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Mapping the Life Cycle Analysis and Sustainability Impact of Design for Environment Principles

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Abstract

As engineers make decisions on how resources are allocated, used, and disposed in pursuit of a product, they impact sustainability's triple bottom line of social, environmental, and economic factors. Design for Environment (DfE) principles help engineers identify possible sustainable paths forward. We collected over 300 DfE principles from 29 different sources, including textbooks, academic references, and industry resources on sustainable design. We coded each principle according to where it impacts the Product Lifecycle, and which Sustainability Impacts it addresses. Future work includes eliciting additional DfE principles for sparse categories, and developing DfE tools to inform sustainable decision making.

Keywords:

Design for Environment (DfE); Design Theory and Methodology

1 INTRODUCTION

Engineers are responsible for creating most of the technological, infrastructural, and material world in which humans live. The ramifications of this artificial world, however, are that it causes social, economic, and environmental impacts. Design that balances this triple bottom line [1,2] is one common definition of sustainable design.

On a pragmatic level, how do engineers make design decisions that consider the broader impacts of what they build? One approach is to apply principles of Design for Environment (DfE), defined by Fiskel [3] as:

> *the systematic consideration of design performance with respect to environmental, health, and safety objectives over the full product and process life cycle.*

There are an overwhelming number of DfE principles that can be found in literature from engineering, industrial design, and architecture disciplines. For example, an engineer redesigning a water kettle may first perform a Life Cycle Anlaysis (LCA) in order to target specific phases of the product lifecycle or specific sustainability impacts that have the biggest potential to be improved. However, at this point the designer will need to identify relevant DfE principles from the hundreds that are available.

We are interested in developing tools and methods to guide engineers and designers towards more sustainable design decisions. To strategically apply DfE principles to Life Cycle, we would like to consider the following research questions:

- Which DfE principles affect each stage of the product lifecycle?
- Which aspects of sustainability or environmental impact are being addressed by DfE principles?
- How do engineers evaluate whether or not they have followed a DfE principle?

By applying this coding scheme to a large number of Design for Environment principles, we can develop a better picture of where engineers have strategies to address environmental and social impact. This structured database of principles also as a backbone for future sustainable design tools. These tools can scaffold conversations with designers on which aspects of the structure are most relevant for a given design problem or activity.

2 RELATED WORK

There are several different frameworks used to help engineers understand the relationships between various Design for Environment principles. Crow [4] proposes three major elements of design for the environment: *environmental manufacturing, design for environmental packaging*, and *design for disposal and recyclability*.

Telenko et al. described their process of compiling a large set of DfE principles and summarizing them down to a concise, hierarchical list of common issues. Their four criteria for good DfE principles were that they are: *designer-oriented*, *actionable*, *general*, and a *positive imperative* [5].

Telenko et al. also developed a methodological framework for designers to develop their own DfE principles, tailored to the particular design problem at hand [6,7].

3 METHODOLOGY

To understand patterns in how engineers work around Design for Environment principles, we gathered 303 Design for Environment (DfE) principles. These principles were taken from 29 different sources, including textbooks [8,9], academic references [5,10–15] and eco design guides [16,17], and industry resources on sustainable design [18–22].

For our initial analysis, we free-sorted the DfE principles, clustering similar principles and assigning emergent themes. These emergent themes included:

Corporate Social Responsibility, Restorative Design, From Physical Product to Service, Reframing the Problem, Human-Centered Design, Consumer/Customer Behavior, Persuasion & Sustainability Education, Mechanical Design, Decreasing Material Variety, Biomimicry, Simplicity, Specific Materials, Upgrading, Packaging, Servicing, Reuse, Transportation/Distribution, Supply Chain, Water Quality, Manufacturing, Quality Control, Air Quality, Weight, Material Contaminants and Additives, Assembly, Disassembly, Durability, Recycling, Biodegradability, Energy Generation

Next, we coded the principles according to the following schema, based on established models:

Product Lifecycle Stage: Which stage of the product lifecycle does this principle affect? Our starting point for our rubric is based on the product lifecycle model in [23].

Sustainability Impacts: Where and how does this DfE principle affect its sustainability? The starting point for this coding scheme is based on environmental impact models from sustainable manufacturing [24] and industrial design [25], and accommodates both the environmental and social impacts.

