A DESIGN OPTIMIZATION FRAMEWORK TO ESTIMATE ENVIRONMENTAL IMPACT OF DESIGN DECISIONS IN CONSUMER PRODUCTS

Carlos M. Briceño,[1] Andres L. Carrano,[2] Brian K. Thorn,[2] and Marcos Esterman Jr.[2]

ABSTRACT

Most products have the potential to negatively impact the environment during all life-cycle stages. However, most environmental impact assessment methods focus on a single product life-cycle and on a specific life-cycle stage. Product design plays a significant role by determining traditional environmental impacts, such as embodied energy of materials, but also by influencing market adoption and production volumes. The main objective of this work is to develop a design optimization framework that estimates the environmental impact of design decisions (e.g. materials choice, etc.) across all life-cycle stages in consumer products. The methodology relies on quality function deployment (QFD), multi-attribute utility theory, non-linear mathematical programming, and life-cycle assessment tools to estimate the utility of the design options to the customer, the producer, and the environment. The proposed framework allows designers and other decision makers to select options that are environmentally sound and also aligned with the business objectives.

KEYWORDS

lifecycle assessment, product design, multi-attribute utility, nonlinear programming

INTRODUCTION

Carew and Mitchell (2002) state "humans have attained the unprecedented capacity to modify the natural environment on a global scale, and with this capacity comes the need for a new type of responsibility". Anthropogenic activities are pressuring every natural system on the planet; many systems are disintegrating under these mounting pressures (UNEP, 2002). Some of the disturbing trends cited by the United Nations Environmental Programme's report include:

- 2.8 billion people live on less than $2 per day; 1.2 billion of these subsist on less than $1 per day.
- approximately 1.1 billion people lack access to safe drinking water.
- approximately half of the planet's rivers are seriously depleted and polluted.
- approximately 24% of mammals and 12% of bird species are globally threatened
- approximately 2 billion hectares of soil (equivalent to 15% of the Earth's land mass) is now classified as degraded as a result of human activities.
- 305 million hectares (about 2.5% of the Earth's surface) is so badly degraded that it can never be restored.
- the atmospheric concentration of carbon dioxide is almost 30% greater than it was 150 years ago. Concentrations of other greenhouse gases are also increasing.

It has become clear that current production and consumption patterns are not sustainable. By failing to account for potential environmental, economic, and social impacts, the current production/consumption system has given rise to numerous unintended and undesirable consequences: increased polarization of wealth, overuse and contamination of water resources, the specter of global climate change, and loss of biological diversity to name a

[1]Toyota Motor Engineering & Manufacturing North America, 25 Atlantic Ave, Erlanger, KY, 41018.
[2]Industrial and Systems Engineering, Rochester Institute of Technology, 81 Lomb Memorial Drive, Rochester, New York 14623-5603, corresponding author emails: alceie@rit.edu and bkteie@rit.edu.

few. Insights into the fundamental stresses on planetary systems are gained by considering the "master equation" of Industrial Ecology (Graedel and Allenby, 2003). This equation provides a conceptual model whereby global impacts, be they environmental, social, or economic, are expressed as a function of global population, standard of living, and the level of technology through which that standard of living is generated for that population.

$$\text{Impact} = (\text{Population}) \times (\text{Affluence}) \times (\text{Technology})$$

In this equation, also known as IPAT, the population term describes the number of individuals for whom the level of impact is sought. Affluence describes the standard of living for the population of interest. Since an individual's standard of living is highly correlated with their level of economic consumption, affluence is often represented in economic terms such as GDP per person. GDP refers to a country's Gross Domestic Product which is the market value of all final goods and services produced within a country in a given period of time. The technology term represents the "degree to which technology is available to permit development without serious environmental consequences and the degree to which that available technology is deployed. This is primarily a technological term, though societal and economic issues provide strong constraints to changing it rapidly and dramatically" (Graedel and Allenby, 1996). The technology term is usually expressed in Unit of Impact per Unit of GDP.

