Green Design with Life Cycle in Mind

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It is not impossible to integrate sustainability into early stages of design. Cradle-to-grave environmental impact analysis methods are rarely used as a metric during product development. In early stages of a project, companies measure feasibility according to money, performance and time metrics. Sustainability is commonly measured at a design cycle's end on finished products when design features cannot be easily modified for sustainability measures. It is ineffective to apply new design metrics to finished products. Evaluating the "greenness" of products is typically done to market the "greenest" product in a line. This does not address the need to create sustainable products at project onset; thus, products remain "un-green" and unsustainable.

It is time for new feasibility metric — Green Design with Life Cycle in Mind. Green design thinking must be accessible and applicable to product development through a set of tools designed for early stages of product development.

Introduction

Over the past century, our consumer society has generated an ever increasing stream of raw materials being harvested from the earth and materials moving about the planet. Currently, many raw materials used are from non-renewable sources or their rate of consumption is much faster than their rate of regeneration. Only 32.5% of solid waste in the United States enters the recycling stream, while the rest enters the waste stream in an alarming and ever-increasing rate. The materials and products that are not recycled are discarded into the environment—whether it is to a landfill or as trash that ultimately washes into waterways. In either case, they concentrate in the environment as persistent non-biodegradable matter and, for some materials, the concentration level is toxic to many life forms—including humans. If the entire population of the planet consumed at the 1995 rate of consumption of an average American, it is estimated that a landmass the size of 3 to 5 earths would be required. At the current rate, material consumption and waste generation is not sustainable. Given that the population of the planet is estimated to grow from 6.8 billion today to 9.5 billion in 2050, the trend is worsening. Fundamental changes in the ways humans consume and generate must be managed.

The most obvious way to reduce of the consumption of raw materials and the generation of waste to sustainable levels is to substantially reduce or eliminate consumerism as we currently know it. However, historical evidence indicates that this is not likely, since economic growth is consistently tied to a population's viability. Consumerism is enabled by a steady supply of new products that do not incorporate measures of sustainability, and product development exists at the front end of this consumer cycle. Rather than treating ecology and sustainability as properties outside of product development and outside of an engineer or designer's control, this paper introduces a method of changing the way the engineers and designers perceive sustainability and ecological impact throughout the design process. Just as it is simply considered good engineering and design to account for mechanical, electrical and cost performance using analytical tools to develop products, this paper proposes that ecological accounting through the use of analytical tools—such as Life Cycle Assessment—and standard practices that measure environmental impact is an element of good product engineering and design.

What is Sustainability?

"Green" is a term that has become synonymous with combating global warming and promoting environmentalism. It has been applied to everything from paper towels to fuel technology to chemicals for cleaning—or generally to just about anything that purportedly helps reduce environmental degradation.

In the view of the author, "green" is an ambiguous term whose ambiguity has been exploited to the detriment and confusion of the general population. This results in the prevalence of "Greenwashing," where the ambiguity in the term "green" allows exaggerated, misleading, and sometimes disingenuous claims. While there are many examples of greenwashing, here are just a few:

- Claims about being CFC-free are misleading because CFCs have been banned since 1987.
- Biodegradable paper products are an exaggeration because all untreated paper products are biodegradable.
- Labeling focused solely on the CO2 footprint may ignore other toxins or high ecological impacts.

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While it is common to think of sustainability as synonymous with "green," sustainability is more than a color or brand. To avoid the term green, the term sustainability will be defined in reference to product development. In 1987, Our Common Future, the UN Brundtland Report, defined sustainability as follows:

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts:

- *the concept of "needs," in particular the essential needs of the world's poor, to which overriding priority should be given; and*
- *the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs."*

Many times, the idea of sustainability is limited to its first bullet point, but I would like to frame this manifesto around the second—sustainable Design and Life Cycle Design engineering and designing sustainable products that must not exceed the capacity of the environment to produce the product (start of product life), maintain and use of the product (useful product life) or absorb or reuse the product at the end of its useful life (end of product life).

At its core, sustainability is about how the flow of materials with us on the planet today are managed to preserve and improve the quality of life for future generations. This is a materials and supply chain management concept for the planet. Materials management, including management of the associated toxins, does not have the commercial or marketing appeal of mainstream environmentalism or being "green." But examining the impacts of materials, their sources, their usage, their recycling and their final end of life disposition, including all of the inputs and outputs resulting from this flow, forms the foundation for understanding sustainability.

