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Design optimization framework to estimate environmental impact of design decisions in consumer products

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Design optimization framework to estimate environmental impact of design decisions in consumer products

by

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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 lifecycle stage. In addition, consumer products can potentially amplify these impacts with their larger production volumes, wide dispersion, and miniaturization trends. The main objective of this project is to develop a design optimization framework that allows for estimating the environmental impact of design decisions (e.g. materials choice, etc.) across all life-cycle stages in consumer products. This work incorporates into one framework customer preferences (including preference for environmental friendliness), consumer adoption translated into utility for the producers, and environmental impact quantification of design options. The methodology relies on QFD, multi-attribute utility theory, non-linear mathematical programming, and Lifecycle Assessment tools to estimate the utility of the design options to the customer, the producer, and the environment. A function that depicts the utility of design perceived by the environment is introduced. Also a "Global Utility" equation is introduced. It incorporates the utilities of all three stakeholders and reflects the overall utility of the design alternatives.

A case study is developed considering two design options of outdoor lighting: solar and low voltage powered lamps. The Global Utility (overall utility of product) is calculated for the two alternatives. Then, the model is flexed to illustrate the response of the model with different design orientations (environmental conscious and environmental oblivious design tendency). Also, a redesign application is exemplified by performing a material substitution in the solar lamp ground pole. Finally, a Monte Carlo sensitivity analysis is performed to demonstrate the robustness of the framework.

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1. Background

From the beginnings of civilization humans have adapted to the surrounding environment modifying it to guarantee the survival and later to make their lifestyle more convenient and comfortable. Most of these changes brought positive impacts to their lives but perhaps not to the environment. Furthermore, during the industrial age the capacity to transform the environment accelerated dramatically. Mass production brought the capacity to satisfy the needs of a constantly growing population, but also required a large amount of resources generating a larger impact to the environment. Also, waste became an important issue. Some of the significant impacts caused to the environment are the release of large amount of greenhouse gases, the discharge of toxic residues into natural water bodies, the deforestation, and the alteration of large areas of land to acquire raw materials or housing spaces among others.

Carew and Mitchell (2002) stated that "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 Program'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 gasses 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 few.

Insights into the fundamental stresses on planetary systems are gained by considering the "master equation" of Industrial Ecology. 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.

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

$$I = P \times A \times T$$

In this equation, 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 & 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 (UNDESA, 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, undeveloped 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).

Along population and affluence, the consumer environmental consciousness is also increasing. A high number of natural events with catastrophic results for population, and an energetic crisis due to high oil prices have triggered and expanded in the society the environmental awareness. 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 compare to a year ago
- 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 a new type of responsibility that Carew and Mitchell (2002) refer to is strongly related with these findings. There is no doubt that companies must strive to design and produce goods with reduced lifecycle environmental impact; however, awareness and acceptance of environmentally friendly products by consumers are even more important. A large number of customers looking “greener” products will increase the demand and more resources could be addressed to the research and development of this type of products. Furthermore, the cost of producing such products could reduce encouraging more companies to assume with interest the environmental trend. This way the consumer will use their purchasing power to recompense or penalize the companies according to the environmental characteristics of their products (CONE Communications, 2007).

Developing technology and integrating that technology into products and systems is the role of industry. The processes used and the decisions made during the design and development of the product will ultimately determine the environmental impact. While

many formal design methodologies do not attempt to explicitly address the environmental and social externalities associated with the delivery of new products, processes and services (Clausing, 1994; Ulrich & Eppinger, 2004), most researchers of the product development process understand that a life-cycle perspective of the product is essential to be successful in the market place in the long-term (Pahl & Beitz, 1995; Otto & Wood, 2000; Ishii, 2004). They generally agree on a model similar to the one shown in Figure 1-1. Inherent in this model is that not only does the product developer need to consider traditional costs, such as product development and manufacturing costs, but they also need to consider and design for operational costs, service and maintenance costs and, increasingly, end-of-life disposition and environmental impacts.

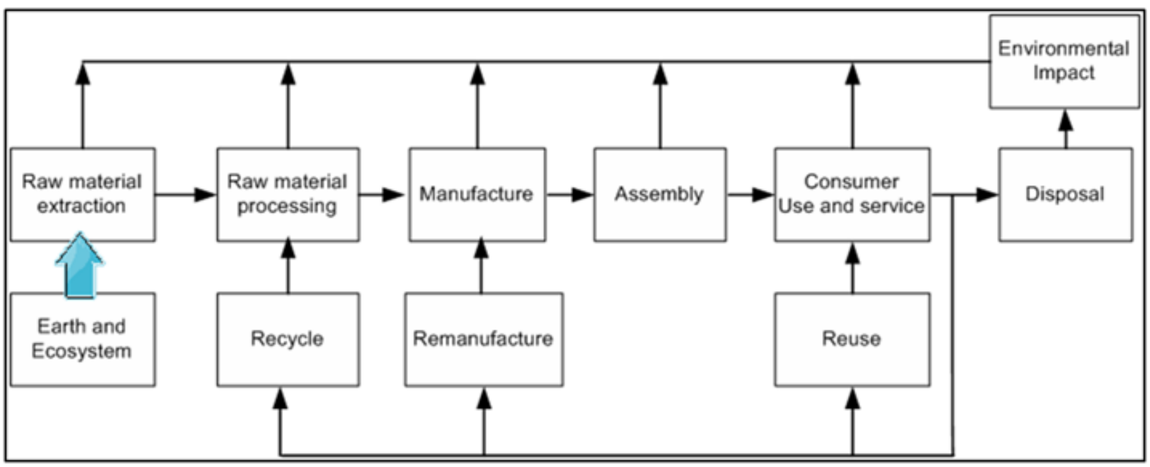

Figure 1-1 Product life cycle

Products have the potential to impact the environment during all life-cycle stages. A well established principle in design is that as much as 80% of the "costs", which includes the environmental impact, are determined at the concept design stage of the product development process. This argument is central to the justification of the use of design tools and methods commonly referred to as design for X (DFX), where X represents a particular life-cycle stage or concern (e.g. design for manufacturability, design for assembly, design for service, etc.). As a DFX area, design for the environment (DFE) is a relatively new field. There are many terms and labels that have been employed that address this broad area of life-cycle design. These include green design,

ecological design, environmentally conscious design and manufacturing, eco-design, and more recently sustainable development (Baumann, Boons, & Bragd, 2002; Gutowski, et al., 2005; Bras, 1997). There are differences between these approaches that have been categorized by Bras (1997), where he identifies three classes of approaches for dealing with environmental impact assessment:

- those which are applied within a *single* product life-cycle and focus on *specific* life-cycle stages
- those that focus on the *complete* product life-cycle and cover *all* life-cycle stages
- those that go *beyond* single product life-cycles

While the scope of these approaches is different, all of them rely on some form of assessment of the environmental impact to guide beneficial changes in the product or system in order to minimize the impact to the environment. However, a wide range of assessment mechanisms exists. In a thorough survey of the existing literature since 1970, Baumann et al. (2002) discovered that the majority of the assessment methods reported fell into the category of those which are applied within a single product life-cycle and focus on specific life-cycle stages[1], with guidelines and checklists being the most commonly employed methods. Gutowski et al. (2005) note that in order to deal with the complex nature of environmental impact assessment, tools, metrics and models are "badly needed" in order to guide improvement direction and to measure progress.

Interestingly, while Baumann et al. (2002) highlight the need for tools at the conceptual stages of design, they also point out that many designers feel that tools in the early stages of design are lacking and would like to see better methods at the early stages of design. They also highlight the need for tools that, in Bras' categorization scheme, cover the entire life-cycle span and go beyond a single product life-cycle. Both studies pointed out that the most common analytic tool in use is life cycle assessment (LCA).

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[1] Note that Baumann et al. (2002) used a different categorization scheme and the author of this work are making a rough map to Bras' categories (1997).

LCA "studies the environment and potential impacts throughout a product's life (i.e. cradle-to-grave) from raw material acquisition through production, use, and disposal" (ISO, 1997). Tools like SimaPro (www.pre.nl/simapro/) and GaBi (www.gabi-software.com/) allow for quantitative metrics to be developed in order to assess environmental impact. Some of the criticisms cited (Baumann, Boons, & Bragd, 2002; Gutowski, et al., 2005) regarding LCA are that it is very data intensive and it requires specialized expertise. As a result, it can take a long time to complete which may be a reason that these tools are not yet very well integrated with other product development tools.

This last observation is particularly important because fundamentally the design process is an exercise in a decision-making process requiring trade-offs. If environmental impacts are going to be considered on-par with traditional product development metrics like performance, time-to-market and costs, then reliable and robust impact assessment metrics are needed. In a study of fifteen different existing ecodesign tools, Byggeth and Hochschorner (2006) concluded that while many of the tools were capable of being used for trade-off decisions they were insufficient, mainly due to the lack of standardization and connection to a sound theory, a view also expressed by Gutowski et al. (2005). However, even with its shortcomings, LCA has been successfully integrated in a decision-analytic framework to study trade-offs between product design, manufacturing and the environment (Carnahan & Thurston, 1998).

Gutowski et al. (2005) question whether evolving environmentally conscious manufacturing efforts will be sufficient to protect the environment. Addressing this issue will be a major focus of this work, as will be the integration of various methods to address the issue of trade-off analysis in the context of product development and the entire life-cycle.

2. Problem Statement

Around a consumer product, three stakeholders can be considered: customers, producers, and the environment, namely the environment. In first place customers are those for whom the products are designed. They look for goods that satisfy their needs and generate the highest value or utility. Utility may be define as the customers overall satisfaction derived from either a design alternative or single attribute (Parsaei & Sulliva, 1993). For instance, a homemaker looks for a vacuum cleaner that reaches narrow gaps, generates good suction, and provides easy handling; as an automotive mechanic might look for tools that help him extract engine valves in a safely and practical manner. Every customer has particular values and needs. Ultimately, customers determine the success or failure of a design.

Secondly, producers are those who develop and produce the goods or provide the services to consumers. They usually rely on the "Voice of the Customer" to supply the customer with the best in the class service or product (VOC: is a process used to capture the requirements/feedback from the customer that constantly changes with time). The producer's interest is to allocate their products in the market and to obtain the major economical benefits from sales. Product designers are included as a stakeholder. Ideally, their focus should be to develop products that satisfy the customer needs while considering the effects on the environment.

The environment provides the resources for both customers and producers. It is the most affected since any action made by the first two stakeholders typically generates a negative impact on the environment. With the ever-growing population, demand for more resources has accelerated exponentially. The incommensurate and irrational consumption has caused important damages to the planet, as such extent that the balance of natural systems have been modified triggering in some cases natural disasters with catastrophic consequences. Other species have suffered the consequence of consumer's and producer's actions, in most cases threaten or destroying some of them. Another important consequence of the irrational consumption is the depletion of natural resources

due to the erroneous administration of the planet resources, transforming it into an unsustainable planet. In this work, this third and important stakeholder will be referred as the “planet”. Figure 2-1 depicts all three stakeholders.

The producers should have responsibility on their shoulders since their decisions, including those made during early phases of the design process generate a series of impacts upon the customer and the environment as well. According to the 2007 Cone Consumer Environment Survey, “93% of Americans believe companies have a responsibility to help preserve the environment”. However, that responsibility is shared with the customers. The consumption of goods in a conscious rather than an impulsive manner will reflect changes on the environmental impact. Consumers can raise or decrease this impact depending on their lifestyle. A large number of Americans (47%) report have purchased environmentally-friendly products. Additionally, they can use their purchase power to punish or reward the Producers for the development of the products. The vast majority (91%) say they have a more positive image of environmentally responsible company. Also 85% of Americans would deem to change of company’s products or services due to a company’s negative environmental practices (CONE Communications, 2007).

In front of the increasingly environmental and social problematic faced by the

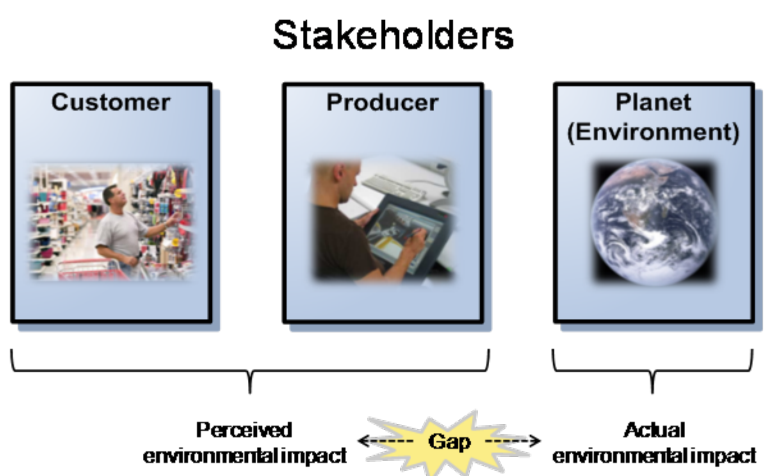


Figure 2-1 Gap between actual and perceived environmental impact.

world today, arises the need for incorporating environmental and societal considerations into the design of products and services. With more environmentally conscious customers, producers have to contemplate into their designs environmental considerations. Although the population is increasing their "green" awareness, this consciousness is still limited. Usually customers and producers are aware of a small number of environmental issues such as energy consumption, recycling, greenhouse gases emissions, and water conservation, typically most mentioned by the media. Besides this short list exists an extensive number of stressors (factors that generates an impact in the environment) bear on the designing, creation, use, and disposal of consumer goods. It is unconceivable to pretend that the population acquires all that knowledge. Thus, this lack of information opens a gap between the environmental impact perceived by Customers and Producers, and the real impact that is actually perceived by the planet. This gap is also depicted in Figure 2-1.

