation has the highest impact.

TABLE 2. Reusable water bottle endpoint ReCiPe LCA results, highlighting the most significant midpoint indicator in each endpoint category

Endpoint	Total value	Most significant midpoint
Resource avail.	2.75E-5 USD	Mineral resource scarcity
Human health	4.74E-11 DALYs	Ozone formation
Ecosystems	6.72E-12 species.yr	Ozone formation, terrestrial

Figure 4 provides example investigations into the highest midpoint categories associated with each endpoint. The left-most chart shows that mineral resource scarcity is mainly affected by stainless steel (60%), electricity (26%), and powder coating (14%) process flows. The powder coating process is one of the final steps of bottle manufacturing, where the specific colors selected for the bottle are coated on the outer layer of the stainless steel bottle. Figure 4 also shows the contributions of each process flow to the other two most significant midpoint indicators, which are both ozone formation. The powder coating process has the highest impact on these midpoint indicators with 27%, followed by electricity (23%) and the carton box packaging (19%). Plastic labeling of the product (11%) and the injection moulding process for cap and seal manufacturing (3%) were also impacting this category.

The micro-pump has a wide range of materials and process flows entered as the LCA inputs, and its life cycle assessment results are summarized in Table 3. Mineral resource scarcity is primarily influenced by the stainless steel (79%) used in micro-pump's components, such as the spring, shell, and armature. Figure 5 shows the other process flow contributions to this category, which are Polyphenylene Sulfide (PPS) material (29%) and electricity (1%). Damage to human health and ecosystem breakdowns show that PPS has the highest impact on these categories (55%), followed by electricity used for processing and manufacturing (36%), and Ethylene propylene dien elastomer (EPDM) material (6%).

TABLE 3. Micro-pump endpoint ReCiPe LCA results, highlighting the most significant midpoint indicator in each endpoint category

Endpoint	Total value	Most significant midpoint
Resource avail.	0.0059 USD	Mineral resource scarcity
Human health	1.13E-10 DALYs	Ozone formation
Ecosystems	1.61E-11 species.yr	Ozone formation, terrestrial

DISCUSSION

As a first step in the process toward developing an integrated sustainable design approach, this paper demonstrates the construction of DSMs followed by the performance of LCAs. All the information and inputs required to perform the LCA were extracted during the process of DSM construction. These data were necessary first to identify the interconnected patterns between the design decisions of the system and then to define the process flows in the LCA. The process of this data extraction and defining dependencies is a manual task that is time-consuming but essential to the analysis. These data were the foundation of the analysis and may need to be validated by multiple design engineers working on the specific product. As other researchers have found, this task may be automated to some extent using CAD models [23].

The reusable water bottle's DSM showed that customer satisfaction has the highest number of dependencies with 17, and seal diameter has the lowest number of dependencies with 2. The

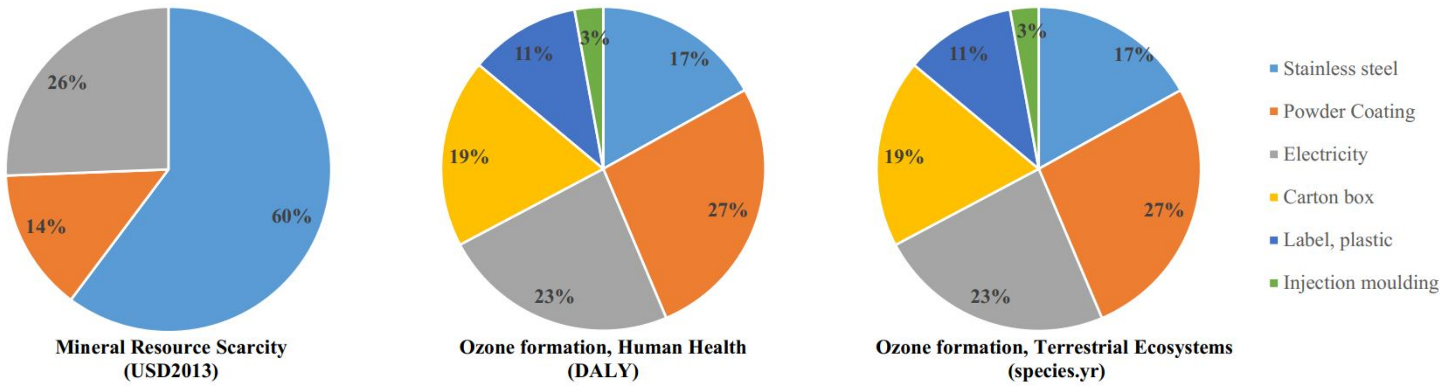


FIGURE 4. Reusable water bottle process flow contributions to three midpoint categories