Principles that did not easily fit within this model were separately clustered based on why they did not fit into the model. These new categories were added to the final rubrics to account for all cases.

4 PRODUCT LIFECYCLE

We sorted the DfE Principles based on which stage of the Product Lifecycle they affect. The full rubric for Product Lifecycle is in Table 1, and a graph of the distribution of principles across Product Lifecycle categories is in Figure 1.

Initial categories for product lifecycle are based on definitions from [23]: *Raw Material Extraction, Material Processing, Component Manufacturing, Assembly, Packaging, Transportation & Distribution, Installation & Use, Service, Upgrading & Maintenance, End of Life.*

We added five additional categories that do not fit into the traditional product lifecycle framework: *Staying Alive, Transmaterialization, Transparency*, *Pervasive*, and *Business Practices.*

Product Lifecycle	Definition	Example
Raw Material Extraction	The DfE Principle impacts the process of extracting raw materials, including material selection, material identification, and the process of extracting raw materials from the environment.	“Uses locally available materials and resources” [26]
Material Processing	The DfE Principle impacts the processes that turn raw materials into finished materials and products.	“Minimizes material variety” [27]
Component Manufacturing	The DfE Principle impacts the manufacture of the individual components of a product.	“Reduces product dimensions” [3]
Assembly	The DfE Principle impacts the final assembly of both individual components produced on-site and components manufactured by suppliers.	“Contains multifunctional parts” [3] “Minimizes the use of fasteners” [20]
Packaging	The DfE Principle impacts life cycle considerations of a product’s packaging.	“Design packaging for refilling rather than replacement” [25]
Transportation &Distribution	The DfE Principle impacts the transportation and distribution of goods, from final assembly to the customer.	"Use an efficient transport system" [28]
Installation & Use	The DfE Principle impacts the use phase of a product’s life cycle, specifically a product’s interactions with the user.	“Incorporates power down features for different subsystems in the product when they are not in use” [8]
Upgrading &Maintenance	The DfE Principle impacts services that address the shortcomings of a product experienced during use.	“Contains an "up cycling passport" that encodes information about material ingredients" [29]
Staying Alive	The DfE Principle impacts all product lifecycle phases, with the goal increasing the amount of time it spends in the use phase, delaying the end of life of a product.	“Design products to be expandable, allowing other devices to be added or attached as they come become available or change” [25]
End of Life	The DfE Principle impacts what happens to a product after it can no longer be made use of in its current condition; includes recycling & biodegradability.	“Develops uses for waste materials and creates products that can be produced from it” [27]
Transmaterialization	The DfE Principle expands the nature of the product, transforming product models into service models.	"Transform product models into service models that can more efficiently use resources and thus reduce impacts” [30]
Transparency	The DfE Principle relates to collection of information throughout the whole life cycle of the product, and open communication of that information.	"Report on and communicate sustainability investments and achievements" [31]
Pervasive	The DfE Principle applies to all phases of the product lifecycle.	"Acknowledges the values and purposes that motivate design" [15]
Business Practices	The DfE Principle concerns business practices; it is independent of the product’s lifecycle or production.	"Incorporate sustainability into the overall business strategy and policy of the company" [11]

Table 1: Rubric to categorize DfE principles based on where it affects sustainability during the product lifecycle.

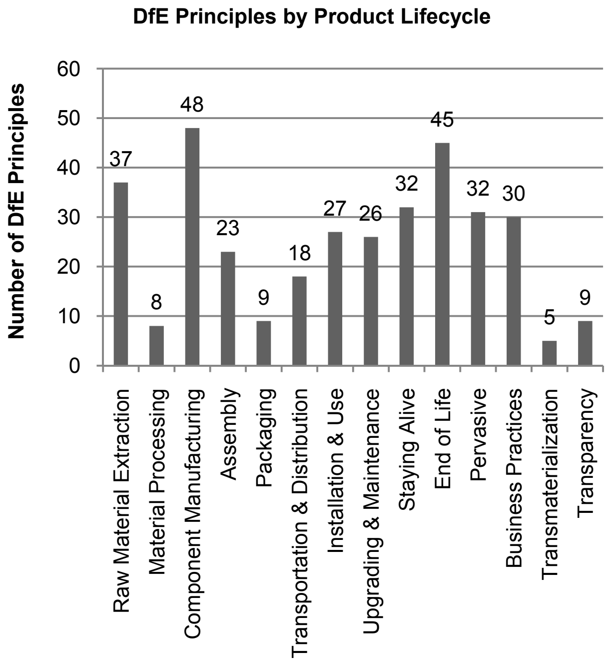

Figure 1: Number of DfE principles that address each stage of the product lifecycle.