Designers have control over design variables and attributes such as material selection and manufacturing process. Changes in design variables and attributes are strongly related with product characteristics such as performance, quality, environmental impact, and cost. The selection of a design option may change the performance of the product but also change the cost and the impact to the environment due to material and/or manufacturing process complexity and characteristics. As an example, consider outdoor lighting, specifically garden lamps. Many options can be found in the market with different characteristics. One attribute in special is the energy consumption. Lamps that work using low voltage bulbs or LED technology like the solar lamps, consume less energy than the traditional 120 Volts lamps, so operating cost is reduced or almost null like in the case of solar powered lamps. In addition, an amount of electricity needs to be produced in power plants contributing to the environmental impact. Also, low voltage and solar lamps do not require professional installation, which also further reduces cost. However, all the options do not deliver the same amount of light brightness. Solar fixtures deliver a fairly anemic light compared with the low voltage and 120V lamps. Additionally, solar lamps operate with rechargeable batteries, which could cause serious damaged to the environment due to the chemical components if they are not properly

disposed. Hence, designers are required to make wise decisions and tradeoffs between the product's variables and attributes to make it more attractive to Customers and thus maximize the utility of the product considering the effects on the environment.

Customers acquired products based on the utility they see on it. Those products meeting customer's expectations and desires are more likely to be purchased than those that do not meet expectations. Improving the product characteristics designers increase the utility to the customer and hence the chances to increase sales. The success of a design might perhaps be measured by the consumer adoption of the product. Hence, more people acquiring the product is translated into more revenue for the producer but, unfortunately, more environmental impact as well.

Designers can justify that the goods they design are green products since environmental stressors are considered and evaluated during the design phase to minimize the impact. However, in order to reduce time and cost of design phase, commonly a *single* life-cycle stage approach is used to deal with environmental impact assessments. Additionally, even though LCA tools are being constantly updated and improved to produce more accurate assessments, they never reflect exactly the actual environment impact due to the broader number of factors related to the impacts. Unfortunately, all this sums up to form a "myopic" environmental awareness of Producers and Customers, and contributes to widen the breach between the Producer and Consumer perceived environmental impact and the real one perceived by the Planet. To better illustrate the problem refer to Figure 2-2.

Hence, the objective of this framework is to provide a design approach to help reduce the gap between perceived and real environmental impact across all LCA stages, while considering the benefits for all stakeholders: customer, producer, and planet, while designing products.

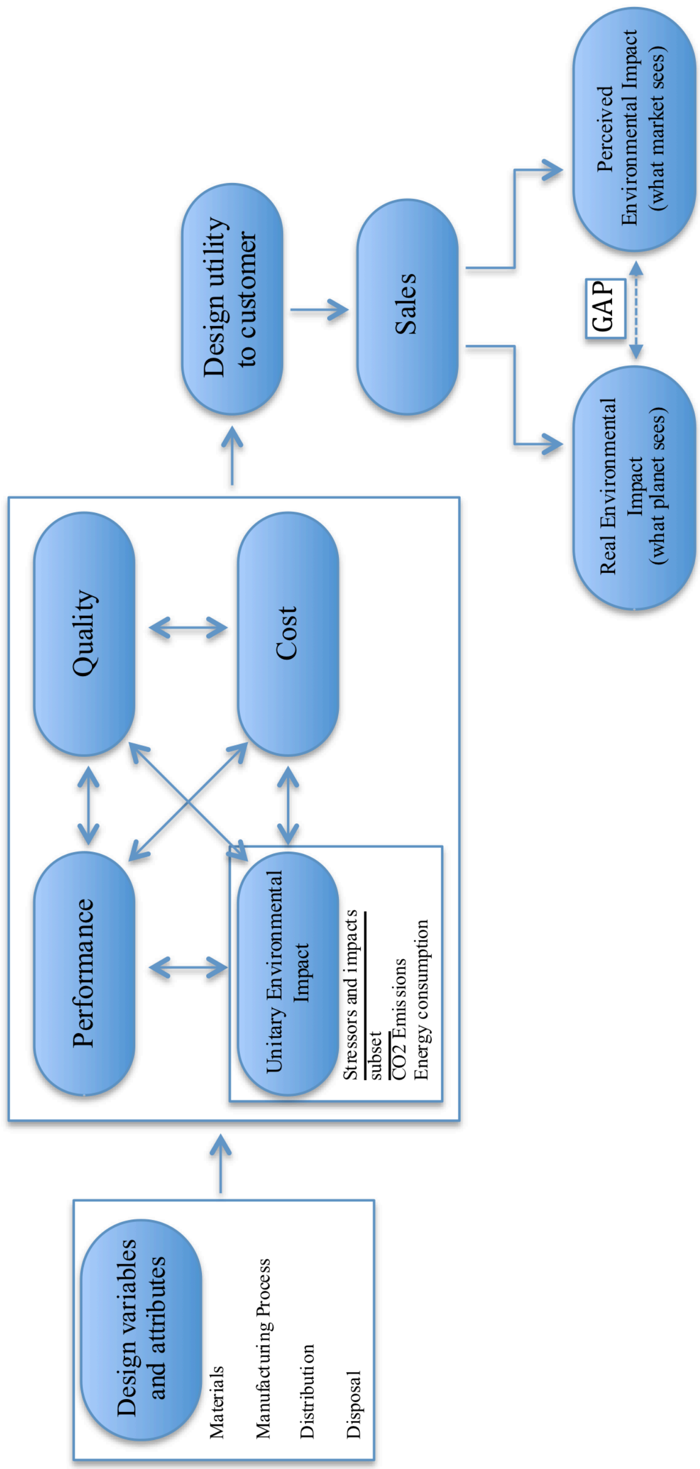


Figure 2-2 Problem scheme

3. Literature Review

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).

Collins and Glysson (1980) presented a decision-theoric procedure for evaluating the environmental consideration of engineering projects. The procedure implements multriattribute utility function to determine an Environmental Quality Index (EQI). The form of the EQI depends on three possible relationships: preferential independence, where preferences for pollution levels remain constant regardless of the levels of other pollutants; utility independence, where the utility assessment for any pollutants is independent of the state of other pollutants; and marginality which is a very restrictive independence condition.

Keeney (1974) demonstrated that when utility independence is satisfied the multiattribute utility function U for n attributes (x_1, … x_i, … x_n) could be additive $U(x)_A$

$$EQI_A = U(x)_A = \sum_{i=1}^{n}[k_i U_i(x_i)], \tag{1}$$

or multiplicative $U(x)_M$

$$EQI_M = U(x)_M = \frac{1}{K}\left[\prod_{i=1}^{n}\left(K k_i U_i\left(x_i(y)\right) + 1\right) - 1\right], \qquad \text{for } K \neq 0 \tag{2}$$

where k_i is single attribute scaling constant and the functional scaling constant K is calculated from the equation

$$K = \prod_{i=1}^{n}(1 + K k_i) - 1 \tag{3}$$

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 & Raiffa, 1976).

A design evaluation method presented by Thurston (1990; 1991) can help evaluate the overall utility of a certain design option by incorporating deterministic multi-attribute utility analysis considering several performance characteristics. The methodology is proposed as a tool to help identify alternative designs that have more potential for success. Early involvement in the design phase facilitates the determination of the performance attributes that leads to best design option. Using an example from the auto industry, Thurston shows through utility functions how automakers have different preferences and tradeoffs between attributes of diverse nature such as cost, weight, quality, and corrosion resistance. Using the multiplicative form of the multiattribute utility function shown in equation 2, the overall utility is calculated for all alternative systems to determine which option has better potential.

Also Thurston et al. (1991) 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 manufacturing cost, as well as technical performance considerations. The set of attributes are captured in the evaluation function of the form of equation 2, which is then maximized.

$$\max U(x)_M = \frac{1}{K}\left[\prod_{i=1}^{n}\left(Kk_iU_i\left(x_i(y)\right)+1\right)-1\right], \tag{4}$$

Maximizing the utility function the decision maker is able to find the optimal set of attribute values; thus, a design alternative is found with respect to the optimal utility.

The House of Quality and Quality Function Deployment are well known and widely used methodologies that contribute for interfunctional planning during the product development (Hauser & Clausing, 1988; Sullivan, 1986). By means of a series of matrices, the voice of the customer is translated into technical requirements that help to

identify and prioritize the necessary attributes and their interrelation for each of the different stages of the product development and production. 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 (Locascio & Thurston, 1993).

Locascio and Thurston (1993a; 1993b; 1994) linked multi-attribute utility analysis with Quality Function Deployment to provide the QFD a mathematical-base procedure to determine the best design parameters. The methodology replaces relative importance of each attribute with multiattribute utility analysis. An optimized utility function, with the form of equation 4, populated with data from each section of the HOQ is constructed integrating all important design criteria into an objective function.

Thurston & Hoffman (1999) presented a tradeoff model in which the designer is responsible to assess the information through a decision tool that considers environmental impacts and cost among other aspects and assign weighting factors that reflect customer preferences for environmental protection.

Thurston and Srinivasan (2003) implemented multiattribute 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.

Michalek et al. (2005) presented a methodology for analyzing the impact of fuel economy regulations on the automotive manufacturers' decision making. The methodology incorporated different models to consider the impact of decisions in different stakeholder: producer, government, consumer, and competitors. The consumer

demand model applied logit model, which presumes that customer purchases products based on the utility value of each option. There is a probability *p* that the customer will choose a particular product if it's utility is higher than the other available alternatives. The utility of the product is taken to be a function of product characteristics.

Thurston and Srinivansan (2003) suggest the use of commercially available software to calculate the environmental impact of products and incorporate green decisions in optimization model. However, simpler assessment tools are employed.

PreConsultant (2000) explains a methodology to assess the impact called Eco-Indicator 99, which is based on damages occurred on human health, ecosystem quality, and resources depletion. The ecoindicator is "a number that indicate the environmental impact of a material or process, based on data from a life cycle assessment. The higher the indicator, the grater the environmental impact". The method multiplies the amount of each material and process by the respective Eco-indicator value and then subsidiary results are sum up together to obtain the overall Eco-points of the product. The absolute value of the ecopoint is not significant since the purpose is to compare relative differences of the impact between products and components.

Green QFD-II is a methodology that integrates Life Cycle Assessment (LCA) Life Cycle Cost (LCC) and QFD into a tool for product development or improvement (Zhang, Wang, & Zhang, 1999). The methodology has 3 phases: I) technical requirements identification, II) product concept generation, and III) product/process design. In phase I, QFD-like matrices are generated for a baseline design to identify the technical requirements. The first matrix, the "quality house" (QH), same as the first matrix of the traditional QFD, documents the quality requirements from customer preferences; the second matrix, the "green house" (GH), documents the environmental requirements by establishing relationship between impact classifications and inventory loads of life-cycle stage; the third matrix, the "cost house" (CH), documents the cost requirements by establishing relationship between factors that are affected by cost reduction and cost items of life-cycle stages. In phase II, design alternatives are developed to fulfill the requirements established in phase I. A "concept comparison"

matrix is generated where the critical requirements from QH, GH, and CH are entered for comparison. A satisfaction degree factor is calculated for each design alternative. Other factors calculated in the previous houses are also entered: total environmental impact, total manufacturer cost, and total user cost. Then, the decision maker compares these 4 factors for all the design alternatives to select the best option. In phase III the methodology is similar to that in the traditional QFD.

This approach considers in some sense all stakeholders and different life-cycle stages. However, the decision maker counts with many factors to make a decision for any alternative, instead of an optimized single factor.

4. Methodology

The idea behind the proposed framework is to design goods considering the product's utility perceived by all stakeholders. Assuming rationality, it starts with the premise that the best product is that which utility is high for the Consumer, the Producer, and the Planet as well. Design alternatives with high utility for all stakeholders will be more attractive to consumers and more likely to be adopted. The overall product's utility, which will be called in this framework "Global Utility", will be composed by the Customer's, the Producer's, and the Planet's individual utility. It will be calculated with following equation:

$$U_{Gk} = a_c U_c + a_p U_p + a_e U_e \quad (4.1)$$

where:

U_{Gk}: Global Utility of option k.

a: weight factor vector (cardinality = 3)

$a = [a_c, a_p, a_e]$

$$a_c + a_p + a_e = 1 \quad (4.2)$$

U_c = Design utility perceived by Customer

U_p = Design utility perceived by Producer

U_e = Design utility perceived by Planet (environment).

Figure 4-1 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 & Thurston, 1993; 1994). The third step is to estimate the Producer's utility on the design alternatives

with a Logit model (Train, 2002). 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, (v) "no-product choice" is not a valid alternative (meaning that a product should be created from the alternatives as result of the design process), (vi) as one alternative's market share increase, the competitor's market share decreases in the same proportion (*Independence from irrelevant alternatives),* (vii) alternatives generate negative or zero environmental impact (no restorative products).

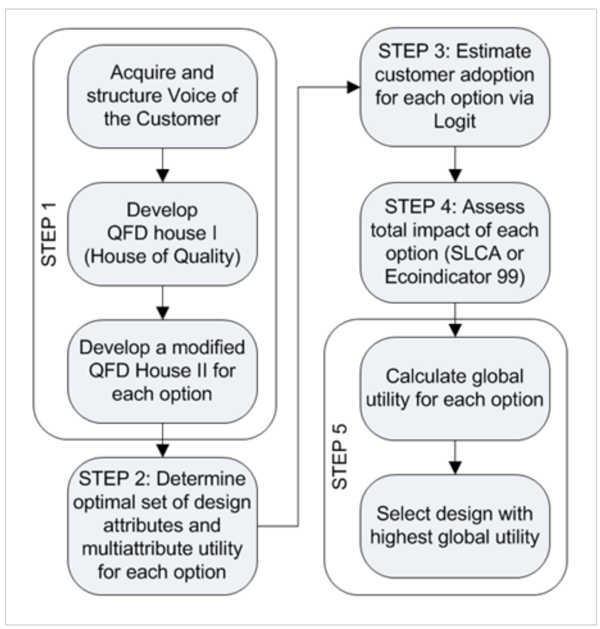


Figure 4-1 High level view of the proposed framework

4.1. Voice of customer and QFD

In order assure the success of a design it is very important for designers to know what the customer expectation is from the product. A product that does not fulfill the customer's needs is easily discarded by consumers and soon replaced by one that does it. Quality Function Deployment (QFD) is a very important qualitative tool that helps design products that are adopted by customers because it incorporates the voice of the customer. According to Hauser and Clausing (1988) the QFD is "a kind of conceptual map that provides the means of interfunctional planning and communications". On it the "voice of the customer" is listened, the customer's requirements identified and translated as product requirements through all the phases of the product development.