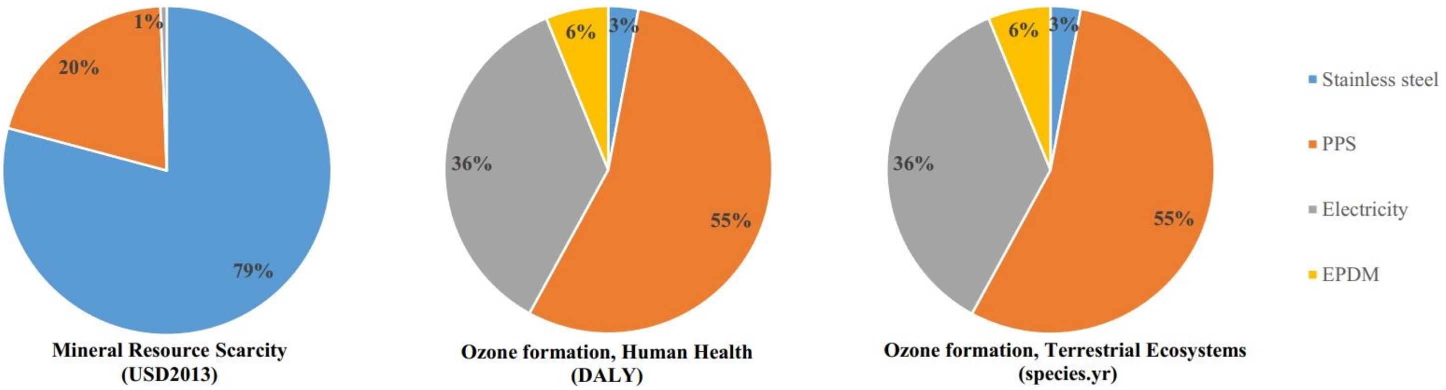


FIGURE 5. Solenoid operated micro-pump process flow contributions to three midpoint categories

other highly connected parameters are bottle material, durability, and total cost. As a consumer-based product and considering its simple mechanism, these parameters primarily influence the design decisions for this product. LCA of the reusable water bottle provided details into the environmental impacts of these design decisions. According to the results, the bottle material (stainless steel) and manufacturing parameters (electricity and powder coating) have the highest environmental impacts. These two are also critical design decisions closely tied to performance parameters such as total cost, reliability, durability, and customer satisfaction. Stainless steel is used for the bottle to satisfy the product's performance parameters such as durability, reliability, and heat efficiency. The bottle material also has a significant effect on the total cost of the product and customer satisfaction. Stainless steel material selected for the bottle has the highest impact on mineral resource scarcity which is understandable considering that the bottle is the majority of the product's total mass. The third contributor to the ozone formation is the packaging design decision (carton box) for both damage to human health and the ecosystem. According to the dependency report produced using the DSM, design parameters that depend on the bottle material are the cap material, bottle manufacturing, total weight, heat efficiency, durability, reliability, recycle/repair, waste, and customer satisfaction.

The micro-pump has a more complex mechanism, but the customized design aspect of the product also makes it highly dependent on the customer satisfaction factor. The other highly influential parameters were performance parameters, such as maximum pressure, working fluid, precision, and flow coefficient. The LCA results illustrated that, in this example problem, stainless steel and polyphenylene sulfide (PPS) have the device's most substantial environmental impacts. The design decisions associated with these two materials are known, and the dependencies of other design decisions on these parameters are determined using the DSM. For example, the environmental impacts of producing stainless steel, which has the highest value in the LCA results, are connected to the specific components made from this material inside the assembly of micro-pump. The DSM shows how many parameters depend on stainless steel material within the design of the micro-pump. To evaluate the magnitude of the impacts of these design decisions on the environment, a sensitivity analysis can be performed to reduce the uncertainty of the results. In fact, the proposed next steps of integrating the DSM with the LCA so that design changes can propagate all the way through to impact assessment results will facilitate such sensitivity analyses.