Further examination of current trends associated with the terms on the right hand side of the master equation yields valuable insights. Worldwide population is increasing. However, the population growth rate appears to be decreasing. The US Census Bureau reports that the Earth's population hit 6 billion in 1999, and is projected to increase to 9 billion by 2042. Annual global population growth is predicted to be between 45 and 80 million until 2042 (U.S. Census Bureau). It is difficult to predict whether, or when, or at what value global population will peak, but it is clear that in the near term, the world's population will continue to trend upward.

Like population, the affluence of the global family is on the rise. The United Nations suggests that global GDP has more than doubled since 1971 (UN-DESA, 2006). In the master equation, the affluence term captures a population's standard of living or quality of life. Presently, the quality of an individual's life is directly correlated with that individual's ability to access and consume goods and services. If the residents of wealthy, developed nations are not willing to reduce their consumption of goods and services, and as the residents of poorer, developing nations strive to reach the consumption levels observed in developed nations, it is expected that the second term in the master equation will continue its upward trend.

Only the technology term offers the possibility of reducing the impacts that result from human activity since the other two terms are increasing and there is little that can be done about it. It has been suggested that a tenfold increase in economic growth will be necessary just to meet the basic needs of a world population of 8 to 10 billion (Hart 1997). The greatest hope for ameliorating undesirable social and environmental impacts is by improving the technologies by which the goods and services that enable a given quality of life are provided. Technologies must be evolved which are capable of supporting simultaneous growth in the world's population and its standard of living, while doing so in more environmentally sensitive and socially appropriate ways, making sustainable development "one of the biggest opportunities in the history of commerce" (Hart 1997).

Additionally, consumer environmental consciousness is also on the rise. Natural events, especially those with catastrophic consequences, and recent energy crises have accelerated societal awareness on environmental issues. The 2007 Cone Consumer Environmental Report Survey states "Americans report increased environmental consciousness and expectation that companies take action". Some of their findings are:

- 32% of Americans reported heightened interest in the environment compared to the previous year.
- 93% believe companies have a responsibility to help preserve the environment
- 47% have purchased environmentally-friendly products in the past year
- Among those: 62% purchased products with recycled content

- 56% performed energy-efficient home improvements
- 13% acquired energy-efficient cars
- 10 % purchased green apparel

The need for the new type of responsibility that Carew and Mitchell (2002) refer to is strongly related to those findings. There is no doubt that companies must manage their efforts in the design and production of goods so that life-cycle environmental impact is reduced.

Spurred, in part, by the heightened consumer awareness of environmental issues, many organizations have made significant efforts to reduce the environmental impacts associated with their particular activities and to encourage others to adopt more environmentally friendly practices. For instance, many university presidents have pledged that their institutions will work toward carbon neutrality, federal and state programs subsidize investment in residential renewable energy systems and promote the installation of energy efficient windows and appliances, and the US Green Building Council promotes its Leadership in Energy and Environmental Design (LEED) system to define and evaluate the environmental impact of structures over their lifespan.

It is expected that more and more consumers will use their purchasing power to recompense or penalize organizations (such as, builders, manufacturers, service providers, governmental and non-governmental organizations) according to the environmental characteristics of their products and activities (Cone 2007). Therefore, a need exists for methods and tools that allow these organizations to make more informed decisions about the impacts of the goods and services that they develop and deliver.