The purpose of the QFD is to integrate in the design and production of the product the customer requirements, so it can be produced with high quality standards defined by the customer. "This ensures that the product is not offered to the customer as seen by the design engineer but rather as seen by the customer itself" (Madu, 2000). Therefore, due to its importance in a successful design, acquiring the voice of the customer and develop the QFD becomes the first step for the proposed methodology.

According to Hauser and Clausing (1988) the interfunctional connection in the QFD is achieved through a series of linked matrices that implicitly conveys the voice of the customer through to manufacturing Figure 4-2. Each matrix contains a set of characteristics to achieve ("what") and a set of means to achieve such characteristics

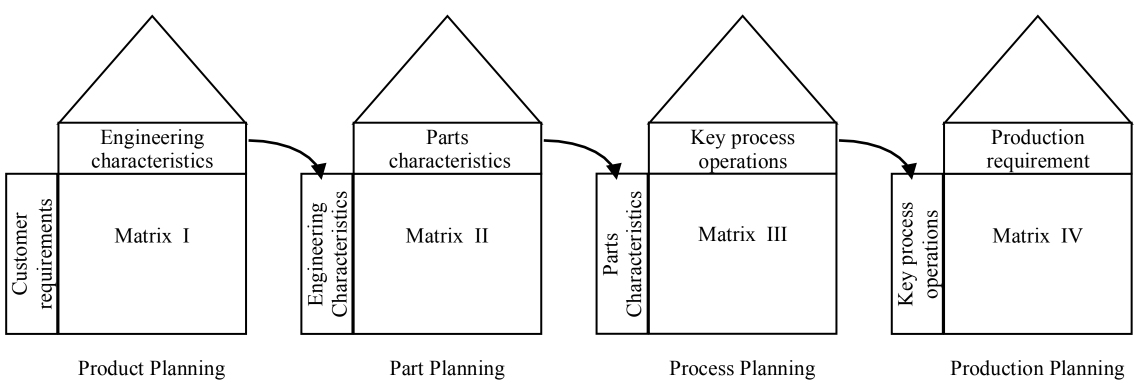


Figure 4-2 QFD linked matrices

("how"). The "hows" of certain design stage becomes the "whats" of the next one. So, the engineering characteristics, which are the "hows" in the first matrix, become the goals in the second matrix and a new set of part characteristics are the means to achieve them (new "hows"). The process continues for a third and fourth phase of process and production planning.

In order to have a well structured design plan the development of all the phases is recommended. However, only the first two matrices are being use for the proposed framework, namely the House of Quality (HOQ) (product planning) and the part planning. The HOQ will reflect what the customer is expecting on the design and the translation into engineering characteristics. This matrix is independent to the number of existing design options, which means that no matters how many design alternatives are available the matrix will be the same for all options. Therefore, only one HOQ showing the engineering characteristic and their relative importance respect to the customer requirements is developed.

Then, the matrix II translates the engineering characteristic into part characteristics. This one do depends on the number of available design options. This is, every alternative should contain and satisfy the same engineering characteristics but, the way they are satisfied could differ from each other depending on the part characteristics. So, a QFD matrix II will be developed for each available design option Figure 4-3 A

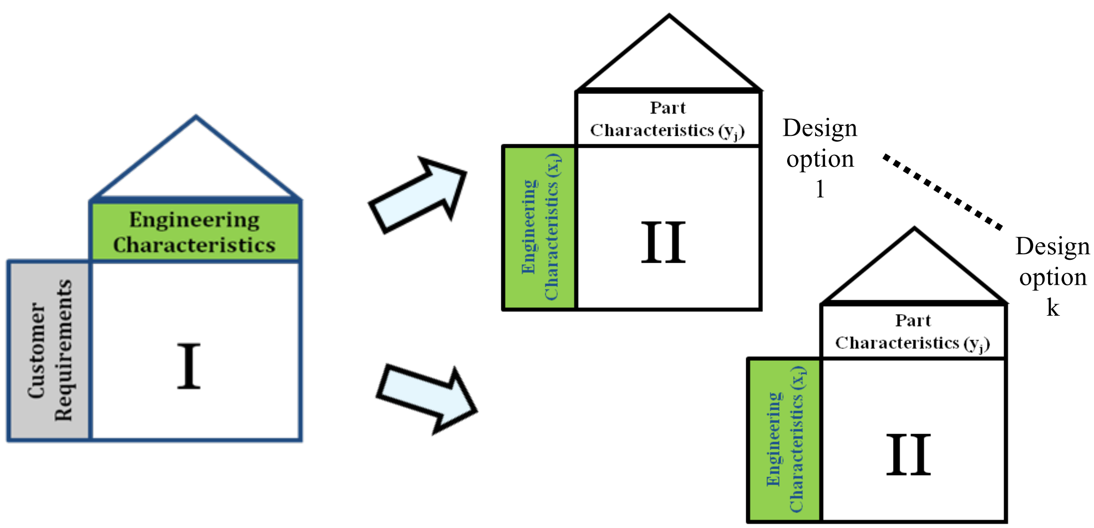


Figure 4-3 A matrix II is developed per available design option

matrix II is developed per available design option. For example, if the designer considers three different alternatives, then three matrices II have to be developed, one per each option. Each matrix will have the same engineering characteristic but might have different parts characteristics. This does not exclude the possibility of having similar parts characteristics for the different design options.

Figure 4-4 shows the process for step 1. First, the voice of the customer is acquired through surveys, focus groups, brainstorm, etc. The information is then organized and structured using techniques such as affinity diagrams. Then, the House of Quality is built: input the customer requirements (based on the voice of customer) on left side of matrix; define and input the importance of the customer requirements; define and input the engineering characteristics x_i on top of matrix; set boundaries for the engineering characteristics; determine the relation between customer requirements and engineering characteristics (center of the matrix); and calculate the relative importance of the engineering characteristics r_i. Then, n is defined as the total number of options and the counter k set to 1 ($k=1,2,...,n$). Next, the QFD matrix for design option 1 is built: enter engineering characteristics x_i on left side of matrix; input the relative importance r_i; determine and input on top of matrix the part characteristics y_j for design option 1; set best and worst performance levels for all part characteristics (y_{jb} and y_{jw}); determine the relation between engineering characteristics x_i and part characteristics y_j (center of matrix); determine correlation between part characteristics y_j (top of matrix, above part characteristics). Then, if counter k is not equal to total number of alternatives n, add 1 to the counter and repeat the House II process for next design option; otherwise, proceed to next process which is to determine the customer utility.

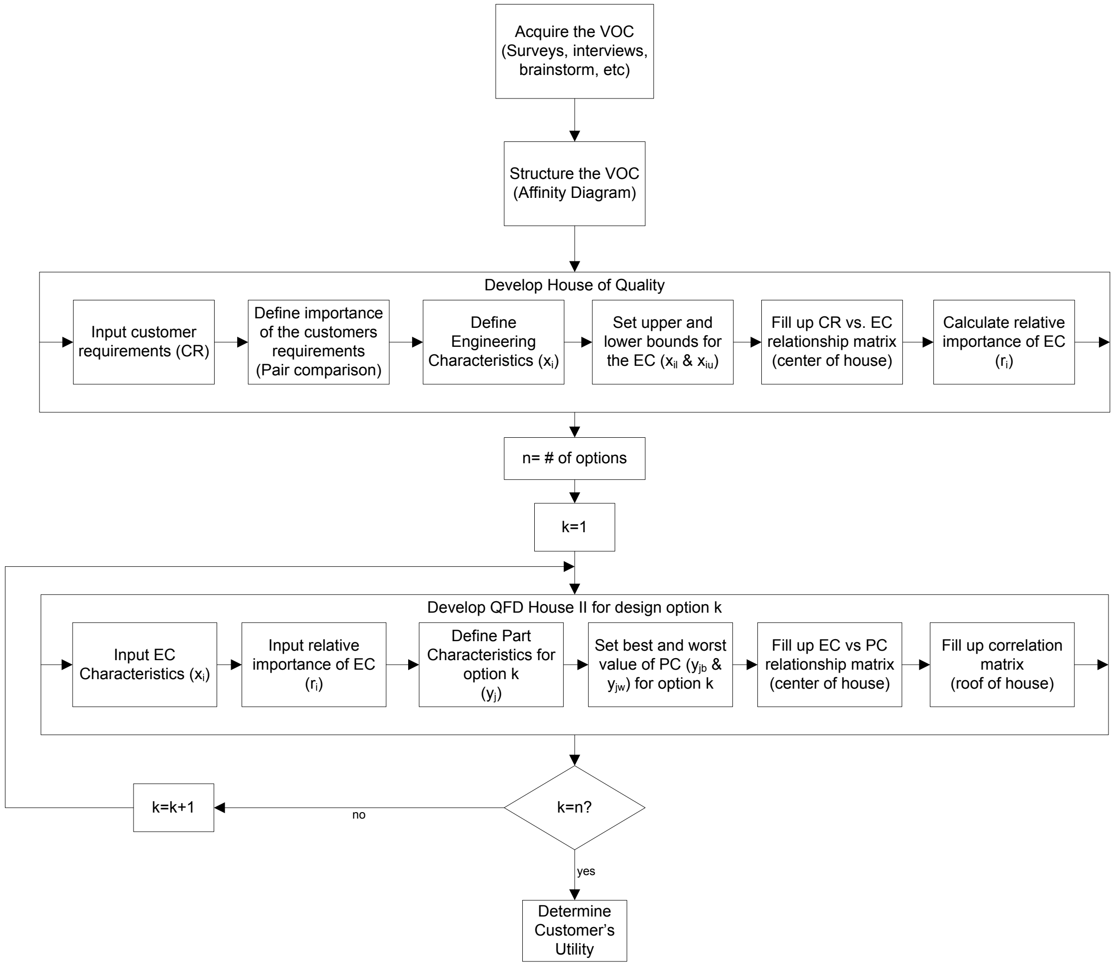


Figure 4-4 Detailed framework for step 1: Voice of the Customer and QFD

4.2. Design Utility Perceived by the Customer

The utility perceived by the customer will increase as the product satisfies the customer needs. To achieve this it would be necessary to find the optimal value of the engineering characteristics the design should have to satisfy the customer requirements. These values could be obtained by using and adapting a design tool that involves multiattribute design optimization proposed by Thurston (Locascio & Thurston, 1993; 1993; 1994). The approach utilizes information from the House of Quality and relates it with multiattribute utility theory. Figure 4-5 shows the interpretation given to the HOQ for the optimization. In the left side of the house, customer requirements are the design goals x_i for $i=1,2,\ldots 3$. The engineering characteristics at the top the house represent the decision variables of the design, which will be y_j *for* $j=1,2,\ldots 3$. The relationship matrix that links the customer requirements with the engineering characteristics represents the constraint functions. The customer relative importance weight is replaced by the utility function $U_i(x_i)$ for each characteristic.

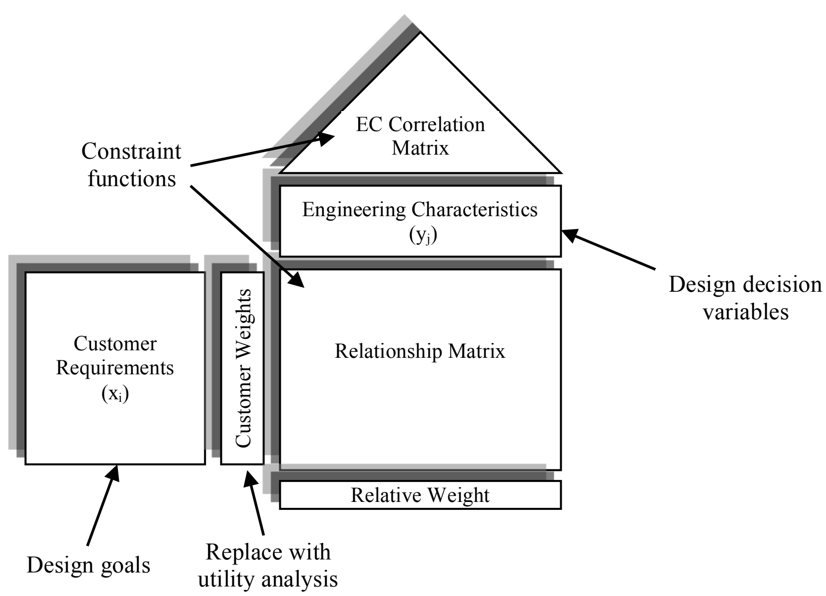


Figure 4-5 Interpretation of House II with respect to optimization model

The objective function is the maximization of the design quality, and quality is of the multiplicative form of the multiattribute utility function. This function is originated from classical multiattribute utility theory (von Neuman & Morgenster, 1947; Keeney & Raiffa, 1976). The function contains each single attribute utility function and models the aggregate contribution of all design attributes towards the goal of maximizing the quality.

$$maxU\big(x(y)\big) = \frac{1}{K}\left[\prod_{i=1}^{n}\big(Ka_iU_i\big(x_i(y)\big)+1\big)-1\right] \tag{4.2}$$

$$subject\ to \qquad x_i = g_{i(y)} \qquad for\ i = 1,2,\ldots,n$$

$$y_{lj} \le y_j \le y_{uj} \qquad for\ j = 1,2,\ldots m$$

Where $U(x)$ = overall utility of a design alternative characterized by the vector of attributes $x=(x_1,\ldots,x_n)$

i = 1,2,…, n attributes

j = 1,2,…, m engineering characteristics

x_i = performance level of attribute i

$U_i(x_i)$ = single attribute utility for attribute i

a_i = single attribute scaling constant

g_i = constraint function relating attribute i to the design variables

K = normalizing constant, derived from

$$1 + K = \prod_{i=1}^{n}(1 + Ka_i) \tag{4.3}$$

The single utility functions for each attribute U_i (x_i) are obtained by asking question based on lottery theory (see Appendix I). These functions depict the utility the customer gives to certain engineering characteristic (x_i) at different levels of performance. For this, the designer considers the same product with two different levels of performance of a specific characteristic x_i. One level is known with certainty to be some value x, and the other level is a lottery of p and $1-p$ of the best and worst performance levels of that characteristic (Figure 4-6). Then, determine the performance

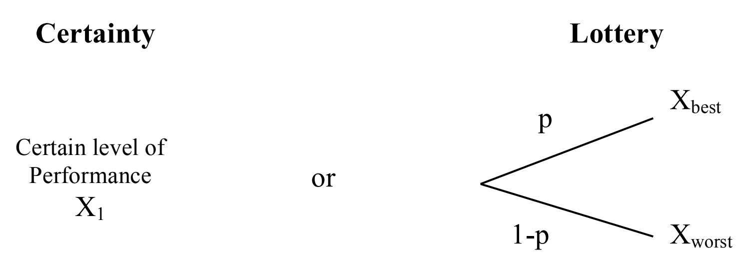


Figure 4-6 Lottery question

level in which the user feels indifferent between the certainty and the probability by responding to the question ‘Which do you prefer, the certainty, the lottery, or are you indifferent?’ If the answer is either the certainty or the lottery, the value of the certainty is changed to a value in between the previous and the last level. Then answers the question again and iterates until the answers is that the user is indifferent between the certainty and the probability. The values derived from answering the lottery questions define the points of the utility functions. Single attribute 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 attribute.