One way to view sustainability is through the concept of an ecological footprint. The ecological footprint of the population today is approximately 1.5 earths. Some estimates put that footprint as high as 3 or more earths and, commonly, these estimates only account for supporting human life and do not include the ecological footprint required to support other species sharing the planet. In order to live sustainably, this footprint *must* be reduced to less than one earth, even as the population continues to rise. But what does it mean to live with the footprint of one or less earths? We are managing to live on one earth now and, if so, how can it be that our footprint is greater than one earth?

At its core, sustainability is about how the flow of materials with us on the planet today are managed to preserve and improve the quality of life for future generations.

Ecological footprint is an accounting method that works to capture the amount of landmass required to support both the replenishing of materials used and the absorption of waste generated by a population. It includes the land needed to produce raw materials, supply fuels and absorb discard materials and toxins to land, sea and air. It aims to account for every molecule required to support human activity. In their book, *Our Ecological Footprint: Reducing Human Impact on the Earth,* Mathis Wackernagel and William Rees' approximation assumed an elastically expanding atmosphere that supplies gaseous inputs and contains gaseous outputs. However, with the increased awareness of global warming, it is known this assumption is no longer valid. The uncertainty of predicting "ecological footprint" is attributed to vastly different human behaviors of consumption—ranging from the "average" American at the top end of the scale to an indigenous tribesman of Papa New Guinea. However, even with this uncertainty, it is widely accepted that humans are consuming and eliminating materials, wastes and toxins faster than those materials can be regenerated, or that the wastes and toxins of these materials can be absorbed.

The planet is currently supporting this cycle of consumption and elimination, but the current rate of this consumption and elimination suggests it is not feasible for the earth to support this activity for many generations beyond our own. Humanity is consuming and eliminating at a rate that requires 1.5 to 3 times or more the land available on the planet. The earth as a single enclosed system functioning only on the materials already existing in the system, and the energy provided by the sun. Rates of consumption far exceed rates of replenishment. The Earth's ecological system is in overshoot—meaning we are depleting resources needed to sustain future generations to consume during our own generation. To support life on earth for now and create a sustainable future, we cannot continually exceed the capacity of the planet. An additional burden for sustainability now is not just to "not exceed the capacity of the planet" but to reach a limit "less than the capacity of the planet' to compensate for the current state of overshoot."

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The Basics of Life Cycle Analysis— A Primer for Engineers and Designers

One may ask how to evaluate a product with regards to its sustainability. We must dispel the myth that measuring the ecological impact of a product is the specialty of environmentalist or only of interest to "treehuggers." Many products make inaccurate claims about sustainability that amount to greenwashing, making it difficult to gauge sustainability per the definition presented in this paper. But, the notion that measuring ecological impact is not based on good, sound or quantifiable engineering or analytical practices is false. As with any other engineering evaluation, ecological impacts are best evaluated using quantitative analysis techniques. Life Cycle Analysis or Life Cycle Assessment (LCA) is one such technique.

LCA is an analytical tool designed to quantify the ecological impacts or sustainability performance of a system. It is a tool designed to account for all of the inputs and outputs of a system. The system under consideration can consist of an entire product, building, community or business—or it can be a sub-component of one of these. LCA also captures a portion of the system's life under consideration, whether it covers the start through the conclusion of a product's life or any subset of that span.

LCA characterizes the product according to input quantities, such as energy (in units of Joules), chemicals and raw materials, and output quantities such as air, water or land polluting elements (in weight or volume based units). The input and output quantities constitute the Life Cycle Inventory (LCI) that define the impacts of the system. Currently, LCI is one of the few tools capable of systematically quantifying the elements that contribute to the ecological impact of a product. When LCI is presented in its raw form, it is a substantial amount of detailed information that is not easily interpreted or comparable. For a product made of one material with a short usable life, such as a paper coffee cup, this dataset contains a dozen or fewer items. However, for a complicated product consisting of several parts and multiple materials with an extensive usable life, this dataset consists of hundreds, if not, thousands of items.

But LCI data is not commonly constructed from scratch for each analysis. The data generally comes from one of only a few available LCI databases, such as the European database Ecoinvent, that are representative of regional information.