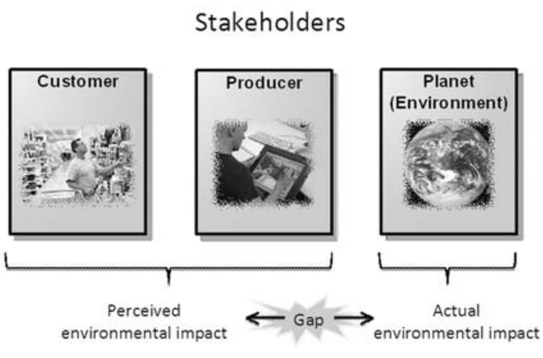
THE NEED FOR A BROADER DESIGN PERSPECTIVE

Traditional design strives to fulfill the needs of a customer and, depending on customer awareness, this may or may not incorporate environmental considerations. Every day, more and more products that claim to be "green" or "environmentally friendly" are developed. This is clearly a consequence of designers assuming a different kind of responsibility and also of listening closely to the ever changing voices of the customer. However, there is a fairly limited environmental literacy level among the vast majority of customers (excluding certain pockets of customers). The reasons include the lack of available (and complete) information to customers on the environmental footprint of products coupled with the enormous amount of media information on very few issues (i.e. global warming, etc.). In this regard, the stressors or characteristics most customers tend to look for in products are recycled content, carbon emissions (e.g. "neutrality"), energy consumption, etc. Rarely do they consider impacts that are somewhat removed from their immediate sphere of understanding, e.g., impact on biodiversity, soil erosion from mining, eutrophication, or even toxicity and impacts on human health. This phenomenon was first documented in *Silent Spring* (Carson, 1962), a seminal work in the environmental literature. Given this situation, designers have little incentive (other than those driven by ethical responsibility) to incorporate design considerations that address stressors or product characteristics that are not rewarded by the customer (Figure 1).

Given the above, good design should incorporate not only the input from customers and producers, but also a fuller picture from the environmental perspective. Several questions may be formulated at this point, for example:

- How large is the gap between the consumer/producer's perceived environmental impact and the true environmental impact (what the planet really sees)?

FIGURE 1. Gap between perceived and true environmental impact.



- Are there design trade-offs that would help achieve a better design from a more complete environmental perspective?
- Is there a "worse" design, from a traditional customer perspective but "better" from a more complete environmental perspective that the "aware customer" would prefer?

Clearly, there are many other questions. Hence, the objective of this work is to propose a framework that can serve as design tool to understand the gap between perceived and real environmental impact, while considering the benefits for all stakeholders: customer, producer, and environment. Such a framework could be flexible enough to accommodate changes as the scientific understanding of impacts associated with various stressors evolves.

RELATED WORK

Many researchers have made efforts to develop methods to improve the iterative design process. These efforts usually are addressed in a specific direction that improves one characteristic of the design. Design for quality, design for assembly, and design for manufacturing are some of these approaches. Although these approaches guide the design in specific product characteristics, they do not aid when multiple design considerations need to be addressed (Thurston 1991). A design evaluation method developed by Thurston (1990) can help evaluate the overall utility of a certain design option by incorporating deterministic multi-attribute utility analysis considering several performance characteristics. Multi-attribute utility analysis considers "incommensurate attributes, quantifies the tradeoffs decision makers are willing to make between them, and allows for non-linearity of these tradeoffs, or situations where the actual tradeoff tolerated depends on the decision maker's current assets position" (Keeney and Raiffa 1976).

Thurston (1991) also developed a methodology that optimizes the overall value of a design alternative. It identifies the arrangement of attribute levels that is most advantageous for the design. Implementing this method in an early stage of the development process is very convenient since it helps to identify the optimal mixture of attributes sooner, thus reducing the number of design iterations. The suggested set of attributes includes design characteristics such as recyclability, manufacturing cost, as well as technical performance considerations. The set of attributes is captured in an evaluation function which is then maximized. Thus, an optimal design alternative is found with respect to the optimal utility. A methodology developed by Locascio (1993) linked multi-attribute utility analysis with Quality Function Deployment. While the QFD approach makes the connections between engineering design decisions and their impact on the customer clear, several limitations exist. First, the information contained in HOQ is only qualitative in nature and therefore not ready for mathematical manipulation. Second, this information only identifies the desired design goals, but provides no direction on how to achieve them. Thurston and Srinivasan (2003) developed a multi-attribute utility function that reflects the willingness to pay for environmental improvement while serving as a basis for an objective function.

These approaches, however, do not attempt to: (*i*) provide a specific assessment of the environmental impact; (*ii*) estimate environmental impacts across all life-cycle stages; (*iii*) optimize for multiple life-cycles (i.e. cradle-to-cradle); and, (*iv*) scale the magnitude of impacts by the adoption of consumer products by markets.