The scaling constant a_i represents the trade-off the designer is willing to make among the attributes and is determined using similar lottery techniques. The designer is asked again to consider the product with two different configurations of part characteristics. One configuration is a certainty that the characteristic x_i is in its best performance level, and the rest of the attributes are in worst level ($x_{1l}, \ldots, x_{iu}, \ldots, x_{nl}$). The other configuration is a probability p that all the characteristics are in their best level ($x_{1u}, \ldots, x_{iu}, \ldots, x_{nu}$) and 1-$p$ of all characteristics in worst performance level($x_{1l}, \ldots, x_{il}, \ldots, x_{nl}$). The constant a_i is the probability p to which the user feels indifferent between the certainty and the lottery.

Constraints $x_i=g_i(y)$ are extracted from the relationship and correlation matrixes in house II. In order to simplify the use of constraints in the model, scaled engineering and part characteristics are used rather than absolute values, to capture the influence of the parts on the engineering characteristics. Relative engineering characteristics x_i', in terms of scaled engineering characteristics y_i', are defined. Relative constraints are given by $x_i'=g_i'(y)$. The allowable range for scaled part characteristics y_i' are 0 to 1; and for engineering characteristics x_i' are the minimum and maximum values of each constraint $x_i'=g_i'(y)$, subject to limits in y' [0,1]. The actual ranges of engineering and part characteristics are known from the development of the house of quality and houses II, so any value of x_i' or y_i' can be mapped to the original unscaled values using a simple variabless transformation.

Thurston's approach applies multiattribute utility theory to the House of Quality (house I of QFD) to translate, in a mathematical form, the customer's requirements into engineering characteristics. However, in order to allow the execution of further steps in the proposed framework, the multiattribute utility theory will be applied in the house II. In that case the same interpretation given to the HOQ will be given to the house II but using engineering characteristics instead of customer requirements and part characteristics instead of engineering characteristic.

The outcome of this process would be the value of customer's utility for each design option and the corresponding vectors of optimal engineering characteristics.

Figure 4-7 shows the process for step 2. This process is an adaptation of the procedure shown by Beroggi (1999). Prior to the calculation of the Customer's utility three assumptions needs to be confirmed in order to use the multiattribute utility analysis: first, the decision maker must be rational; second, the engineering characteristics x_i should be utility independent of their compliment; and third, the engineering characteristics x_i should be mutually utility independent. If any of these conditions are not met, multiattribute utility function may not be used and, the framework may become ineffective. Otherwise, proceed to assess the utility function of each engineering characteristics U_{xi} via lottery questions. Then, assess the scaling constant a_i also employing lottery questions. Again n is defined as the total number of design alternatives and the counter k reset to 1 ($k=1,2,...,n$). If the sum of all scaling constants is 1, the multiattribute additive model $U_{ck}=\Sigma a_i U(_{xi})$ may be employed (not considered in the proposed framework); otherwise, employ multiplicative model $U_{ck}=1/K[\Pi k_{ai} U(_{xi})+1]-1$ for design option 1. K is calculated from the equation $1+K=\Pi(1+Ka_i)$. Next, constraints are defined from the from the relationship and correlation matrices in the house II of design option 1. Next, maximize the objective function U_{ck} to obtain the customer utility of option 1. Then, if counter k is not equal to total number of alternatives n, add 1 to the counter and repeat the Customer's utility assessment process for the next design option; otherwise, proceed to estimate the Producer's utility.

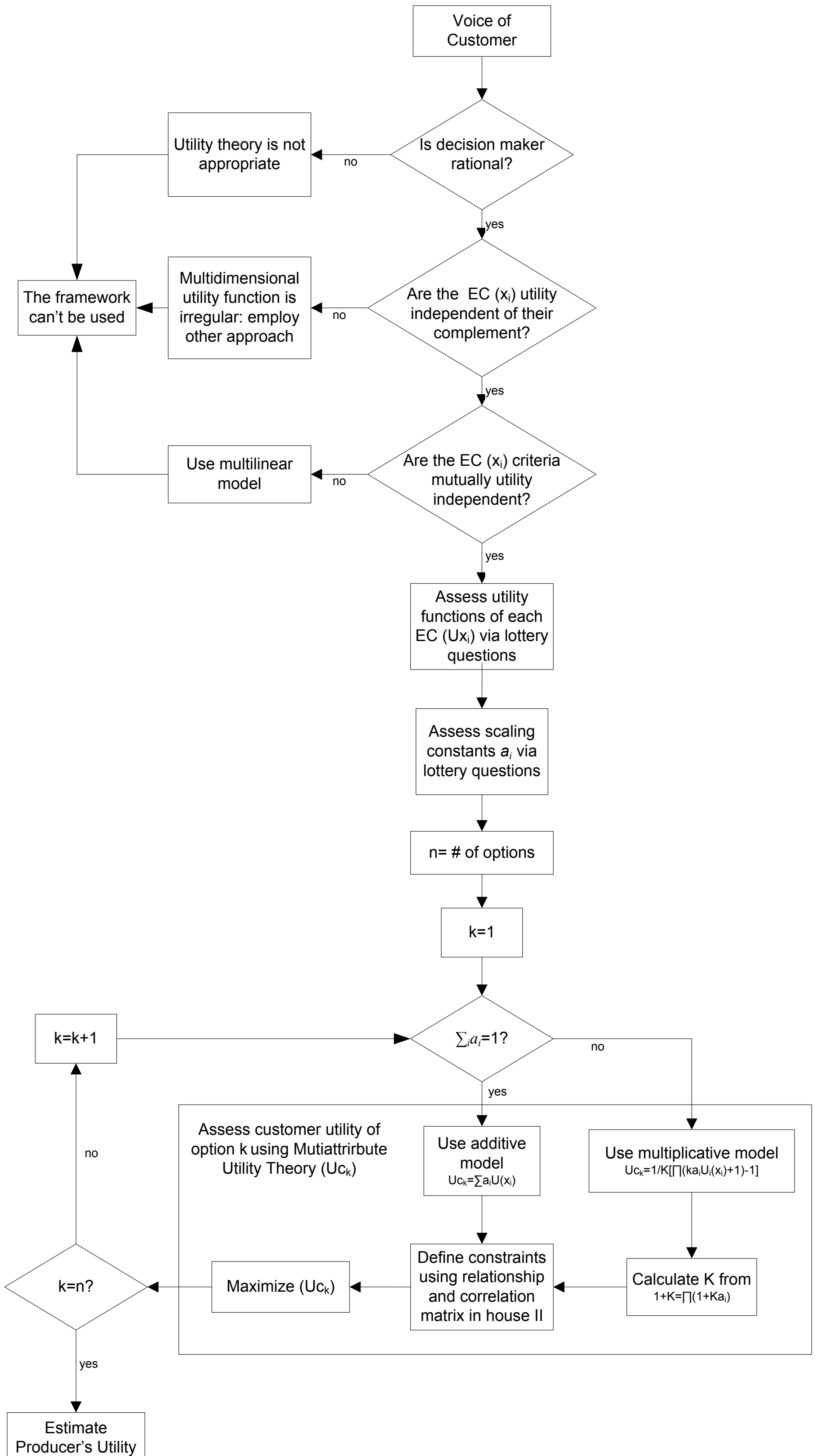


Figure 4-7 Detailed framework for step 2: Customer Utility

4.3. Design Utility Perceived by the Producer

The design utility for the producer should reflect the degree in which customers acquire the product. 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 the discrete choice analysis method Logit to estimate consumer demand (Train, 2002). It assumes that the customer buy based on the utility value of each product alternative. It also assumes that "as one product's market share increases, the shares of all competitors are reduced in equal proportion" (Skerlos, Morrow, & Michalek, 2005). This property is called *independence from irrelevant alternatives* (IIA). In this framework, the model will used to estimate the utility of design alternatives to the Producers.

Let Uc_k be the utility of option k 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 that 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 perceives the attributes xi of the products chosen by the customer, and perhaps only a few customers' attributes (***s***). These two attributes compose a utility function that can relate the observed factors to the customer's utility. The function is denoted $Vk = V(xi, s) \; \forall i$, and called "representative utility". Since there are utility attributes of which the designer are not aware of then, $\boldsymbol{V_k \neq Uc_k}$. 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 $\boldsymbol{Uc_k = V_{nk} + \varepsilon_{nk}}$. The designer does not know the value of $\boldsymbol{\varepsilon_{nk}}$, 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:

$$\boldsymbol{P_k = Prob(V_k + \varepsilon_k > V_l + \varepsilon_l) \quad \forall\, k \neq l}$$

The Logit 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 acquire the product ***k*** will be

$$P_k = \frac{e^{V_k}}{\sum_K e^{V_k}} \quad (4.4)$$

where ***K*** is the total number of available alternatives. The representative utility usually is considered in parameters $\boldsymbol{V_k = \beta' x_k}$, where $\boldsymbol{x_k}$ is a vector of observed attributes of option ***k*** and $\boldsymbol{\beta}$ is a corresponding vector of coefficients of the observed attributes which represents the importance that the customer gives to each attribute. The vector $\boldsymbol{\beta}$ links the producer's utility to the customer preferences. So, the probability can be written as follow:

$$P_k = \frac{e^{\boldsymbol{\beta' x_k}}}{\sum_K e^{\boldsymbol{\beta' x_k}}} \quad (4.5)$$

In order to determine the probability that a customer will acquire a design option, the vector of attributes, $\boldsymbol{x_k}$ is approximated to the vector of optimal values of engineering characteristics determined in the previous step (customer's utility). Thus, the calculated probability will be based on optimal values that generate high utility for the customer. The coefficients $\boldsymbol{\beta}$ are defined by the relative weight of the engineering characteristics, which are derived from the house of quality. These values are located at the bottom of the HOQ (relative weights), and they should be equal for each design alternative (Figure 4-8).

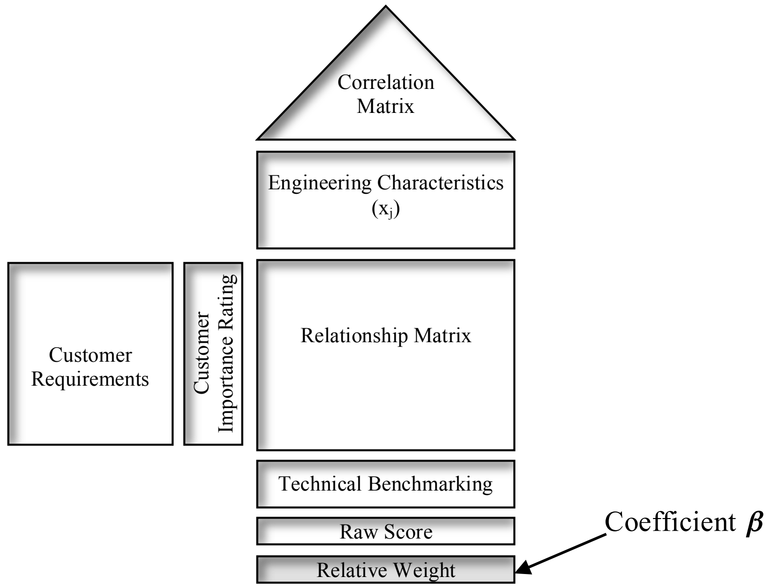


Figure 4-8 Logit model coefficients

Figure 4-9 shows the detailed process for step 3. For this step, 3 more assumptions need to be confirmed: the design options are mutually exclusive, meaning that if one option is selected, the other options are not; the option set must be exhaustive, meaning that the decision maker must choose one alternative; and the number of options must be finite. If any of these conditions are not met, the LOGIT model can not be employed, therefore the framework is can not be used either; otherwise, once again n is defined as the total number of design alternatives and the counter k reset to 1 ($k=1,2,...,n$). Then, proceed to assess the Producer's utility of option 1 by entering the set of values of attribute x_i and the set of relative importance r_i into the equation $Up_k=e^{\beta x_k}/\Sigma_k e^{\beta x_k}$. Then, if counter k is not equal to total number of alternatives n, add 1 to the counter and repeat the Producer's utility assessment process for the next design option; otherwise, proceed to estimate the Planet's utility.