To present the data in the understandable format, a process called Life Cycle Impact Assessment is used to normalize and weigh the LCI according to environmental and sustainability values and goals. Commonly, normalizing sorts the dataset according in one of the following categories:

- **Global Warming:** Substances with the "capacity to absorb infrared radiation." These substances contribute to trapping heat inside of the Earth's atmosphere, thereby increasing the average temperature of the earth's climate.
- **Ozone Depletion:** Substances that act as catalysts for reducing ozone in the stratosphere. Ozone stratosphere reduction increases the amount of potentially harmful ultraviolet radiation that reaches the Earth's surface.
- **Toxicity:** Substances that cause mortality (human or ecological) for exposure beyond a certain concentration level.
- **Photo-Oxidants:** Pollutants that are generated from exposure of hydrocarbons to sunlight. The pollutants generated are commonly referred to as volatile organic compounds (VOCs) which are harmful at high concentrations. Additionally, many plastics typically break down to micrometer size pieces due to photo-oxidation. At this size, they can disrupt biological functions.
- **Acidification Potential:** Substances with the ability to produce acids (low pH substances). This is based on the substances ability to produce H+ ions compared to the ability of SO2 to produce H+ ions. Low pH environments result in things like acid rain which disrupts biological functions.
- **Eutrophication or nitrification:** The proportion of nitrogen, phosphorus, carbon and oxygen in a substances chemical formula. The balance of these substances relates to rates of soil, ground water and coastal water depletion.

To weigh each category according to its relative importance, an impact factor is applied to each of the categories. For example, the data can be normalized and weighed in a way to characterize the global warming potential, or human and ecological toxicity for the system. This results in a single value, or small subset of values, that characterize the environmental performance of the system in reference to the normalizing and weighing of goals. Data is normalized and weighed according values and goals that are defined at onset of the analysis. A single value characterization assigns a point value in a common unit to each category and sums these values to quantify ecological impacts according to a single number score. Various combinations of units may be used to create subsets. This is useful for understanding how various aspects of a life cycle may change the balance between the categories.

This process of normalization and weighing is admittedly subjective. However, this is not a far cry from assumptions made in prescribing the boundary conditions for a typical engineering analysis such as Finite Element Analysis or Computation Fluid Dynamic Analysis. Normalization and weighting help present a complex LCI dataset in a succinct and focused way to provide a framework for comparative analysis.

The choices made in defining system boundaries with the underlying assumptions and associated implications associated affect the outcome of LCA. For example, the source of a metal component in a product may trace back to the ore from a mine, and the end of life of that same component may be a landfill. LCA evaluates the inputs and outputs for that component for every step of the life of that component. An in-depth and precise LCA evaluates the manufacturing, assembly, packaging, shipping, usage and disposal that are specific to that product. As with any analytical engineering tool, there is a trade-off between accuracy, precision, effort and interpretation. The more detail that is incorporated into the system, the better the accuracy and precision of the analysis. However, as the resolution in detail or accuracy and precision increases, the intensity of effort, difficulty of interpretation, and time and resources required for computation also increase.

So, what does an LCA have to do with sustainability? It is true that LCA is an accounting tool that summarizes impacts in their elemental form. The process of normalization categorizes and sorts the LCI data into a common unit of measure, allowing impacts to be summed into a manageable number of categories. On its own, normalized LCI provides insights into product sustainability. For example, under the category of toxicity, if the normalized data shows that the toxicity level of a product exceeds concentration levels that increase human or ecological mortality, then it is not sustainable. Weighing adds another layer of interpretation by applying factors to categories according to their overall relevance to sustainability. Weighing steps remain controversial—evidenced by the number of weighing methods currently in use.

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Per the definition of sustainability outlined in the previous section, product analysis for sustainability encompasses the entire product under consideration, including its share of packaging and materials consumed during its life. For sustainable product design, the life cycle process is framed from the start of product life through its useful life and concludes at end of product life.

The ever-increasing flow of raw materials and products moving about the planet, and within this flow, is very diverse. This diversity makes it a difficult task to establish acceptable values of global warming, ozone depletion, toxicity, photo-oxidants, acidification potential and eutrophication for a single product, let alone for the many classes and sub-classes of products available. While the LCA of an independent product can stand alone to evaluate the overall impact of that product, LCA is also a tool for evaluating the impact of a product *relative* to similar products—or relative to older versions of a product. From the experience of the author, LCA is commonly used as a marketing tool in this manner where several similar products or older versions of a product are compared in order highlight the product with the least impact.

According to the preceding discussion, LCI and LCA are precise analytical tools. However, like other analytical tools, there are practical methods for simplifing the analysis to provide an initial insight into expected performance as a guide for making decisions during the design process. In the world of engineering, this is the celebrated "back of an envelope" calculation. Similarly, in the world of LCA, this is a Single Factor Analysis approach. Single Factor Analysis uses a predefined set of LCI that has been normalized and weighed into a single value. The LCI used in single factor analysis is averaged across a broad range of data and is not defined specifically for the product under evaluation. However, it provides enough insight to inform design decisions, especially when the specifics of a design are not yet defined.