METHODOLOGY

The idea behind the proposed framework is to design products considering the product's utility perceived by all the stakeholders. Assuming rationality, the best products are those where utility is highest for the consumer, the producer, and the environment altogether. Under this premise, design alternatives with high utility for all stakeholders are more likely to be adopted. A proposed overall utility of the product (i.e. global utility), is composed of individual utilities as perceived by the customer, the producer, and the environment:

$$U_{Gk} = f(U_c, U_p, U_e)$$

where:

U_{Gk}: Global utility of option k
U_c = Design utility perceived by customer
U_p = Design utility perceived by producer
U_e = Design utility perceived by environment

FIGURE 2. High level view of the proposed approach.

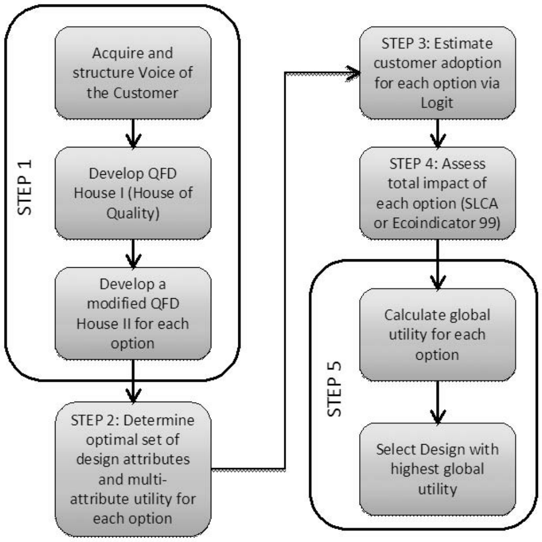


Figure 2 shows a high level view of the proposed framework to obtain the global utility function. The first step is to acquire the voice of the customer and develop Houses I and II of the Quality Function Deployment. The second step is to estimate the customer's utility on the design alternatives by using multi-attribute utility theory, in particular, by adapting approaches developed in the literature (Locascio and Thurston 1993, 1994). The third step is to estimate the producer's utility on the design alternatives with a Logit model. The fourth step is to estimate the environment's utility on the different design alternatives via streamlined LCA or full-LCA Ecoindicator 99 methods. Finally, the last step is to calculate the aforementioned Global Utility function.

The underlying assumptions of this framework include: (*i*) the decision maker is rational; (*ii*) there are a finite number of design alternatives, (*iii*) one alternative must be chosen, (*iv*) alternatives are mutually exclusive.

Voice of the Customer and QFD

In order ensure the success of a design, it is very important for designers to know what the customer is expecting of the product. The purpose of QFD is to capture the voice of the customer and to integrate these customer requirements into the design and production of the product. This is a process well known by product designers. For the purposes of this framework, only the first two houses need to be developed. The first house (HOQ), which translates the customer expectations into engineering characteristics, is ideally independent of the embodiment of design solutions and need be developed only once. The second house, which translates engineering characteristics into part characteristics, is developed for each design alternative. Finally, this framework proposes modifying House II by developing a correlation matrix (similar to the "roof" in House I) among part characteristics for later use.

Design Utility Perceived by the Customer

The utility perceived by the customer should increase with the degree to which the product satisfies the needs of the customer. With proper QFD mapping, this translates into finding the optimal set of values for the part characteristics that results in satisfy the engineering characteristic targets within a specified range. As mentioned before, this approach relies on previous efforts in the area (Locascio and Thurston 1993, 1994) which propose multi-attribute design optimization with information from HOQ (House I) but this work extends them for use with House II.

Figure 3 shows the interpretation and modifications for House II with respect to the optimization framework proposed. On the left side of the house, the engineering metrics are represented by (x_i). The part characteristics at the top the house represent the decision variables of the design (y_j). The correlation matrix that links the engineering characteristics with the part characteristics, which is typically not created for House II, represents the constraint function set. An important modification is introduced to allow for use of utility theory: the engineering characteristics relative importance weight is replaced by the utility function $U_i(x_i)$ for each characteristic.