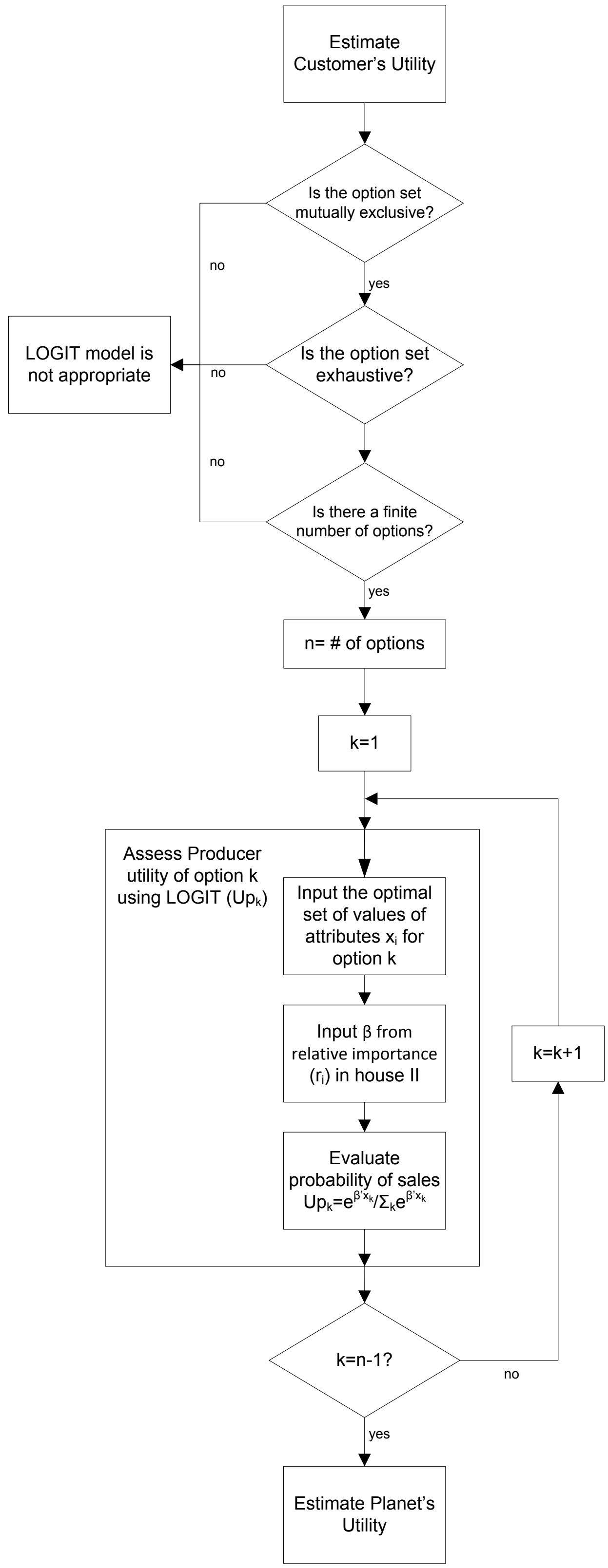


Figure 4-9 Detailed framework for step 3: Producer's Utility

4.4. 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 process-based LCAs Eco-Indicator 99) tend to be more time consuming and rely on a detailed bill of materials which may not be available early on the design stage. Streamlined LCAs are simpler and can be developed with a less defined bill of materials but provide somewhat subjective information. Ultimately, the selection of the environmental assessment approach will depend on the level of product definition that can be achieved.

From the environments' perspective, producing products with zero or positive environmental impact is the ideal condition. However, almost all products generate a negative impact throughout its respective lifecycles, or at least in some stages of it. Consider the lifecycle of synthetic carpet. Negative environmental impacts that accrue along the lifecycle of this product include the harvesting of a non renewable material (natural gas and 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 impact is minimal. In other words, the utility to the environment increases as the product's environmental impact decreases.

The design utility to the environment will be described by the following proposed function:

$$U_e = \frac{1}{(IX+1)} \tag{4.6}$$

where:

U_e : utility of the design perceived by the environment,

I: an impact factor that is a function of the nature of the product

X: the impact assessment of the design (obtained from LCA tools).

The function depicts a family of curves some of which shown in Figure 4-10 where the environmental impact (units in eco-points or equivalent) is drawn with respect to the environments's utility of the design.

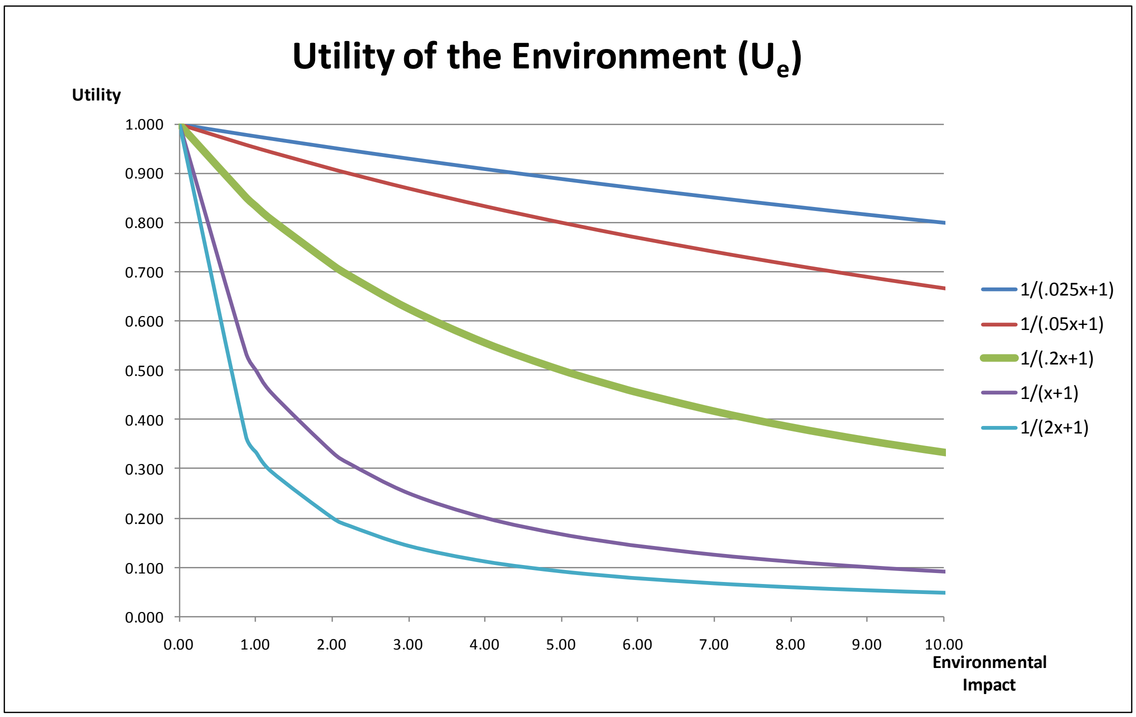


Figure 4-10 Family of curves depicted by the utility function of the environment.

Ideally the highest utility to the Planet will be reached either having a product with no environmental impact, or by not manufacturing any product, which is not considered as a possible option in the framework; therefore, a design with no environmental impact will generate the highest utility to the Planet. This ideal case would have 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.

For example, consider two types of vehicles, compact and SUV. Assume that they are fabricated using similar materials. Compact vehicles pose smaller mass, and are equipped with smaller engines that typically consume less gas than SUVs; therefore, they may cause less environmental impact and generate higher utility to the Planet (Figure 4-11). But, even if the compact vehicle is improved to reduce the impact (e.g. Hybrid technology, use of recycled materials, etc) there always exists a minimum impact associated with the creation of the product. 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.

Now consider two different types of products, a wooden ruler and a vehicle. The ruler and the vehicle will have different environmental impacts. The quantity of material and processes required to fabricate one finished wooden ruler is significantly smaller than the quantity required for one vehicle; additionally, the logistics involved in the transportation of materials and final products is much smaller for the wooden ruler than

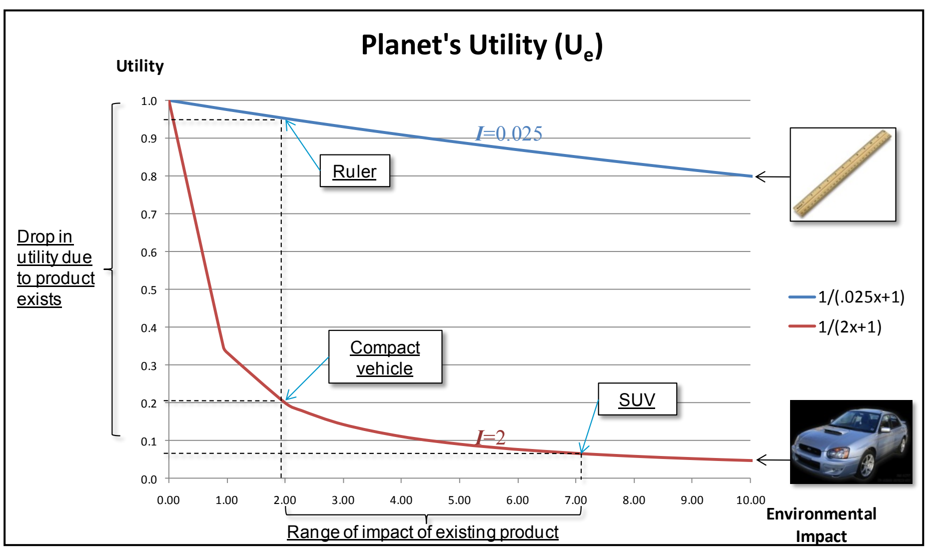


Figure 4-11 Scaling of the utility function of the planet.

for the vehicle. Therefore, can be implied that the environmental impact of a ruler is much smaller than the generated by the vehicle. Compared to the vehicle, the initial “fixed impacts” of the wooden ruler are minor; hence the utility of the vehicle drops faster as both products are created (also Figure 4-11). Thus, the impact factor ***I*** is used to scale the utility curves depending on the nature of the products. It is assigned by the designer based on his/her criteria about the products nature. In general, more complex and bigger products may generate more environmental impacts compared to simpler and small ones, so the factor ***I*** is greater.

For the proposed framework, Eco-Indicator 99 will be employed to estimate the environmental impact of the products. Although it is a time consuming process, it becomes very useful due to the outcome which is a value called Ecoindicator. This single and simple indicator can then be easily incorporated into the framework to calculate the design utility perceived by the environment using the equation 6.

Figure 4-12 shows the process of step 4. After the producer’s utility is estimated, the bill of materials for each of the design alternative is created. Then, the designer based on the products nature sets the value of impact factor *I*. Once again *n* is defined as the total number of design alternatives and the counter *k* reset to 1 (*k=1,2,...,n*). Next, the bill of material for alternative 1 is entered in the LCA form (streamline LCA or eco-indicator 99). The use of one or the other LCA methodology depends on the availability of the information for the bill of materials and/or the level of detail desired for the assessment. Next, the LCA score is assessed and the Planet’s utility calculated with the formula $U_e=1/(IX+1)$ where, I is the impact factor and X is the lifecycle assessment score. Then, if counter *k* is not equal to total number of alternatives *n*, add 1 to the counter and repeat the planet’s utility assessment process for the next design option; otherwise, proceed to next process, which is to determine the global utility.

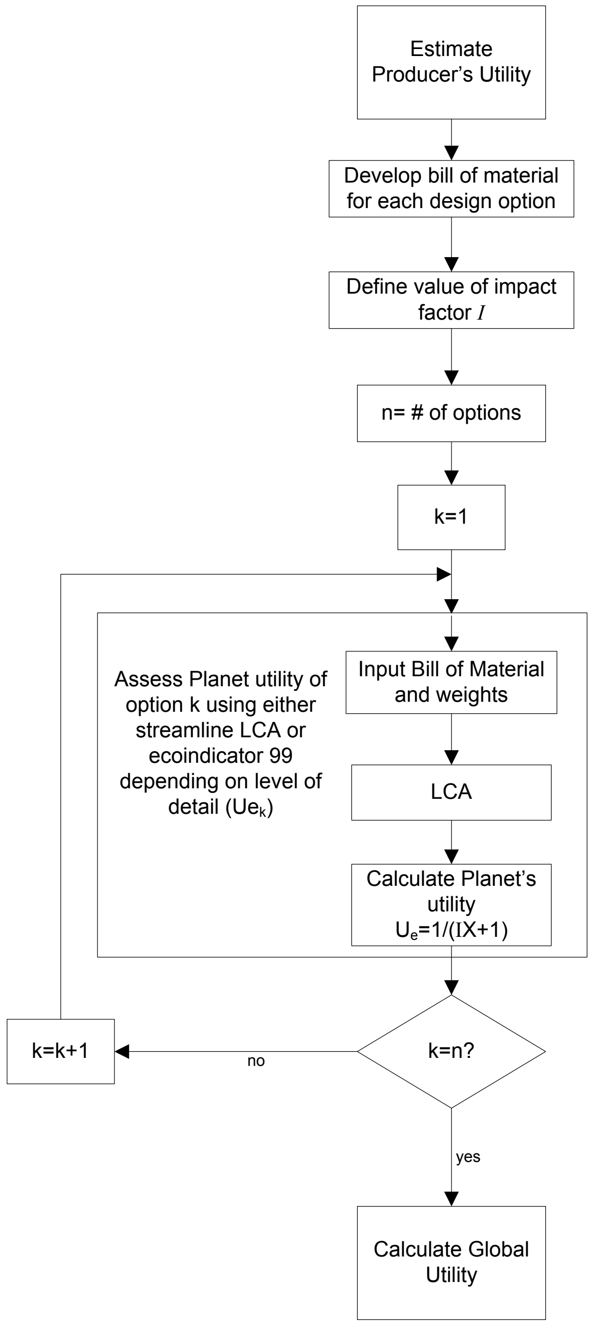


Figure 4-12 Detailed framework for step 4: Planet's Utility

4.5. Global Utility

Lastly, the Global Utility will be defined by the sum of the products of the utility to the customer, the producer, and the planet by the respective weight coefficient

$$U_{Gk} = a_c U_c + a_p U_p + a_e U_e \tag{4.7}$$

where :

U_{Gk}: Global Utility of design option k.

a: weight factor vector (cardinality = 3)

$a = [a_c, a_p, a_e]$

$$a_c + a_p + a_e = 1 \tag{4.8}$$

U_c = Design utility perceived by customer

U_p = Design utility perceived by producer

U_e = Design utility perceived by the environment.