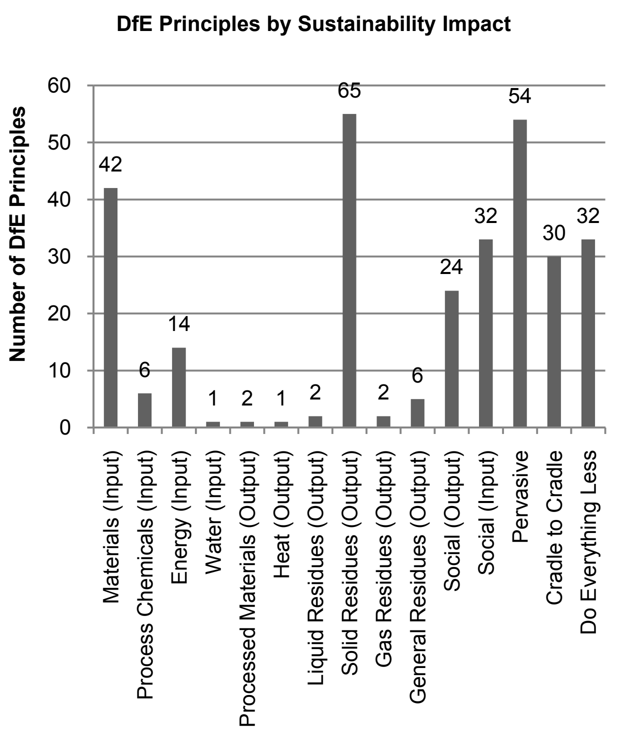

Figure 2: Number of DfE Principles that address each sustainability impact category.

3.1 Staying Alive

Staying Alive delays the end of life of a product by increasing the time it spends in the use phase, thus reducing the number of times a company has to go through a product lifecycle at all. As a result, “Staying Alive” includes principles that enable extended functionality, including durability (e.g., "Reinforce the parts most likely to fail"[19]), modularity (e.g “Design products to be expandable, allowing other devices to be added or attached as they become available or change” [25]), and love ability (e.g., "Design products to be loveable" [27]).

3.2 Transmaterialization

This category includes principles that reject a product lifecycle framework and instead focus on turning a product into a non-material service. For example, "transmaterialize the functions so that the physical device can outlast changes in features and interface without requiring a redesign" [25].

3.3 Transparency

This category includes principles that focus on collecting and communicating information throughout the entire product lifecycle. For example, “develop an indicator to describe the safety of the workplace within an organization; the indicator will increase as the social sustainability improves. This included the use of metrics (e.g., “the ratio of average days not injured to the total days worked (per employee) as an indicator" [12]) and data gathering strategies (e.g., "Includes sensing RFIDs that contain both the designer's details of product composition, but also which sense and memorize what has happened to the material during the complex path of manufacture and assembly, all to tell the right story to the disassembler” [31])

3.4 Pervasive

This category includes principles that apply across the entire product lifecycle, or lack specificity on where in the product lifecycle they would apply. This included principles along the themes of Biomimicry (e.g., "Emulates the inherent designs of nature in anthropogenic management systems" [13]), Customer Behavior (e.g., “Creates high connection through values and meaning" [30]), and Reframing the Problem (e.g., "Challenges flawed briefs and suggests better alternatives" [27]). These principles often were at a high level and included a broad scope (e.g., “Is respectful of those who make the product, the community where it is made, those who handle and transport it, and the customer" [29].)

3.5 Business Practices

This category includes principles that do not apply to the product lifecycle as much as to the overall business organization. This included principles about Corporate Social Responsibility, Business Models, and adopting a Triple Bottom Line as a definition for success. For example, "incorporate sustainability into the overall business strategy and policy of the company" [11].