From a DfS perspective, some opportunities for improving the environmental impacts of the reusable water bottle and micro-pump were identified through this approach. These include overall design and configuration changes such as more sustainable materials, optimized tolerances, and specific component re-designs. The component mapping and DSM step broke down these products by their components and systems to facilitate the analysis of these hypothesized areas of improvement, while the LCA step focused on assessing the product's environmental footprint.

LCA results present their own limitations and assumptions. Several processes or materials are not found in the available databases, and identifying equivalent inventory items is challenging. Some components are also composite materials or manufactured in a multi-process operation where plating two or more materials occurs. According to McNamara, multi-functional and multi-property composite materials present unique challenges to LCA tools, as well as the functional unit selection and determination [38]. Utilizing a more comprehensive LCI and more complete data about the product, its logistics, and manufacturing information can significantly reduce the uncertainty in the LCA results. Despite these challenges, design decisions dependencies and environmental impacts were identified for both case studies.

Outside of minimizing costs, there are other business and sustainability drivers to designing and engineering a micro-pump that maximizes its precision, accuracy, and reliability. This is especially true since this micro-pump has critical applications in waste effluent removal, chemical dosing, and sterilizing application. Additionally, the magnitude of the voltage plays a substantial role in how a micro-pump performs under maximum loads. Therefore, changing the parameters, components, or design of any part of the micro-pump has significant risks, which may not be accounted for in the current DSM. Consequently, DfS goals need to be clearly defined before applying this methodology, because sub-categories like product longevity, repairability, and recyclability all contribute to sustainability. Roughly 78 percent of discarded products still function correctly when they are replaced, which suggests that the repairability of components of the micro-pump should be considered when determining areas for DfS improvement [5].

One of the key benefits of this approach to combining DSM and LCA is in analyzing and understanding design trade offs. Counterintuitively, sometimes shortening the lifetime of a product may be environmentally preferable and a step towards DfS [39, 40]. This becomes true if future generations of those products use fewer toxic materials, require significantly less resources and electricity to operate, or are designed in a way where components are recycled or repaired by the user. Furthermore, if a product has anticipated areas of failure, then the designers can build in a modular repair system for that specific component, using fewer resources in manufacturing the component. Components that see significant levels of wear and tear are examples where this design philosophy may be followed. On the micro-pump, this could be the diaphragm which provides a seal between the actuator (drive mechanism) and the compression chamber, which is under constant pressure while generating suction and discharge flow alternately.

CONCLUSIONS

This paper presents and demonstrates an early application of a new approach that integrates DSM and LCA tools to improve designing products for sustainability. In particular, this paper illustrates a simple application through analysis of two existing products in the marketplace, breaking down their components through detailed component mapping, constructing a DSM to group those components within sub-functions, and inputting that information, along with its materials and resource needs in regards to manufacturing, into an LCA for further analysis. Detailed dependency results were obtained from the DSM that identified the fundamental design decisions of the water bottle and micro-pump. These parameters were grouped into categories and organized according to their dependencies. By inputting these data and additional product specifications into the LCA, the result is an ability to trace the relationships between the design decisions and the environmental impacts of the product. Eventually, with an integrated DSM and LCA model, sensitivity analyses and optimization capabilities may add substantial value and lower the barrier to DfS adoption in general design practice.

The reusable water bottle and micro-pump were used to demonstrate the utility of the proposed approach and present initial results on its feasibility. The results in this paper show a proof of concept and make a case for the value of applying this approach across a wide range of product types in an effort to improve DfS. The findings for the micro-pump, in particular, revealed specific environmental impact areas and significant potential areas for improvement towards sustainable design. Moreover, the findings lay the foundation for future extensions that will enable trade-off analysis and design decision exploration to support more sustainable design decision making.

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REFERENCES

[1] Brundtland, G. H., 1987. *Report of the World Commission on Environment and Development: Our Common Future*. United Nations.

[2] UN General Assembly, 2015. Transforming our world: The 2030 agenda for sustainable development. https://www.refworld.org/docid/57b6e3e44.html. Accessed: 2022-01-21.