The global utility must be scale between 0 and 1. Therefore, the sum of coefficients a_c, a_p, and a_e add up to 1. These coefficients reflect the importance each utility have respect to each other. Manipulating these factors, different design tendencies can be described. For example, a neutral global utility is that one that gives equal importance to each of the stakeholders, so no preference is defined. But, a designer with environmental consciousness that strives to reduce the impact to the environment will assign higher importance to the planet increasing a_e and diminish the importance to one or both the customer and the producer utilities a_c and a_p respectively. On the other hand, an environmentally oblivious designer that is focused on the benefits to the producer and customer will increase one or both the customer and/or producer's utility a_c and a_p at expenses of the environment impact reducing the importance of the utility to the planet a_e.

Generally the customer drives the products success by using the purchase power to buy or not the product and thus rewards the producer. Therefore, designers ideally will not diminish the importance of the utility to the customer a_c below the importance of the producer and planet.

The process for the calculation of global utility is shown in Figure 4-13. Once the utility for the Planet is calculated, individual utility weights a_c, a_p, and a_e are set according to the design tendency (customer, producer, or environmentally focused). The sum of the utility weights should be equal to 1. Again, n is defined as the total number of design alternatives and the counter k reset to 1 ($k=1,2,...,n$). Then, the Global utility for option 1 is calculated by entering the utility values U_c, U_p, and U_e, and the respective utility weights a_c, a_p, and a_e in the equation $U_{Gk}= a_c U_c+a_p U_p+a_e U_e$. Then, if counter k is not equal to total number of alternatives n, add 1 to the counter and repeat the planet's utility assessment process for the next design option; otherwise, all Global utilities are calculated and the information can be analyzed to make design decisions.

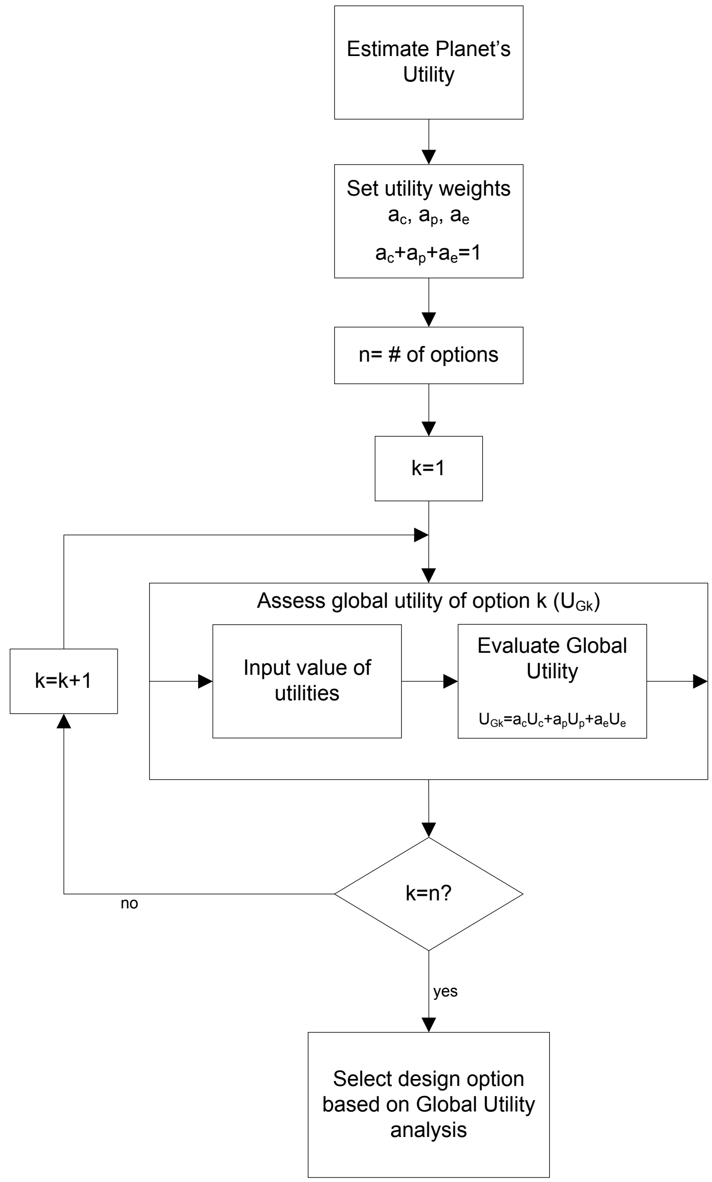


Figure 4-13 Detailed framework for step 5: Global Utility

5. Case Study

The following is a hypothetical case involving real products to illustrate how the framework can be used.

According to the Energy Information Administration, in 2009 U.S. homes consumed approximately 15.3% of the energy in lighting (indoor and outdoor) (US Energy Information Admninistration, 2009). Illuminating outdoor spaces, safety and security, beauty, and home best usage are some of the benefits of having illuminated home outdoors.

A producer of light devices has identified in this area a business opportunity. So, it was decided to research and design a product that satisfy these customers' needs while increasing market share and being environmentally responsible. The producer also decided to investigate existing alternatives implementing the proposed framework. Using the framework, the producer will be able to benchmark these existing products estimating their global utility, and predict the impact of design changes during design iterations.

5.1. Voice of the Customer and Quality Function Deployment

The designer begins the process by acquiring and structuring the voice of the customer. Brainstorming and surveying potential customers, a matrix with all the customer requirements can be generated. Suppose 5 characteristics are identified that the customer is looking for in the product: low price, durability, low energy consumption, environmentally friendly, and good light quality. Each requirement is weighted using a method such as Scaled Pair Comparison (see appendix II). Each characteristic is compared in pair against all the other and determined which is more important relative to the other. The letters recorded in the matrix of Table 5-1 Scale Pair Comparison denote the more important items in the cell representing the intersection of the two items. The number next to the letter represents a scale of how important is that item respect to the other: 1 is slightly important, 2 is reasonably more important, and 3 is much more important. As an example, to the customer is much more important the product's low

price (letter A in the

Table 5-1 Scale Pair Comparison

A	Low price
B	Last a Long Time
C	Low energy consumption
D	Environmentally friendly
E	Good light quality

	B	C	D	E
A	A 3	C 2	D 1	E 1
B		C 1	B 2	E 2
C			C 2	C 1
D				E 2
E				

Requirement	Rating	Rating %
A	3	18%
B	2	12%
C	6	35%
D	1	6%
E	5	29%
Σ=	17	100%

Criteria
1- Important
2- Very Important
3- Extremely Important

matrix) than the longevity of the product (letter B) but, slightly less important than the eco-friendliness of it (letter D). Then, each numerical score totaled for each requirement. The result is the rating of each characteristics respect to the others. In this case the most important characteristic is the low energy consumption.

Then the HOQ is constructed defined by customer requirements (Figure 5-1). The customer's requirements are input on the left side of the house along with the respective rating. Next, engineering characteristics that influence the customer requirements are identified and input in the upper part of the house. The identified characteristics are for example: lamp efficiency, recyclability, lamp brightness, lamp energy consumption, manufacturing cost, and weight. The relationship between each customer requirements and engineering characteristics is assessed, and values of 1, 3, or 9 are written in the matrix in center of the house, where 1 is some relation, 3 is moderate relation, and 9 is strong relation. Blank spaces means that the relation is irrelevant or that there is no relation at all. For instance, suppose the energy consumption of a lamp strongly depends on the efficiency of the lamp and how much energy it uses from the electrical grid, and depends moderately of its brightness. On the other hand the percentage of recycled

Customer Requirements	Customer Weights	Lamp efficiency	% Recyclable	Lamp brightness	Lamp energy consumption from Grid (Use phase)	Manufacturing Cost	System weight
		Engineering Characteristics (x_i)					
Low price	18%	9	3	3	3	9	3
Last a Long Time	12%					3	
Low energy consumption	35%	9		3	9		
Environmentally friendly	6%	9	9		9		3
Good light quality	29%			9	3	9	
Technical Targets		%	%	lumens	Watt/h	$	Lb
Technical Benchmarking	Best	22	100	2000	0	5	0.4
	Worse	1.5	0	50	20	60	6
	Raw score	5.29	1.06	4.24	5.12	4.59	0.71
	Relative score(r_i)	25.2%	5.0%	20.2%	24.4%	21.8%	3.4%

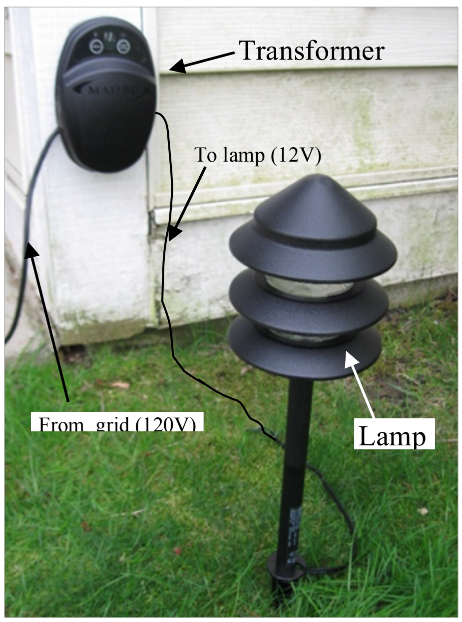
Figure 5-1 House of Quality

material content, manufacturing cost, and weight of the lamp has no effect on the energy consumption.

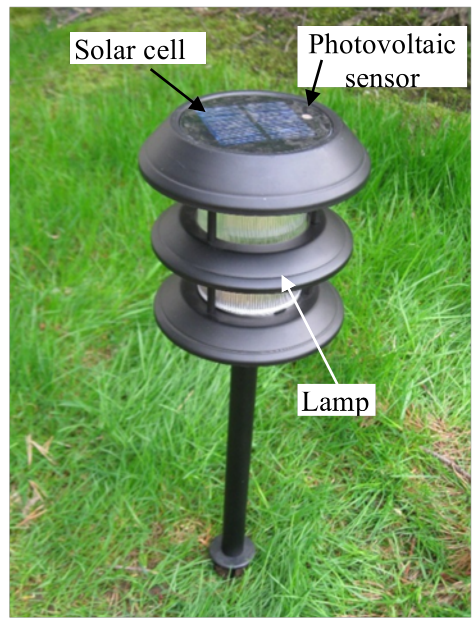
Next, a technical benchmarking is made and engineering characteristics performance value limits assigned. For instance, outdoor lamp energy consumption from the electrical grid could be 20 watts per hour in the case of a lamp connected to the grid, or 0 watts per hour in the case of the same lamp powered by solar panels. Next, compute the sum of the products between customer weights and the corresponding relation value. This calculation results are the scores of each engineering characteristic based on the importance of the characteristics given by the customer. Finally, calculate each score (r_i) relative to all engineering characteristics and write them at the bottom of the HOQ matrix. Note that for this case study only the relevant fields for the proposed framework

are shown in Figure 5-1; although, for a product development a complete HOQ is recommended.

Now, suppose "Low energy consumption" has been identified as one of the customer requirements. As technology advances, the number of alternatives for low energy consuming outdoor lamps has increased in the last decades. Infrared activated, low voltage wired spotlights, solar powered lamps, and compact fluorescent lamps are some of the available options. A wide variety of shapes, materials, and capacity are also



(a) Low voltage lamp



(b) Solar lamp

Figure 5-2 Example of the two cases

available out in the market. To simplify this case study, only two alternatives will be considered: hardwired low voltage and solar powered lamps.

Figure 5-2a shows the main components and set up for low voltage lamps. The system is energized from the 120V electrical outlet in the house. The transformer unit converts it to 12V or 24V and then distributes the energy through wires to all the lamps in the system. This unit also includes a photovoltaic sensor that turns the system on and off depending on the level of the environment brightness. Also, it has the capability for time presets to turn the system on and off. The lamps use incandescent light bulbs which life

span generally could go from 750 to 3.000 hours. They provide very good brightness and directional capability. The lamp life expectancy could overcome the bulbs life, so the system is designed so the user can replace the bulbs. Although these bulbs are low voltage and low wattage driving to moderate energy cost, energy is still being consumed from the grid that has to be generated by power plants. The number of lamps that can be installed is limited by the total wattage the transformer can support. Low-volt systems require some installation, but generally no professional skill is required to perform the full installation.

On the other hand, Figure 5-2 b shows a solar lamp. This type consists in a single standalone lamp that obtains its power from the sun light through a solar panel installed in the top cap of the lamp. The energy is stored into a set of batteries (2 AA rechargeable batteries) also located at the top cap below the solar panel. Also in the top cap is a photovoltaic sensor that makes the lamp remain off during the day and turns it on automatically when the level of environment light reaches certain darkness. Solar lamps implement LED technology, which requires minimal amount of power to work. LEDs' life is much longer than incandescent bulbs, 50.000 hours in most cases. However, the life expectancy of the whole lamp could be too short due to cheap structure. Electrical grid connection is not required for this type of lamp since the energy obtained from the sun is stored in the batteries. However, solar lamps generally deliver a dim light not powerful enough to illuminate larger areas compare to low volt lamps. Also, the rechargeable batteries contain chemicals that, if not properly disposed or recycled, could potentially cause an important environmental impact considering that they are produced in large quantities. The standalone characteristic of these lamps makes them easy to install and the number of units is limitless.

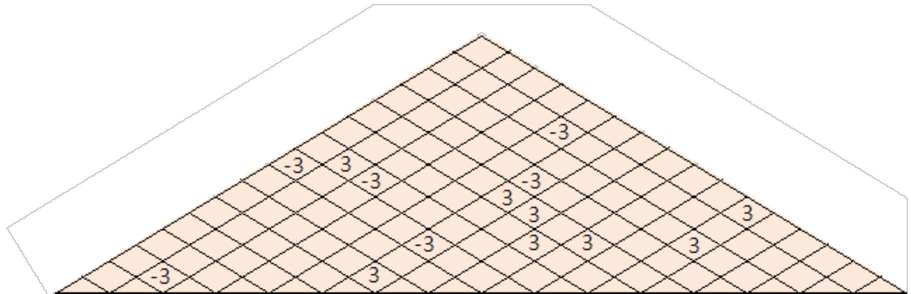
Table 5-2 Comparison between low-voltage and solar lamps shows some comparison for the two alternatives in consideration.