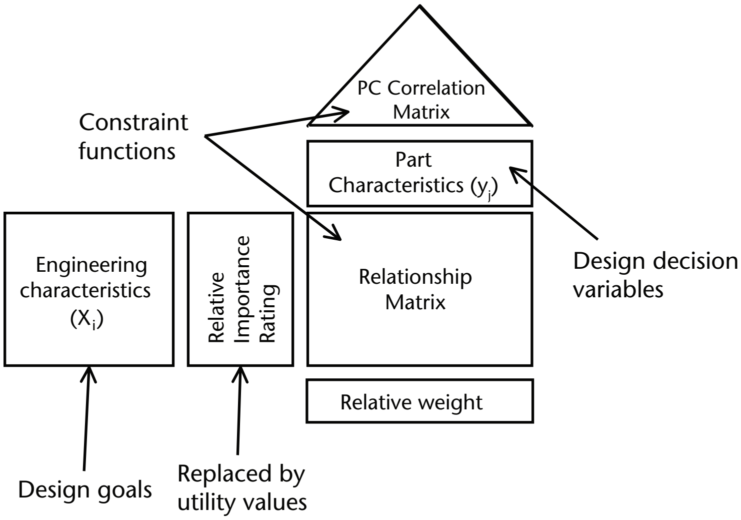
The objective function will be given by the multiplicative form of the multiattribute utility function.

$$\max U_c(x(y)) = \frac{1}{K}\left[\prod_{i=1}^{n}(Ka_i U_i(x_i(y))+1)-1\right]$$

subject to

$$x_i = g_{i(y)} \quad \text{for } i = 1,2,\ldots,n$$
$$y_{lj} \le y_j \le y_{uj} \quad \text{for } j = 1,2,\ldots m$$

FIGURE 3. Interpretation of House II with respect to optimization model.



where:

$U_c(x)$ = overall utility of a design alternative characterized by the vector of attributes $x=(x_1,..., x_n)$
i = 1,2,..., n engineering characteristics
j = 1,2,..., m part characteristics
x_i = performance level of engineering characteristic i
$U_i(x_i)$ = single attribute utility for engineering characteristic i
a_i = single attribute scaling constant
K = normalizing constant, derived from

$$1+K=\prod_{i=1}^{n}(1+Ka_i)$$

The single utility function for each engineering characteristics $U_i(x_i)$ is obtained by asking questions based on lottery theory. The utility functions are normalized where $U_i(x_{ui}) = 1$ is the highest utility and $U_i(x_{li}) = 0$ is the lowest utility of the engineering characteristics. The scaling constant a_i represents the trade-off the designer is willing to make among the engineering characteristics and is found using similar lottery techniques.

To reiterate, this multi-attribute optimization approach is applied to House II, which was modified to contain a correlation matrix (roof) among the parts characteristics. This non-linear optimization model can then be solved for each design alternative by using commercial mathematical programming software such as Lindo. Solving this model produces a vector of optimal part characteristics.

Design Utility Perceived by the Producer

The design utility for the producer should increase with the degree in which the product is acquired by customers. Among other factors, this is a function of the utility of the product design as perceived by the customer. The underlying idea in this section is to estimate the probability that a design alternative is acquired by the customers based on the utility of such an alternative as perceived by the customer. This is accomplished by adapting a discrete choice analysis method (Logit) to estimate consumer demand based on the utility of each option. One important assumption in this framework is that of independence from irrelevant alternatives (IIA), which states that "as one product's market share increases, the shares of all competitors are reduced in equal proportion" (Skerlos et al. 2005).

Let Uc_k be the utility of option k as perceived by customer. Assuming rationality, the customer will acquire option k rather than option l if and only if the utility of k is higher than the utility of l, that is, $Uc_k > Uc_l \; \forall \; k \neq l$. This utility, well known by the consumer, is not fully known by the designer, since the designer only sees the engineering characteristics x_i of the product chosen by the customer, and perhaps only a few customers' attributes (s). These two sets of attributes compose a utility function that can relate the observed factors to the customer's utility. The function is denoted $V_k = V(x_i, s) \; \forall \; i$, and called "representative utility". Since there are utility attributes of which the designer are not aware, then $V_k \neq Uc_k$. These unknown factors are denoted ε_k and are defined as the difference between the true customer utility and the customer utility as captured by the designer. Hence, the true customer utility would be $Uc_k = V_k + \varepsilon_k$. The designer does not know the value of ε_k, so it is here modeled as a stochastic error component. Therefore, the probability that option k be acquired over option l by the customer is:

$$P_k = Prob(V_k + \varepsilon_k > V_l + \varepsilon_l \; \forall \; k \neq l)$$

The model assumes that the component ε of the utility U is identically independent distributed (iid) for each alternative and follows an extreme value or double exponential distribution. Then, the probability that the customer acquires product k is:

$$P_k = \frac{e^{V_k}}{\sum_K e^{V_k}}$$

where K is the total number of available alternatives. The representative utility usually is considered in parameters: $V_k = \beta x_k$, where x_k is a vector of observed attributes of option k. The coefficients β are either known or estimated by the designer. So, the probability can be rewritten as follows:

$$P_k = \frac{e^{\beta' x_k}}{\sum_K e^{\beta' x_k}}$$

In order to determine the probability that a customer will acquire a design option, the vector of attributes, x_k, is approximated as the one previously found for the customer's utility. Thus, the calculated probability is based on optimal values that generate high utility for the customer. The coefficients β are defined by the relative weight of the engineering characteristics which are derived from the the house of quality. These values are located at the bottom of the HOQ, and should be equal for each design alternative (Figure 4).

Design Utility Perceived by the Environment

To estimate the environmental impact of the products, life cycle assessment tools are suggested. Typically, these approaches consider impacts on human health, ecosystem quality, and resource depletion. Although preferred, quantitative approaches (such as Eco-Indicator 99) tend to be more time consuming and rely on a detailed bill of materials. Streamlined LCAs are simpler and can be developed with a less defined bill of materials but provide subjective information. Ultimately, the selection of the environmental assessment approach will depend on the level of product definition that can be achieved.

From the environment's perspective, producing products with zero or positive environmental impact would be the ideal condition. However, almost all products generate negative impacts throughout their respective lifecycles, or at least in some stages of it.

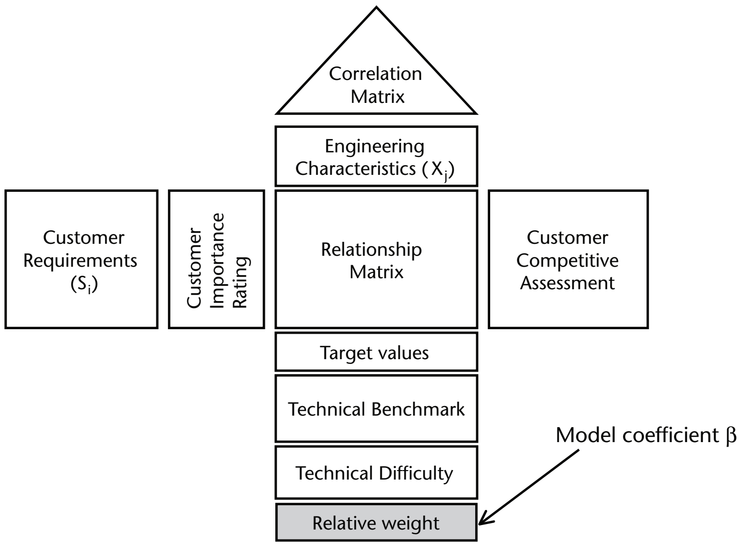


FIGURE 4. Logit model coefficients.

Consider the lifecycle of synthetic carpeting. Negative environmental impacts that accrue along the lifecycle of this product include the harvesting of a non renewable material (petroleum) as the feedstock, emissions associated with the generation of the power used during the manufacturing stage, emissions associated with the transportation of the product from the producer to the consumer, outgassing of potentially hazardous vapors during the use stage, and the eventual disposal of the material in a landfill. Many products, be they appliances, automobiles, or building materials exhibit similar impact patterns.