[3] Moreno, M., De los Rios, C., Rowe, Z., and Charnley, F., 2016. "A conceptual framework for circular design". *Sustainability,* ***8***(9), p. 937.

[4] Elkington, J., 1997. *Cannibals with Forks: The Triple Bottom Line of 21st Century Business*. Capstone, Oxford.

[5] Ceschin, F., and Gaziulusoy, I., 2016. "Evolution of design for sustainability: From product design to design for system innovations and transitions". *Design Studies,* ***47***, pp. 118–163.

[6] Holt, R., and Barnes, C., 2010. "Towards an integrated approach to "Design for X": an agenda for decision-based DFX research". *Research in Engineering Design,* ***21***(2), pp. 123–136.

[7] Finkbeiner, M., Inaba, A., Tan, R., Christiansen, K., and Klüppel, H.-J., 2006. "The new international standards for life cycle assessment: ISO 14040 and ISO 14044". *The International Journal of Life Cycle Assessment,* ***11***(2), pp. 80–85.

[8] Telenko, C., O'Rourke, J. M., Conner Seepersad, C., and Webber, M. E., 2016. "A compilation of design for environment guidelines". *Journal of Mechanical Design,* ***138***(3).

[9] Rousseaux, P., Gremy-Gros, C., Bonnin, M., Henriel-Ricordel, C., Bernard, P., Floury, L., Staigre, G., and Vincent, P., 2017. ""Eco-tool-seeker": A new and unique business guide for choosing ecodesign tools". *Journal of Cleaner Production,* ***151***, pp. 546–577.

[10] Hölttä-Otto, K., and De Weck, O., 2007. "Degree of modularity in engineering systems and products with technical and business constraints". *Concurrent Engineering,* ***15***(2), pp. 113–126.

[11] Eppinger, S. D., and Browning, T. R., 2012. *Design structure matrix methods and applications*. MIT press.

[12] Kalligeros, K., de Weck, O., de Neufville, R., and Luckins, A., 2006. "Platform identification using design structure matrices". In Sixteenth Annual International Symposium of the International Council On Systems Engineering (INCOSE), Citeseer, pp. 8–14.

[13] Wilschut, T., Etman, L., Rooda, J., and Adan, I., 2017. "Multilevel flow-based markov clustering for design structure matrices". *Journal of Mechanical Design,* ***139***(12), p. 121402.

[14] Danilovic, M., and Browning, T. R., 2007. "Managing complex product development projects with design structure matrices and domain mapping matrices". *International Journal of Project Management,* ***25***(3), pp. 300–314.

[15] Bio-Chem Fluidics, 2022. Solenoid operated micro pumps. Online, https://biochemfluidics.com/products/solenoid-operated-micro-pumps. Accessed 24 January 2022.

[16] Michalek, J. J., 2008. "Design for market systems: Integrating social, economic, and physical sciences to engineer product success". *Mechanical Engineering: The Magazine of ASME,* ***130***, pp. 32–36.

[17] Buchert, T., Kaluza, A., Halstenberg, F. A., Lindow, K., Hayka, H., and Stark, R., 2014. "Enabling product development engineers to select and combine methods for sustainable design". *Procedia CIRP,* ***15***, pp. 413–418.

[18] Hepperle, C., Biedermann, W., Böcker, A., and Lindemann, U., 2011. "Design for X—guidelines and lifecycle phases with relevance for product planning—a MDM-based approach". In DSM 2011: Proceedings of the 13th International DSM Conference.

[19] Ross, D., Ferrero, V., and DuPont, B., 2022. "Exploring the effectiveness of providing structured design-for-the-environment strategies during conceptual design". *Journal of Mechanical Design,* ***144***(3).

[20] Platanitis, G., Pop-Iliev, R., and Barari, A., 2012. "Development of a DSM-based methodology in an academic setting". *Journal of Mechanical Design,* ***134***(2).

[21] Nguyen, N. C., and Bosch, O. J., 2013. "A systems thinking approach to identify leverage points for sustainability: a case study in the Cat Ba Biosphere Reserve, vietnam". *Systems Research and Behavioral Science,* ***30***(2), pp. 104–115.