Table 5-2 Comparison between low-voltage and solar lamps

	Low Voltage	Solar
Aesthetics	-Many styles and sizes	-Many styles and sizes
Installation	-Do-it-yourself installation -Some installation required	-No wiring needed -Very easy to install -Need to be installed in sunny spot
Light quality	-Stronger light output -Very good directional capability	-Cover a small area -Light tend to be dim -Poor directional capability
Nightly duration	-Flexible -Timer capable	-Short
Miscellaneous	-Can connect to home security system -Require extra equipment to control input-output	-Solar panel charges batteries -Auto on-off
Safety	-Wiring posses no shock hazard	-No shock hazard at all
Durability	-Low price plastic fixture may not last outdoors -Bulb can be replaced	-Low price plastic fixture may not last outdoors -LED's posses long life time -LED is not replaceable -Batteries are replaceable
Energy consumption	-Moderated	-Zero
Price (per fixture)	\$5 - \$200	\$10 - \$50

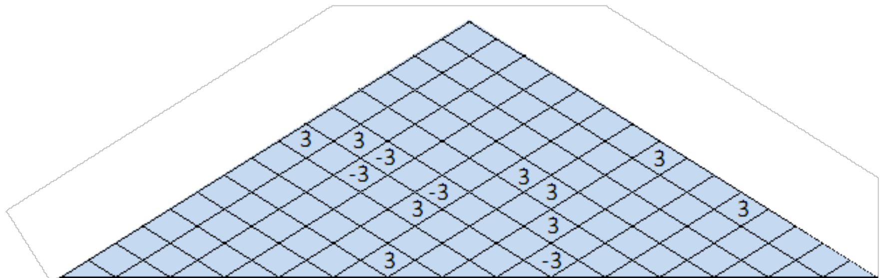
Once the benchmark study is completed, the construction of matrices II is performed, one per each design alternative (Figure 5-3 and Figure 5-4). The engineering characteristics (x_i) that were identified in the HOQ (previous step) are copied in the left column of the matrices along with the respective relative score (r_i) from the bottom of the HOQ. Next the design variables are identified, namely part characteristics (y_i) that characterize each option, and copied in the top row of the house. Engineering characteristic represents technical considerations that all alternatives must have in order to satisfy the customer needs, independently of the specific part characteristics of each option. Therefore, all houses must have the same set of engineering characteristics but

different set of part characteristics specific to each option. The set of part characteristics could include some characteristics that are common among all or a number of the different options, basically because the products share the same nature. In this case, 16 part characteristics are identified for the solar alternative and 15 for the low voltage, where 11 are common to both options: electrical to optical energy conversion efficiency, electrical to thermal conversion losses, reflector efficiency, pole stiffness, pole weight, screen transmissivity, screen weight, pole weight fraction, ground stick weight, top cap weight, and screen thickness. The solar option unique part characteristics are: solar to electrical energy conversion, battery lifetime, solar panel size, LED brightness, and battery size. On the other hand, the low voltage unique part characteristics are: electrical to electrical energy conversion efficiency (transforming from 120V to 12V), bulb lifetime, system voltage, and bulb brightness.



		y_1	y_2	y_3	y_4	y_5	y_6	y_7	y_8	y_9	y_{10}	y_{11}	y_{12}	y_{13}	y_{14}	y_{15}	y_{16}
Preferred		up	up	dwn	up	up	up	up	up	dwn	up	dwn	dwn	dwn	dwn	dwn	dwn
		Part Characteristics ($y_{j\ solar}$)															
Engineering Metrics (x_i)	**House I Relative Scores** (r_i)	Solar to Electrical Energy Conversion Efficiency	Electrical to Optical Energy Conversion Efficiency	Electrical to thermal conversion losses	Reflector Efficiency (Ireflected/Iemmitor)	Batteries lifetime	Pole Stiffness	Pole weight	Screen Transmissivity	Solar panel size	LED Brigthness	Screen weight	Pole weight fraction	Ground Stick weight	Top cap weight	Battery size	Screen thickness
x_1 **Lamp efficiency**	25.2%	3	3	1	9	1			3	1	9	3					9
x_2 **% Recyclable**	5.0%							9				9	9	9	9	3	
x_3 **Lamp brightness**	20.2%		3	1	3				9	9	9	9					9
x_4 Lamp energy consumption from Grid (Use phase)	24.4%	3	3	1		9										1	
x_5 **Manufacturing Cost**	21.8%	3	3	1	1	3	9	9	3	9	3	9	9	9	9	9	3
x_6 **System weight**	3.4%						9	9		3		9	9	9	9	9	9
		%	%	%	%	years	Lb/in	Lb	%	inch^2	lumens	lb	%	lb	lb	inch^3	inches
Technical Benchmarking	**Best**	**25**	**40**	**15**	**90**	**3**	**300**	**0.10**	**95**	**2.3**	**150**	**5**	**5**	**5**	**10**	**0**	**0.3**
	Worst	5	10	5	50	1	3	0.02	70	25	50	20	20	15	25	5	0.1
	Raw score	2.1	2.7	0.9	3.1	3.1	2.3	2.7	3.2	4.1	4.7	5.3	2.7	2.7	2.7	2.7	5.0
	Relative Weight	4.3%	5.5%	1.8%	6.2%	6.2%	4.5%	5.4%	6.4%	8.2%	9.4%	10.5%	5.4%	5.4%	5.4%	5.3%	10.0%

Figure 5-3 Solar Lamp House II



		y_1	y_2	y_3	y_4	y_5	y_6	y_7	y_8	y_9	y_{10}	y_{11}	y_{12}	y_{13}	y_{14}	y_{15}
	Preferred	up	up	dwn	up	up	up	dwn	up	dwn	up	dwn	dwn	dwn	dwn	dwn
		Part Characteristics ($y_{j\ lowvolt}$)														
Engineering Metrics (x_i)	**Phase I Relative Weights** (r_i)	Electrical to Electrical Energy Conversion Efficiency	Electrical to Optical Energy Conversion Efficiency	Electrical to thermal conversion losses	Reflector Efficiency (Ireflected/Iemmitor)	Bulb lifetime	Pole Stiffness	Pole length	Screen Transmissivity	System voltage	Bulb brightness	Screen weight	Pole weight fraction	Ground stick weight	Top cap weight	Screen thickness
x_1 Lamp efficiency	25.2%	9	9	9	9	3			3	3	9	3				1
x_2 % Recyclable	5.0%							9				9	9	9	9	
x_3 Lamp brightness	20.2%		9	1	3	3			9	3	9	9				9
x_4 Lamp energy consumption from Grid (Use phase)	24.4%	9	9	9		3				3	9					
x_5 Manufacturing Cost	21.8%	3	3	1	1		3	9	3	3	3	9	9	9	9	3
x_6 System weight	3.4%							9		9		9	9	9	9	9
Technical Benchmarking	Best															
	Worst															
	Raw score	5.1	6.9	4.9	3.1	2.1	0.7	2.7	3.2	3.1	6.9	5.3	2.7	2.7	2.7	3.0
	Relative Weight	9%	13%	9%	6%	4%	1%	5%	6%	6%	13%	10%	5%	5%	5%	5%

Figure 5-4 Low Voltage Lamp House II

Similarly to the HOQ, the relationship between the engineering and the part characteristics are assessed, writing values of 1 for some relation, 3 for moderate relation, and 9 for strong relation in the matrix located at the center of the house. For example, the efficiency of the solar lamp depends moderately in the efficiency of the solar panel to transform light into electricity and the efficiency of the LED to convert the electricity into light. So, number 3 is assigned to each box. Also, lamp efficiency is strongly related to the LED brightness and the efficiency of the reflector to reflect the light emitted by the LED. So, the number 9 is assigned to each box. In addition, the lamp efficiency is somehow related to the thermal losses related to the conversion of electricity into light and the batteries lifetime so, the number 1 is assigned to each box. This process is repeated through the entire matrix determining the relation, if any, between engineering characteristics and part characteristics.

Next, the part characteristics correlation matrix in the roof of the house is filled. It incorporates the relation within part characteristics. It is done by assigning value of -3 to those fields where a part characteristic influences negatively another part characteristic, and +3 to those fields where the influence is positive. For example, the LED efficiency to convert electrical energy into light as well as the LED brightness could reduce when the thermal conversion losses increases; the relation is negative so -3 is assigned to the box intersecting these part characteristics. On the other hand, as the LED efficiency increases, its brightness could do too; the influence is positive so +3 is assigned to the box relating these two part characteristics.

Afterwards, benchmarked values are input for each part characteristic at the bottom of the matrix. These values will help in determining how the option characteristics perform relative to the existing best and worst cases.

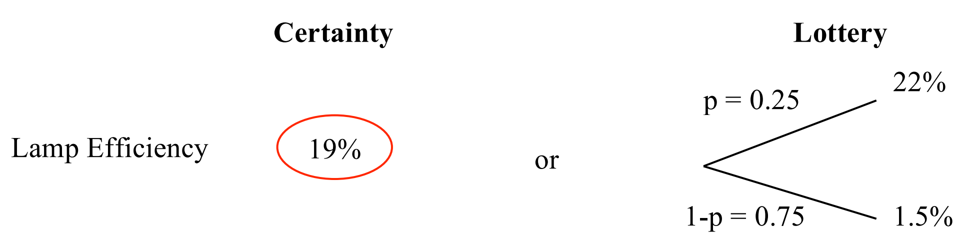
Finally, the raw score of each part characteristics is calculated by summing the product of each engineering characteristics relative score from house I with the engineering vs. part characteristics relation score in the middle matrix. The results are written under the technical benchmark. Then, the relative weight of each raw score is calculated to determine how important each part characteristic is to the product.

5.2. Utility Perceived by Customer

The designer estimate the customer utility by maximizing the function

$$U(x(y)) = \frac{1}{K}\left[\prod_{i=1}^{n}\left(Ka_iU_i(x_i(y)) + 1\right) - 1\right] \quad (5.1)$$

Single attribute utility functions $U(x_i)$ are assessed via lottery questions. These functions depict the utility the customer gives to certain engineering characteristic x_i at different levels of performance. To create these functions the designer considers each attribute x_i in two different levels of performance, one level is known with certainty to be a specific value and the other is a probability of *p* and *1-p* of the best and worst performance levels for that characteristic. Then, the preference between the certainty and the lottery is determined. This process is repeated for different levels of performance until the decision maker is indifferent between the certainty and the lottery. For example, based in the HOQ of Figure 5-1, the best level of lamp efficiency performance is 22% and the worst 1.5%. Then two scenarios were considered: the certainty that the product achieves 19% of lamp efficiency and, the probability of 0.25 that it achieves the best performance level of 22 %.



Then, the designer determines if choosing either scenarios is indifferent by answering the question ‘which is preferred, the certainty, the lottery, or is indifferent?’ Suppose that the answer is that the certainty is preferred over the probability for the considered scenarios (Table 5-3 Preferences between certain performance level and probabilities of best and worst performance levelsa). Then, the value of the certainty is changed to different level, say 16%, and the question is asked again. Suppose the answer is that the certainty is preferred. So, the process is repeated until the answer is that it is indifferent to choose between the certainty of 7% and the probability of achieving the

best performance. These values of certainty and probability (7,0.25) define the second point of the utility function.

Table 5-3 Preferences between certain performance level and probabilities of best and worst performance levels

(a)

Performance Boundaries	22	1.5
Probability	0.25	0.75

Performance Level	Certainty	Probability
22.00	x	
19.07	x	
16.14	x	
13.21	x	
10.29	x	
7.36	INDIFFERENT	
4.43		x
1.50		x

(b)

Performance Boundaries	22	1.5
Probability	0.5	0.5

Performance Level	Certainty	Probability
22.00	x	
19.07	x	
16.14	x	
13.21	INDIFFERENT	
10.29		x
7.36		x
4.43		x
1.50		x

(c)

Performance Boundaries	22	1.5
Probability	0.75	0.25

Performance Level	Certainty	Probability
22.00	x	
19.07	INDIFFERENT	
16.14		x
13.21		x
10.29		x
7.36		x
4.43		x
1.50		x

Next, the value of the probability *p* is increased to a value in between the previous level and the last level. Suppose the value *p* is increased to 0.50, and the question is asked again (Table 5-3 Preferences between certain performance level and probabilities of best and worst performance levelsb). The process is repeated until obtaining the desired number of points for the utility function (Table 5-3 Preferences between certain performance level and probabilities of best and worst performance levelsc). Thus, the utility function is obtained by iterations between the extreme values of *p*.

Table 5-4 Utility function points shows the results of each iteration and values to define the utility functions. The first point of the utility function is defined by the lowest performance level, which utility to the user is zero (1.5,0), and the last point is the highest performance level, which has the best utility 1 (22,1).

Table 5-4 Utility function points

	$U(x_1)$	x_1
Worse	0	1.50
	0.25	7.36
	0.5	13.21
	0.75	19.07
Best	1	22.00

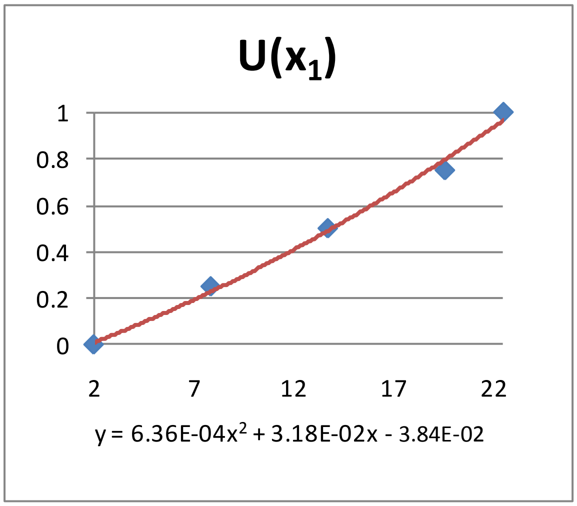


Figure 5-5 Utility function for lamp efficiency

Using a computer tool like MS Excel, these points can be plotted and the tendency line drawn and its respective equation found (Figure 5-5). This equation is the utility function $U(x_1)$.