To support life on earth for now and create a sustainable future, we cannot continually exceed the capacity of the planet.

The Typical Product Development Process

For the reader to understand how to integrate Life Cycle Design into the product development process, the steps of the product development process are outlined. Many design and product development groups, university courses and companies outline their product development processes as unique and different, but after sorting out the differences in terminology, the product development process boils down small variations of, or iterations within, the following six steps:

- Step 1 – Research and Investigation
- Step 2 – Conceptual Generation
- Step 3 – Prototyping
- Step 4 – Detailing
- Step 5 – Pre-production
- Step 6 – Production

On the path from Step 1 to Step 6, creative and effective designers and engineers develop a new product not by a flurry of innovation and “eureka” moments, but rather by implementing a series of methodical and continuous decisions to minimize potential pitfalls while enhancing the positive aspects of an evolving concept and design. It is commonly a circuitous process iterating through the six steps above to continually evaluate design feasibility.

Design feasibility is commonly gauged using a series of weighted project metrics such as development cost, development schedule, product cost and product features (performance). Development cost boils down to the monetary and other resources required for developing a product. An ample budget may allow for a large, multi-disciplinary team and access to any tool necessary to design the product. Development schedule is associated with the time required to get the product to market. A long schedule allows for a team to exhaustively explore design alternatives and methods for design perfection. Product cost is linked to the material costs and assembly complexity (assembly cost) of the final product. An unlimited product cost allows the team to utilize exotic and rare materials with complex assemblies—requiring highly skilled, time intensive labor for construction. Product features or product performance relates to the how well and how many functions are included with the product. Limitless numbers of product features allow the team to include a multitude of product features for interfacing with the user, anticipating the needs of the user and aiding the user in interacting with the product. Commonly, these metrics are structured in terms of minimizing development costs, minimizing development schedule, minimizing product costs or maximizing product features.

At the initiation of Step 1, the project metrics are evaluated and ranked according to their relative importance to the project goals. Ranking the metrics early in the product development process is critical activity for two reasons. First, the metrics inform design decisions throughout the product development. Second, the metrics are somewhat contradictory, so it is difficult, if not impossible, to design a product if all of the metrics carried the same weight. Minimizing or maximizing any one of the metrics commonly has some degree of adverse affect on one or more of the other metrics. For example, minimizing development cost may require either reducing the team size, thus impacting the schedule or reducing the design effort, thus increasing the product cost or decreasing the number of features incorporated into the design. Prioritization or ranking helps teams identify which alternative best fits with the project goals. The ranking of project metrics is commonly revisited throughout the product development process and project goals are adjusted accordingly at those times.

While the first step of product development is research and investigation, these activities are less focused on the product itself and more focused on defining and understanding the problem the product will solve. Let's take a car design as an example. During Step 1, one would research means of transporting passengers between two locations as an alternative to walking. Additional goals, but not necessarily restrictions, of the research may be related to efficiency (speed and convenience), capacity (number passengers and size of their loads), range (total distance) and mode (on streets). Under this definition, research and investigation extends beyond the automobile to all areas of transportation. Research and investigation includes a range of activities such as evaluating literature and products, interviewing users, participating in activities and so forth. The problem statement and goals are intentionally left vague at this stage to learn about technologies and solutions that are not automobiles and explore ways those technologies may apply to a means of transporting passengers between two locations. Of course, depending on the project metrics, the problem statement may require more refinement or research and investigation activities may be limited by time or scope.

This step results in a deeper understanding of the problem and a broader definition of how the problem may be solved. Returning to the example of the car, following Step 1, the team has a better understanding about means of transportation, possibly including details like what motivates a user to employ an alternative to walking, what alternatives exist, how the alternatives work, what technologies are used, which users use which alternatives and why, and identify which features work the best and which features can be improved. The amount of information acquired depends on the breadth, depth and intensity of Step 1, which are defined by the project metrics.

Once research and investigation are exhausted sufficiently to satisfy the project metrics, Step 2 begins by exploring concepts for solving this problem. First, the problem statement is revisited, refined and divided in problem subsets to guide the Step 2 activities. In the case of the car, the problem subsets may be related to mechanical design (drive train, steering, braking, ect), electrical design (diagnostics, user controls, electrical hardware, ect) passenger space, external design, construction materials, During this step, the team first brainstorms ideas to solve the primary problem as well as the subset of problems. Following brainstorming, ideas are evaluated for merit, physical feasibility, how well they address the problem and meet the overall goal of the design. Again, these ideas extend beyond the automobile to explore general ways to solve these problems. The research and investigation from Step 1 informs and inspires the ideas generated during brainstorming and evaluation.