Here, a design option is considered to have high utility to the environment if its environmental impact is minimal. In other words, the utility to the environment increases as the product's environmental impact decreases. This is described with the proposed function (Briceño 2009):

$$U_e = \frac{1}{(IX+1)}$$

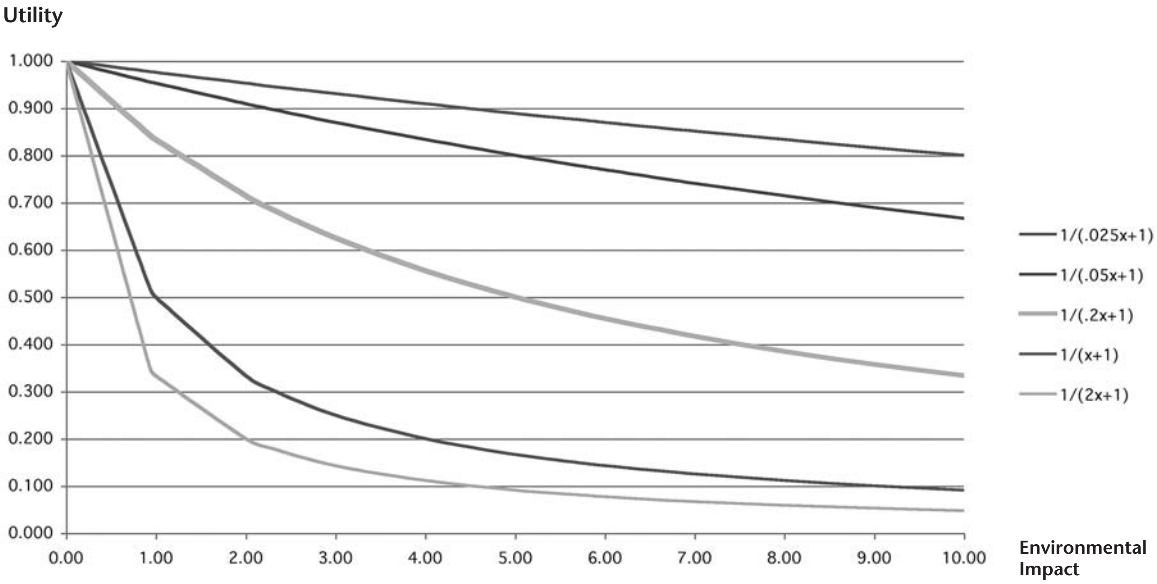
where:

U_e: utility of the design as perceived by the environment,
I: impact factor. A function of the nature of the product
X: impact assessment of the design (obtained from LCA tools).

This function depicts a family of curves (Figure 5) where the environmental impact (units in eco-points or equivalent) is drawn with respect to the environment's utility of the design.

Ideally, the highest utility to the Environment will be reached either having a product with no environmental impact (or by not manufacturing a product, which is not an option). This ideal case would have a utility value of 1. The steep initial decline depicts the impact associated with the mere existence of the product. A large portion of this can be thought of "fixed impacts", a consequence of the fact that a new product, regardless of how environmentally friendly it happens to be, would always require some amount of raw materials, energy, etc. This changes the status quo in a significant way which is reflected in this function. Different products will impact the environment in different ways, hence the Impact Factor (I) and the different curves. The asymptotic shape of the curve implies a diminishing rate of impact with marginal increases of environmental impact. Different design choices, technological advances, etc. will position the design along different points in the curve.

FIGURE 5. Family of curves depicted by the utility function of the environment.



Global Utility

The global utility is defined as the weighted sum of the previous three utilities:

$$U_{Gk} = a_c U_c + a_p U_p + a_e U_e$$

where:

U_{Gk}: Global Utility of option k
a: weight factor vector (cardinality = 3)

$$a_c + a_p + a_e = 1$$

U_c = Design utility perceived by customer
U_p = Design utility perceived by producer
U_e = Design utility perceived by environment (earth).

CONCLUSIONS

In this work, several independent approaches are adapted and integrated into one framework that allows for understanding the impact of design decision with respect to three stakeholders: the customer, the producer and the environment. This framework allows decision makers to select options that are environmentally sound and also aligned with the business objectives.

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