[22] Kimita, K., Matschewsky, J., and Sakao, T., 2021. "A method for remanufacturing process planning and control using loosely coupled systems". *Journal of Manufacturing Science and Engineering,* ***143***(10), p. 101001.

[23] Gopsill, J., Snider, C., Mcmahon, C., and Hicks, B., 2016. "Automatic generation of design structure matrices through the evolution of product models". *Artificial intelligence for engineering design analysis and manufacturing,* ***30***, pp. 424 – 445.

[24] Ramanujan, D., Bernstein, W. Z., Chandrasegaran, S. K., and Ramani, K., 2017. "Visual analytics tools for sustainable lifecycle design: Current status, challenges, and future opportunities". *Journal of Mechanical Design,* ***139***(11).

[25] Hellweg, S., and i Canals, L. M., 2014. "Emerging approaches, challenges and opportunities in life cycle assessment". *Science,* ***344***(6188), pp. 1109–1113.

[26] Kota, S., and Chakrabarti, A., 2010. "A method for estimating the degree of uncertainty with respect to life cycle

assessment during design". *Journal of Mechanical Design,* ***132***(9).

[27] Vigon, B. W., Tolle, D. A., Cornaby, B. W., Latham, H. C., Harrison, C. L., Boguski, T. L., Hunt, R. G., and Sellers, J. D., 1993. Life-cycle assessment: Inventory guidelines and principles. Tech. rep., United States Environmental Protection Agency, Cincinnati.

[28] Suppipat, S., Teachavorasinskun, K., and Hu, A. H., 2021. "Challenges of applying simplified lca tools in sustainable design pedagogy". *Sustainability,* ***13***(4), p. 2406.

[29] Brundage, M. P., Bernstein, W. Z., Hoffenson, S., Chang, Q., Nishi, H., Kliks, T., and Morris, K., 2018. "Analyzing environmental sustainability methods for use earlier in the product lifecycle". *Journal of Cleaner Production,* ***187***, pp. 877–892.

[30] Telenko, C., and Conner Seepersad, C., 2010. "A methodology for identifying environmentally conscious guidelines for product design". *Journal of Mechanical Design,* ***132***(9).

[31] Faludi, J., 2017. "Recommending sustainable design practices by characterising activities and mindsets". *International Journal of Sustainable Design,* ***3***(2), pp. 100–136.

[32] Bouchouireb, H., Jank, M.-H., O'Reilly, C. J., Göransson, P., Schöggl, J.-P., Baumgartner, R. J., and Potting, J., 2021. "The inclusion of end-of-life modeling in the life cycle energy optimization methodology". *Journal of Mechanical Design,* ***143***(5), p. 052002.

[33] Wu, M., 2017. Hydroflask 21oz water bottle (white). Online, https://grabcad.com/library/hydroflask-21oz-water-bottle-white-1. Accessed 20 March 2022.

[34] Laboratory for Product Development and Lightweight Design, 2019. The design structure matrix (DSM). Online, https://dsmweb.org/design-structure-matrix-dsm/, accessed 30 September 2021.

[35] Millet, D., Bistagnino, L., Lanzavecchia, C., Camous, R., and Poldma, T., 2007. "Does the potential of the use of lca match the design team needs?". *Journal of Cleaner Production,* ***15***(4), pp. 335–346.

[36] Recanati, F., and Ciroth, A., 2019. Product environmental footprints: Secondary data in openLCA. Online, https://nexus.openlca.org/ws/files/16088. Accessed 20 Feb 2022.

[37] Ciroth, A., 2016. Recipe 2016 v1.1: A harmonized life cycle impact assessment method at midpoint and endpoint level. Tech. rep., National Institute for Public Health and the Environment, Netherlands, Bilthoven.

[38] McNamara, G., 2021. "Undertaking an LCA for composites: Challenges and limitations". In *Encyclopedia of Materials: Composites*, D. Brabazon, ed. Elsevier, Oxford, pp. 230–234.

[39] Van Nes, N., and Cramer, J., 2005. "Influencing product lifetime through product design". *Business Strategy and the Environment,* ***14***(5), pp. 286–299.

[40] Stahel, W. R., 2014. "The business angle of a circular economy: Higher competitiveness, higher resource security and material efficiency". In *A New Dynamic: Effective Business in a Circular Economy*. Ellen MacArthur Foundation, London, pp. 46–60.