DfE Principles dealing with packaging paralleled the life cycle of the product itself, with a particular emphasis on reducing waste at the end-of-life. Some of the packaging principles discussed how packaging concerns should be integrated into all aspects of product development (e.g., “Integrates packaging design into the product design process from the beginning” [27]) while others were more specific on the impact during specific lifecycle stages of the packaging itself (e.g., "Uses degradable packaging" [32], "Uses packaging that is refillable, recyclable, or repairable" [22]).

Several DfE principles applied to multiple stages in a product's life cycle. For example, 14 DfE principles were applicable across Material Processing, Component Manufacturing and Assembly.

4 SUSTAINABILITY IMPACT

We sorted the DfE Principles based on which environmental, social, or financial impacts it affected. The full Sustainability Impact Rubric is in Table 2, and a graph of the distribution of principles across Product Lifecycle categories is in Figure 2. The initial rubric is based on frameworks used to measure the sustainability impact of manufacturing processes [24]: *Materials (Input), Process Chemicals (Input), Energy (Input), Water (Input), Processed Materials/Product (Output), Heat (Output), Liquid Residues (Output), Soild Residues (Output), Gas Residues (Output), Social (Input), Social (Output)*.

We added three additional categories that are did not fit into the traditional product lifecycle framework: *Pervasive, Cradle to Cradle, Do Everything Less.*

4.1 Pervasive

These principles broadly apply on a high-level across multiple inputs and outputs. Often these are vague principles that do not imply having an effect on any particular sustainability impact. For example, "Challenges flawed briefs and suggests better alternatives" [27].

4.2 Cradle to Cradle

Cradle to Cradle contains principles that advocate "closing the loop", where the product/process outputs later become inputs. This simultaneously reduces the amount of waste created and reduces the amount of raw materials required as input. For example, "Standardize components to a product so that they can be used in different models/iterations of the product (increasing the lifespan of the subsystem even when other components change over time)" [25].

Sustainability Impacts	Definition	DfE Example
Materials (Input)	The DfE principle changes the materials used as input into the life cycle of the product, during manufacturing and use.	"Uses locally available materials and resources" [26]
Process Chemicals (Input)	The DfE principle changes the chemicals needed to process materials for manufacturing.	"Limit contaminants- additives, coatings, metal plating of plastics" [4]
Energy (Input)	The DfE principle changes the amount or quality of the energy required as input during all stages of the product life cycle.	"Reduces energy use in production" [3,10]
Water (Input)	The DfE principle changes the amount or quality of water consumed during the product's life cycle	"Assesses and improves water usage and discharge quality" [10]
Processed Materials/Product (Output)	The DfE principle changes the quality of the manufactured materials/products that are delivered to the user; the final product itself.	"Eliminate unused or unnecessary product features" [27]
Heat (Output)	The DfE principle changes the amount of heat generated as the biproduct of a manufacturing process that uses energy.	"Reclaiming and reusing the waste heat from manufacturing and other purposes" [25]
Liquid Residues (Output)	The DfE principle changes the amount or quality of liquid residues, pollution, or waste created throughout the entire product lifecycle.	"Assesses and improves water usage and discharge quality" [10]
Solid Residues (Output)	The DfE principle changes the amount or quality of solid residues, pollution, or waste created throughout the entire product lifecycle.	"Choose materials that gain character with wear and weather" [19]
Gas Residues (Output)	The DfE principle changes the amount or quality of gas residues, pollution, or waste created throughout the entire product lifecycle.	"Avoids ozone-depleting chemicals" [3]
Social (Output)	The DfE principle changes the amount or quality of the company's impact on its customers, community, or society as a result of its products or activities.	"Maximizes its benefit to the community" [13]
Social (Input)	The DfE principle changes the amount or quality of the company's impact on its employees, labor, and supply chain that create its products.	"Reduces adverse impacts to worker health", "visit suppliers' plants to ensure that they are not using sweat shop labor" [14]
Pervasive	The DfE principle applies across multiple inputs and outputs.	"Products, processes, and systems should be "output pulled" rather than "input pushed" through the use of energy and materials" [33]
Cradle to Cradle	The DfE principle connects the output of a system back into the input.	"Is restorative, as biological and technical nutrients" [29]
Do Everything Less	The DfE principle reduces the number of products that need to be made, and therefore the overall inputs and outputs required.	"Contains upgradable components" [3]

Table 2: Rubric to categorize DfE principles based on where it affects the inputs and outputs.