At the end of this step, the many ideas generated for solving the initial problem and its subsets are further reviewed and integrated to form design concepts. The number and type of concepts selected for further evaluation in Step 3 will be influenced by the project metrics. This is the first point where solutions begin to take shape. However, the concepts at this stage are little more than sketches, descriptions and estimates about feasibility of physical realization. There is little detail at this stage and the concepts are not yet sufficiently refined to know whether they can be realized physically or if they sufficiently solve the problem and all of its subsets. While it is hard to postulate what concepts for a car may arise from this step, it is reasonable to assume that some of the concepts will not have 4 wheels, a gasoline engine, a single driver with 4 or 6 passenger, the shape of an automobile or any number of features normally associated with a car.

In Step 3, the feasibility of concepts from Step 2 is evaluated through various stages of prototyping. Prototyping does not always mean building a physical object. Prototyping may start with rudimentary mathematical or paper models to explore the appearance, behavior and interaction of a system or subsystem. As the understanding of the physical nature of the concept is better understood, prototypes become more refined and physical, mathematical or computer models are built to better describe the form, behavior and interaction of the system or subsystem. Prototypes are typically built using whatever methods are readily available, which may not be reflective of the methods prescribed for final manufacturing.

Depending on the project metrics, one or more prototypes to solve each sub-problem may be generated to compare their appearance, behavior and interactions. This may also include multiple versions of the same prototype. For example, a scaled prototype of a complex system may be built first out of components readily available to demonstrate that the design is physically possible and has the potential of behaving as desired. Next, another scaled prototype may be built with custom parts to evaluate the appearance, behavior and interactions that occur while being of a size that is easy to handle, modify and may be more cost or time effective. A final, actual size prototype may be built to mitigate complications and improve understanding.

Prototyping is a tool used to characterize the behavior and interactions of a system. The more fully the design is characterized across a broad range of circumstances, the less likely complications will arise later in product development. Project metrics may dictate minimizing prototypes, but typically, the more times prototypes are iterated to minimize undesired behaviors, the less time is required in later steps. For example, a small-scale prototype of a 5-wheeled vehicle may perform well or exhibit behaviors that are thought to be insignificant. It may be found that the fifth wheel is superfluous only after the first production cars are built. Generally, it is best to prototype often.

Throughout Step 3, the concepts are continually being evaluated for their feasibility and performance. It is possible for any one or all of the concepts selected from Step 2 to be deemed unfeasible during this step and it may be necessary to re-evaluate the concepts generated in Step 2, or return to Step 2 all together. Once prototype performance indicates the concepts successfully address the problem, Step 3 concludes, with at least functional prototypes of each subsystem that, ideally, is actual size with all subsystems fully integrated. At this stage, the refined concept likely has several components and materials specified, identified or even selected.

Step 4 takes the prototype design and further refines it to include all of the details necessary for manufacturing the product. In this step, the solution to a problem takes shape as the final product. If Step 3 resulted in a fully integrated, fully functional, actual size prototype that specifies many of the components necessary for manufacturing, then Step 4 is likely to be fast and smooth. Otherwise, the time and effort required to complete Step 4 varies greatly. Depending on the maturity of the prototype, it may also be necessary to revisit Step 3 or even Step 2 as the detailed design progresses.

At the end of Step 4, the design file is complete and includes specifications for all of the components of the product. The industrial designs defining the final product appearance are completed. The materials for construction are selected. The most appropriate manufacturing and assembly methods are indicated. This process may include the preliminary identification of component manufacturers and manufacturing partners. In short, at the end of this Step, the details of the product fully exist on paper. This is more or less a set of instructions that can be used to manufacture and assemble the car.

For the purposes of this paper, Steps 5 and 6 will be discussed together. While the product can technically be manufactured and assembled from the design file generated in Step 4, the appearance, behavior and interactions within the manufacturing and assembly process need to be designed and evaluated. Steps 5 and 6 are reflective of Steps 3 and 4 except, in this case, rather than designing the product, the team is designing the manufacturing process. In essence, Step 4 is the manufacturing concept stage.

During pre-production, the team prototypes and tests the manufacturing and assembly processes identified during the detailed design. In the process of producing initial parts, the team is continuously evaluating and improving the manufacturing and assembly procedures by refining the design file. As may be the case, the team may find it necessary to revisit any of the previous steps in order to optimize the manufacturing process. Once the performance of the manufacturing and assembly procedure indicates a functional product can be successfully manufactured with the speed, efficiency and reliability desired, the product design moves into production.