4.3 Do Everything Less

Do Everything Less DfE principles may not necessarily change any inputs or outputs, but change the number of times it is necessary to complete a production process. This reduces the number of times inputs are required and outputs are generated from a manufacturing process. This included principles along the themes of Servicing, Product to Service, Simple, Manufacture, Durable, Quality Control, Business Model, and Reuse. For example, “Encourages rental, leasing, and borrowing programs to use fewer products more efficiently" [24].

Materials (Input), Solid Waste (Output), and Pervasive principles dominate the DfE landscape; there are many principles that guide materials selection and use in the detail of the design. There is little guidance as to how engineers can address other inputs and outputs of manufacturing processes (e.g., process water input, heat output, gas residues). There are also relatively few principles related to water required for manufacture, as well as liquid residues. We found this surprising, particularly as water scarcity looms as an upcoming environmental concern.

As we categorized each principle, we also found that the framework of Social(Input) and Social (Output) does not yet capture the complexity of social interactions a company or designer may have with various stakeholders. We intend to address the nuances of social impact DfE principles in our future work.

5 DISCUSSION

We identified two overarching themes in Design for Environment principles that parallel the product development process:

Business Practices: In addition to producing products, business entities have a social impact on their employees, suppliers, communities, and society. How a company chooses to run its business adds to overhead costs, and affects their products’ overall sustainability. For example, businesses that address corporate social responsibility issues act as an exemplar of sustainable decision-making; purchasing products from that business supports more sustainable business practices.

Packaging Design: Packaging is designed in parallel to the product itself; the output supports the distribution of product itself. While packaging design impacts the main product primarily during distribution and use, it also must be manufactured from raw materials, and has its own, independent end of life.

5.1 Principle Specificity and Scope

In conducting our clustering analysis, we noted that there were clusters of principles that addressed the same issue with varying levels of specificity. For example, "Fosters debate and challenges the status quo surrounding existing products" [26] is very general, and applies across the entire Product Lifecycle, across all Sustainability Impact Areas. On the other hand, "Avoid the use of PVC" [25] specifically dictates that a certain material input never be used, a decision on raw material extraction that is made during detail design.

5.2 Conflicting DfE Principles

There were many examples of DfE principles that have conflicting goals. For example, there are often conflicts between simplicity (e.g., “Make it less complex” [20], "Simplify structure and form" [18]) and added complexity (e.g., “Make it Modular” [20], “Make it more useful” [20]).

5.3 Satisfaction Condition

We additionally tracked the satisfaction condition for each Design for Environment principle that indicates that there’s something the designer must:

Do: "Use standard size modular parts to enable interchangeability and customization" [18]

Avoid: “Do not user paper stickers on plastics” [21]

Minimize: "Minimize the number of production methods and operations" [28].

Maximize: “Extends Performance Life” [3]

Figure 3: Number of DfE principles that imply minimize, maximize, do, or avoid satisfaction conditions.

A chart summarizing the number of DfE principles that have each of these satisfaction conditions is in Figure 3. The principles that encourage minimization or maximization of a given feature are particularly interesting, as they imply relative metrics – it may be difficult for a designer to minimize a feature that has already been minimized in the last design. This coding scheme helps connect each principle with a metric that helps determine whether or not a DfE principle has successfully been applied. However, it also can help identify conflicting or irrelevant DfE principles.

6 FUTURE WORK

We are exploring how these principles might be presented to engineering designers and better inform how they pursue sustainability in their design projects. A design tool could give engineers a sense of how much DfE guidance there is within a particular product lifecycle phase or sustainability impact. Additional features could include an opportunity for engineers to add additional DfE principles or examples that they have found to be effective in their practice. Also, a tool may be able to encourage creative, sustainable thinking through the use of metaphors.

This work is also informing future exploration into specific areas of Design for Environment – particularly the development and use of DfE principles that affect society (in our rubric, the sustainability impacts of social input and output). Given how other DfE principles are phrased, and how to understand societal impacts at each stage of the product development process, we can guide engineers to offer more societal benefit through the products that they create.

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