Throughout the product development process, the continuation of a particular concept or design is evaluated with respect to the project metrics. For example, assume the car team-determined development schedule was the most important project metric, and a promising concept generated in Step 2 uses a nuclear powered drive system. While that concept may be appealing and it may have merit, it is likely to be eliminated because the time to develop it is unreasonable. Although every project is different and all projects do not exclusively use the four metrics identified, it is common that the project metrics that are used remain tied to monetary and schedule costs without regard to ecological costs.

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What are LCA and Sustainability Design Metrics

A complete product Life Cycle Analysis (LCA) is a detailed, in-depth and intensive process that, on the surface, does not easily lend itself to the early stages of a fluid product development process. It is difficult to apply LCA, a precise measuring instrument, to an ever-evolving and changing design until many of the details of the design are finalized. These complications result in a complete LCA most commonly being applied to pre-preproduction designs or finalized products; a step of the product development process when changes are difficult to implement due to cost, time and design constraints. The outcome is a product designed without regard to ecological costs and life cycle analysis information that may only be partially applicable to the next generation of the product design.

While LCA is a precision measuring instrument, standards and tolerances that set limitations on the inputs and outputs of a product's LCI do not currently exist. Furthermore, defining limitations for every class and sub-class of products is a daunting task. This means that a stand alone LCA on a single product exists only to catalog the inputs and outputs of that product, and without baseline or reference value, there is no way of gauging whether those inputs and outputs are good or bad. This leads to LCAs most effective application as a comparative instrument.

At its core, sustainability is about how the flow of materials about the planet today is managed to preserve and improve the quality of life for future generations.

However, the LCA of a product can only be compared to the LCA of another product if both products are at a similar stage of development. This is further complicated by the fact that, unless every product in a product line meets the exact same engineering and design specifications, it is not a direct apple-to-apple comparison of ecological impacts. The ecological comparison is only valid across the features that each product shares implicitly with the other product. For example, it is not an accurate representation to compare the LCAs of an electronic device designed specifically for power performance to that of an electronic device designed for system performance. For each product, the intent of the design in Step 1 and, ultimately, the resulting engineering specification in Step 5 and 6 are not equivalent.

Just as with the design process outlined earlier, sustainable products do not happen in a vacuum.

To design a product with the goal of minimizing its ecological impact, a method to compare the concepts and designs developed throughout the process with the same design intent—that target the exact same engineering and design specifications—must be used. This method uses the broader concepts of LCA principles during the early stages of the design process and, just as in any other good product development process, it iteratively and continually evaluates and refines those princi-pals as the design evolves. In the early stages of the design process, broad assumptions and com-parisons between concepts can be made. These may be imperfect, but as with any other design metric, they are informative and fluid. As the design progresses, the assumptions are systematically and methodically replaced with stronger assertions that influence design direction. Unlike applying LCA only in pre-production and final product designs, the lessons learned and ecological decisions made in the early stages of the process now inform the detailed LCA and will guide the manufactur-ing and production methods.

An Improved Product Development Process

With an understanding of Life Cycle Analysis, the Product Development Process and Sustainability Metrics, a method for an improved product development process is at hand. This process is the foundation of Green Design with Life Cycle in Mind. To do this, we return to the steps of the product development process outlined previously. The table below defines each step according to its product development step, an associated sustainability metric and the expected outcomes for each step with respect to product features and ecological features. It is important to note that while the ecological features are defined separately for the purposes of demonstration, they are not divisible from the product, but rather integral to it.

Step	Sustainability Metric	Outcomes
Research and Investigation	Sustainability targets for the system	*Product features*: Basics of performance constraints and considerations. | *Ecological features*: Basics of sustainability constraints and considerations.
Conceptual Generation	Preliminary comparison of sustainability of concept	*Product features*: Comparative performance ratings of design concepts. | *Ecological features*: Comparative sustainability ratings of design concepts.
Prototyping	Evaluation and comparison of sustainability of prototype options. Preliminary comparison of sustainability of manufacturing techniques.	*Product features*: Estimate of performance and major design risks.Identification of options for manufacturing techniques. | *Ecological features*: Estimate of sustainability and major ecological risks for design. Comparative sustainability ratings.
Detailing	Baseline LCA of final design. Evaluation and comparison of sustainability of manufacturing decisions.	*Product features*: First articles are made, inspected and iterated as needed. | *Ecological features*: High-confidence and high-specificity LCA.
Pre-production	Full LCA of final design and manufacturing. Establish comparison with competitors.	*Product features*: First articles are made, inspected and iterated as needed. | *Ecological features*: High-confidence and high-specificity LCA.

Just as with the design process outlined earlier, sustainable products do not happen in a vacuum, but rather through the implementation of an iterative process of minimizing harmful ecological impacts while enhancing positive ecological impacts as the design evolves through the six steps. In this Life Cycle Design process, life cycle activities are initially less intense than engineering and design activities. In earlier steps, the Life Cycle Design activities are primarily research based with high-level screening to establish system boundaries and build the foundation for final analysis. As the process proceeds, Life Cycle Design activities become more specific to inform design decisions and ultimately guide manufacturing decisions.

Earlier, design feasibility gauged metrics related to feature performance. In this process, they are also gauged according to ecological performance and ecological costs. In this case, the ecological cost relates to the ecological footprint required for developing a product. An unlimited ecological budget allows for a product that uses any resources, materials or manufacturing process required to achieve the product features and performance required. Essentially, this is how products are designed according to the previously defined product development process, and the only ecological limits arise from those resulting as an offshoot of the other project limits.

It may be tempting to rank the ecological costs relative to development cost, development schedule, product cost and product features (performance). This line of thinking assumes that sustainability metrics adversely impact the other design metrics and that they are in direct competition with design metrics. Neither is the case. Unlike with the other metrics, minimizing or maximizing any one of the metrics commonly should not have an adverse effect on sustainability metrics. Life cycle design equates sustainability metrics with design metrics and treats them as complimentary. Just as selecting a material that lacks sufficient strength is counter to good engineering practice, selecting a material that disregards negative ecological impacts is also poor engineering practice. The ecological impacts of a product can be minimized regardless of how development cost, development schedule, product cost and product features (performance) are ranked.

Life Cycle Design Step 1 activities focus defining and understanding the system under consideration. When the project metrics are evaluated at the initiation of Step 1, the general sustainability metrics are established by determining the features of system. At this stage, the relative scale of system impacts will be roughly evaluated through research and preliminary calculations. Returning to the car design example, one would research similar systems to identify useful data and analysis for similar modes of transportation. One would learn what impacts are important to transportation. In the transportation industry, there is a particular focus on emissions, efficiency and repair costs. This includes a preliminary investigation into other ecological information such as regional concerns, typical manufacturing locations, established supply and recycling channels, and existing infrastructure. As with the previous definition, this research and investigation extends beyond the automobile to all areas of transportation.

This step results in a preliminary understanding of sustainability constraints and considerations related to the type of product under development. The constraints and considerations include establishing sustainability goals. The goals are associated with where the greatest gains in minimizing ecological impacts can be achieved. This may mean focusing on one or several sustainability goals for the whole system or for each subsystem. These sustainability goals include things like sourcing low impact materials, minimizing impacts due to the use phase, establishing a design for recycling strategy, incorporating design consistencies from generation to generation of a product, reducing manufacturing waste and other product specific goals. Although they can be continuously refined, establishing these sustainability goals early in the design process is essential for guiding designers and engineers in later decision making.

During Step 2, concepts for solving the problem are generated. Each of the system level and sub-system level concepts is generated through a series of brainstorms, evaluations and refinements. Life Cycle Design can lend itself to this step in several ways. First, It may be practical to brainstorm specifically to address certain ecological concerns. Brainstorms of methods for achieving the sustainability goals from Step 1 can be included. For a car design, this may be brainstorming ways to minimize emissions, or ways to integrate design for recyclability of the engine, or ways of manufacturing body panels with minimum waste.

Life Cycle Design also reviews the many concepts generated during this step with a high level concept screening. While there is little detail at this stage, assumptions about how a concept may come together must be made for the screening. An experienced engineer familiar with materials, components, manufacturing and construction methods—who is able to incorporate sufficient design information on concepts to evaluate its physical feasibility—is also able to use that knowledge to complete an ecological screening of the concepts. Rating concepts according to how well they meet performance expectations is an approximate method, just as rating concepts according to how well they meet ecological performance expectations is approximate. However, just as predicting performance expectation improves with experience and understanding, predicting ecological performance improves with experience and understanding.

Step 3 carries out various stages of prototyping, which is where Life Cycle Design activities begin specificity to inform design decisions. Since the product systems and subsystems are taking shape in this step, the boundaries of the system for a full LCA are established and a preliminary LCA of prototypes are conducted. Looking at a car, comparative LCAs can be prepared for prototype options of drive trains. The information from these comparative LCAs can be used to guide the drive train design to the most sustainable options. In this case, the assumption is that all prototypes under consideration perform as expected where the LCA can differentiate them ecologically or reveal prototype sub-system combinations with lower ecological impact.

At this stage, it is also feasible to start conducting formal comparisons with competitor's products. This is resource intense activity that is typically not initiated until the design is complete. Initiating this activity in Step 3 has two advantages. The comparisons can be more thorough and may be continually refined over a longer period of time. Comparative LCAs may highlight disproportionately large or small ecological impacts which can inform and guide the current design process by avoiding or embracing similar product features.

As the prototypes evolve, the associated LCAs also evolve. It is likely LCAs of individual subsystem prototypes are completed in this step and eventually integrated into larger systems. Ecological impacts related to behaviors and interactions within the larger system are easily characterized with this method of systematic integration. It also allows impacts of various prototype options to be characterized and compared across a broad range of circumstances. This results in guiding the design toward lower ecological impact. As with the original product development process, the more times prototypes are iterated to minimize undesired ecological impact, the less time is required to do so in later steps.

Preliminary characterization of the ecological impacts due to manufacruting is also evaluated during Step 3. As components are selected for prototypes, options for manufacturing techniques are also explored. The relative impacts are compared with an LCA of the various manufacturing options.

Step 3 results in tested prototypes of various systems and subsystems. These prototypes estimate the performance of the final product and establish component specifications, identify potential component options and propose options for manufacturing techniques. A resulting detailed LCA of the prototypes is completed. Baseline LCAs of competitive products are established and an ecological comparison of potential manufacturing techniques is completed. During Step 4, this design, engineering and ecological options are used to inform the final product design. The maturity of the prototype designs will dictate the maturity of their associated LCA and the maturity of the manufacturing comparisons.

Thorough and frequent prototyping in Step 3 constrains many of the engineering and design features, so changes in engineering and design direction are minimal during Step 4. During this step, final component selection and manufacturing techniques are established. Using the Life Cycle Design information established in Step 3, ecological impacts are used to inform component selection and manufacturing technique decisions that minimize the ecological impact of the product. As the design becomes detailed, the LCA becomes more detailed. At the end of this step, not only do the details of the product fully exist on paper, but the ecological impacts are also fully characterized with a high-confidence and high-specificity LCA. Depending on the LCA methods and LCA practitioners, these are potentially publishable results with regards to the product and competitive products.

The engineering and design of the product do not change Steps 5 and 6 unless preliminary findings during the manufacturing and assembly process dictate the need for improvements or a return to Step 4. Findings from Step 4 are verified in light of the limitations and information of the actual manufacturing and assembly process. As the manufacturing process is tested and refined, the LCA of the product is corresponding tested and refined—until the product enters Step 6. At this stage, a final and potentially publishable high-confidence and high specificity result.

Throughout this refined product development process, concepts are continually evaluated for their ecological merit and conscience decisions are made to minimize the ecological impacts. Waiting until Step 5, Preproduction, to initiate sustainability activities results in characterizing products that are not designed with the intent of minimizing the ecological impact. In contrast, the process outlined here establishes sustainability goals in Step 1 and uses these goals to guide design decisions. The result is a product designed for minimizing ecological impact.

Conclusions

In design, there is a misconception that innovation is a matter of genius combined with eureka moments. In a similar manner, it is also believed that sustainable design is exclusive to treehugger-type products. Ultimately, in both cases, the method of applying a conscientious and thorough decision making process to minimize negative attributes while maximizing positive attributes is the secret to success.

It is commonly believed that ecological merit comes at the cost of performance. This misnomer is a result of initiating sustainability late in the product development process. In this case, it is difficult to reverse performance based design decisions without incurring additional costs, or additional costs may result from substituting "greener" options at this stage. This is not different than waiting until later design steps to conduct something like a thermal analysis and finding the need to backtrack or implement expensive solutions to improve or meet necessary thermal performance. However, by implementing sustainability goals early in a design process, it is feasible to integrate both ecological and performance metrics in a cost effective manner. Evaluating the ecological performance early is no different than evaluating other performance metrics early.

Just as it is good engineering and design practice to analyze a design early and frequently for performance, it is a good engineering and design practice to analyze a design early and frequently for ecological performance.

info

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As Mechanical Engineer with Master's Degree and 8 years of diverse experience, Kimi Ceridon worked technical roles ranging from contributor to lead engineer and project manager of multidisciplinary teams, including working with Sustainable Health Enterprises (SHE), MIT's D-Lab and the International Development Design Summit to develop appropriate technology for third world applications. She aims to develop technologies for a positive social impact on the world in two areas: 1. Design for Sustainability: applying principles of life cycle analysis to product development and 2. Technology for International Development: develop appropriate technology for third world applications.

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