The process is repeated for each of the six engineering characteristics x_i. The results are depicted in Figure 5-6 and the corresponding equations to each attribute are:

Lamp Efficiency: $$U(x_1) = 6.36x10^{-4}x^2 + 3.18x10^{-2}x - 3.84x10^{-2} \quad (5.2)$$

Recyclability: $$U(x_2) = -2.67x10^{-5}x^2 + 1.22x10^{-2}x + 3.17x10^{-2} \quad (5.3)$$

Lamp Brightness: $$U(x_3) = 1.79x10^{-7}x^2 + 1.42x10^{-4}x - 8.31x10^{-3} \quad (5.4)$$

Energy Consumption: $$U(x_4) = -2.11x10^{-3}x^2 - 7.04x10^{-3}x + 9.94x10^{-1} \quad (5.5)$$

Manufacturing Cost: $$U(x_5) = 8.83x10^{-5}x^2 - 2.32x10^{-2}x + 1.08 \quad (5.6)$$

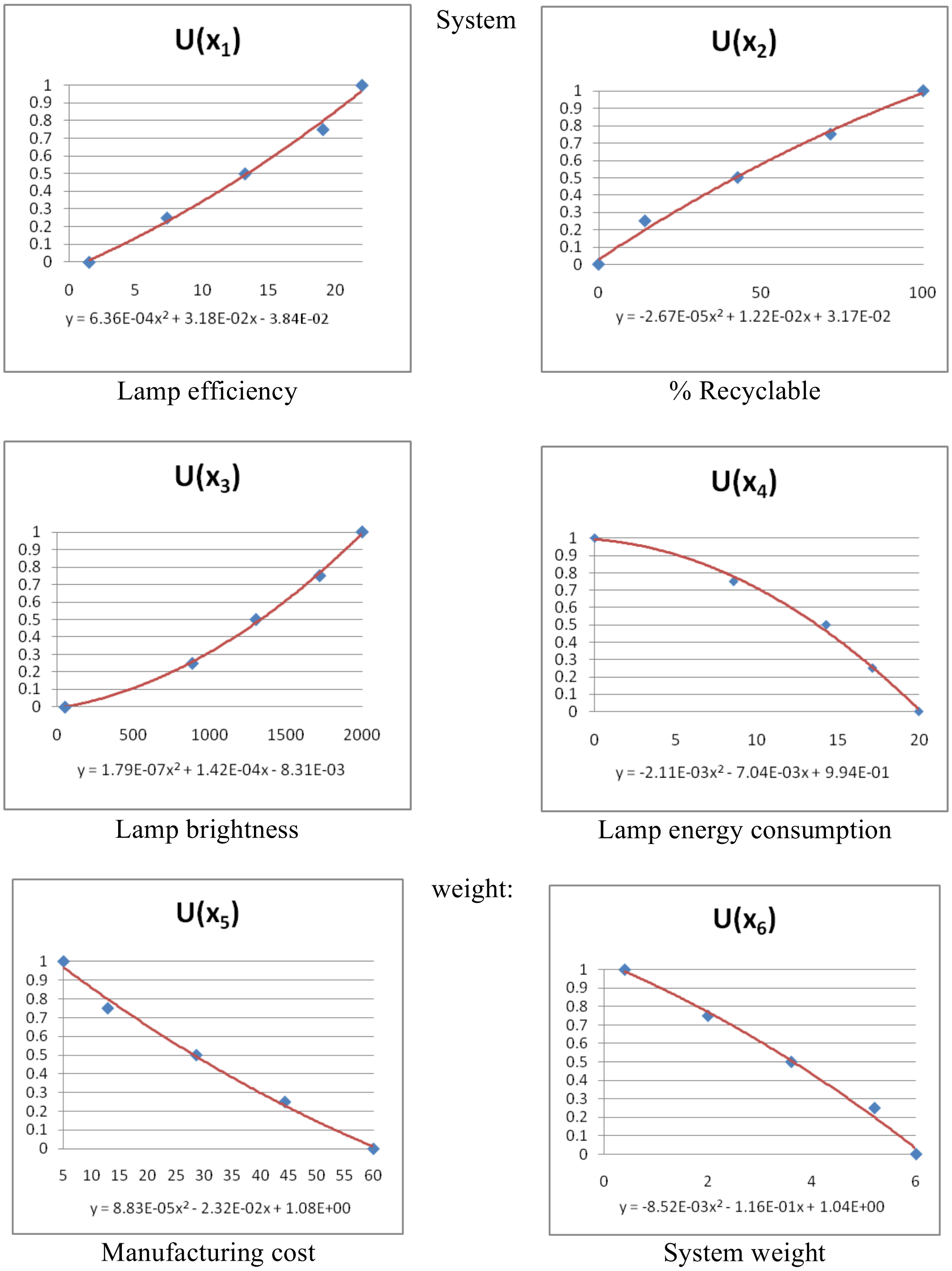


Figure 5-6 Utility functions resulted from iteration process

$$U(x_6) = -8.52x10^{-4}x^2 - 1.16x10^{-1}x + 1.04 \qquad (5.7)$$

Note that for some attributes the utility curves increases as the attribute level increases but for others the utility decreases. For instance, as the lamp efficiency

increases, less electricity is wasted and less is required to illuminate, and the product becomes more environmentally friendly. Therefore, the more efficient the higher the utility is. Thus, the single attribute utility $U(x_1)$ goes up as the efficiency increases. Also, the more recyclable content the design has, the more environmentally friendly it becomes. So, the single attribute utility curve $U(x_2)$ goes up as the recyclable content increases. On the other hand, as the design gets higher manufacturing costs the final product becomes more expensive; potentially impacting in a negative manner on what the final customer will pay for it. So, the single attribute utility $U(x_5)$ goes down as the cost increases.

Now, the single attribute scaling constants a_i are calculated. They represent the trade-off between attributes the designers is willing to make and, similarly to the utility functions, they are also assessed via lottery questions. Suppose two scenarios are considered with different configurations of part characteristics. One is the certainty that the characteristic x_i is in its best performance level, and the rest in worst level ($x_{1l}, \ldots, x_{iu}, \ldots, x_{nl}$). The other is the probability p that all the characteristics are in their best ($x_{1u}, \ldots, x_{iu}, \ldots, x_{nu}$) and 1-$p$ of all characteristics in worst performance level($x_{1l}, \ldots, x_{il}, \ldots, x_{nl}$). The constant a_i is the probability p to which the user feels indifferent between the certainty and the lottery.

To calculate the lamp efficiency scaling constant a_1 suppose the "best-worst" certainty scenario $(x_{1u}, x_{2l}, x_{3l}, x_{4l}, x_{5l}, x_{6l})$=(22, 0, 50, 20, 60, 6) and the "best-best, worst-worst" lottery scenario $(x_{1u}, x_{2u}, x_{3u}, x_{4u}, x_{5u}, x_{6u})$=(22, 100, 2000, 0, 5, 0.4), $(x_{1l}, x_{2l}, x_{3l}, x_{4l}, x_{5l}, x_{6l})$=(1.5, 0, 50, 20, 60, 6) (Table 5-5 Lottery question for scaling constant x_1). Again, the best and worst attribute values are obtained from HOQ (Figure 5-1).

Table 5-5 Lottery question for scaling constant x_1

Certainty

x_1	=	22	%	best
x_2	=	0	%	
x_3	=	50	lumens	
x_4	=	20	Watt/h	worst
x_5	=	60	$	
x_6	=	6	Lb	

or

Lottery

p = ?

x_1	=	1.5	%	worst
x_2	=	0	%	
x_3	=	50	lumens	
x_4	=	20	Watt/h	worst
x_5	=	60	$	
x_6	=	6	Lb	

1-p

x_1	=	22	%	best
x_2	=	100	%	
x_3	=	2000	lumens	
x_4	=	0	Watt/h	best
x_5	=	5	$	
x_6	=	0.4	Lb	

Then, the probability in which the decision maker feels indifferent between the certainty and the probability is determined. It is done by assigning values of p, starting from 0 going up to 100%, and responding to the question 'Which do you prefer, the certainty, the probability, or are you indifferent?' on each iteration. When there is indifference between the certainty and a lottery with probability p the process is stopped, and p becomes the value of the scaling constant. For example, assume that for the lamp efficiency there is preference for the certainty over the lottery for values of p equals to 0%, 10%, and 20%. But, there is indifference for value of p equal to 25% (Table 5-5). Thus, the value for a_1 is 25% and expressed in a scale from 0 to 1 is a_1=0.25. This process is repeated for each attribute.

Table 5-6 Scaling constant a_1

Probability	Certainty	Lottery
0%	x	
10%	x	
20%	x	
25%	INDIFFERENT	
30%		x
40%		x
50%		x
60%		x
70%		x
75%		x
80%		x
90%		x
100%		x

The hypothetical scaling constant values are:

Lamp Efficiency	a_1=0.25
% of Recyclability	a_2=0.50
Lamp Brightness	a_3=0.30
Energy Consumption	a_4=0.35
Manufacturing Cost	a_5=0.45
System Weight	a_6=0.40

Then, the overall scaling constant K can be determined, by using the equation

$$1 + K = \prod_{i=1}^{n}(1 + Ka_i) \tag{5.8}$$

Expanding the equation and substituting the values of a_i, the equation becomes:

$$1.250 + 2.087K + 1.021K^2 + 0.228K^3 + .0399K^4 + .002K^5 = 0 \tag{5.9}$$

Solving this polynomial the solution provides 5 roots. In order to preserve the property of utility independence the value of K should be $-1<K<0$ (Keeney R. L., 1974). So, the value is K= -0.988265.

As a remark note that as the number of engineering characteristics increases, the constant becomes more difficult to calculate since the polynomial degree of the expression increases.

Then, the optimization model can be constructed. The objective function contains only engineering characteristics; therefore, this utility function is used for all the design options. However, the utility function is constrained by engineering characteristics dependent on part characteristics, which sets differ from one option to another. As result, two maximization functions with same objective function but different constraints are set.

So, expanding and maximizing the Eq. 5.1 the objective function is obtained:

$$maxU(x(y)) = \frac{1}{K}\left[\left((Ka_1U_1(x_1) + 1) - 1\right) * \left((Ka_2U_2(x_2) + 1) - 1\right) * \left((Ka_3U_3(x_3) + 1) - 1\right) * \left((Ka_4U_4(x_4) + 1) - 1\right) * \left((Ka_5U_5(x_5) + 1) - 1\right) * \left((Ka_6U_6(x_6) + 1) - 1\right)\right] \tag{5.10}$$

where

K= -0.988265

a_1=0.25

$$U(x_1) = 6.36x10^{-4}x^2 + 3.18x10^{-2}x - 3.84x10^{-2}$$

a_2=0.50

$$U(x_2) = -2.67x10^{-5}x^2 + 1.22x10^{-2}x + 3.17x10^{-2}$$

a_3=0.30

$$U(x_3) = 1.79x10^{-7}x^2 + 1.42x10^{-4}x - 8.31x10^{-3}$$

a_4=0.35

$$U(x_4) = -2.11x10^{-3}x^2 - 7.04x10^{-3}x + 9.94x10^{-1}$$

a_5=0.45

$$U(x_5) = 8.83x10^{-5}x^2 - 2.32x10^{-2}x + 1.08$$

a_6=0.40

$$U(x_6) = -8.52x10^{-4}x^2 - 1.16x10^{-1}x + 1.04$$

The constraint functions can be built from the relationship and the correlation matrices in both houses II. These matrices define the relationship between the engineering and the part characteristics, and the influence of each part characteristic into the others. From Figure 5-3, the constraints functions are built for the solar option as follow:

<u>Solar lamps</u>

$$x_1' = 3y_1 + 3y_2 + 1y_3 + 9y_4 + 1y_5 + 3y_8 + 1y_9 + 9y_{10} + 3y_{11} + 9y_{16} - 3y_1y_9 - 3y_2y_3 + 3y_2y_{10} - 3y_3y_{10} - 3y_5y_{15} + 3y_6y_7 - 3y_6y_9 + 3y_6y_{12} - 3y_6y_{13} + 3y_7y_{12} + 3y_8y_{11} + 3y_9y_{12} + 3y_9y_{14} + 3y_9y_{15} + 3y_{11}y_{14} + 3y_{11}y_{16}$$

$$x'_2 = 9y_7 + 9y_{11} + 9y_{12} + 9y_{13} + 9y_{14} + 3y_{15} - 3y_1y_9 - 3y_2y_3 + 3y_2y_{10} - 3y_3y_{10} - 3y_5y_{15} + 3y_6y_7 - 3y_6y_9 + 3y_6y_{12} - 3y_6y_{13} + 3y_7y_{12} + 3y_8y_{11} + 3y_9y_{12} + 3y_9y_{14} + 3y_9y_{15} + 3y_{11}y_{14} + 3y_{11}y_{16}$$

$$x'_3 = 3y_2 + 1y_3 + 3y_4 + 9y_8 + 9y_9 + 9y_{10} + 9y_{11} + 9y_{16} - 3y_1y_9 - 3y_2y_3 + 3y_2y_{10} - 3y_3y_{10} - 3y_5y_{15} + 3y_6y_7 - 3y_6y_9 + 3y_6y_{12} - 3y_6y_{13} + 3y_7y_{12} + 3y_8y_{11} + 3y_9y_{12} + 3y_9y_{14} + 3y_9y_{15} + 3y_{11}y_{14} + 3y_{11}y_{16}$$

$$x'_4 = 3y_1 + 3y_2 + 1y_3 + 9y_5 + 1y_{15} + 1y_{16} - 3y_1y_9 - 3y_2y_3 + 3y_2y_{10} - 3y_3y_{10} - 3y_5y_{15} + 3y_6y_7 - 3y_6y_9 + 3y_6y_{12} - 3y_6y_{13} + 3y_7y_{12} + 3y_8y_{11} + 3y_9y_{12} + 3y_9y_{14} + 3y_9y_{15} + 3y_{11}y_{14} + 3y_{11}y_{16}$$

$$x'_5 = 3y_1 + 3y_2 + 1y_3 + 1y_4 + 3y_5 + 9y_6 + 9y_7 + 3y_8 + 9y_9 + 3y_{10} + 9y_{11} + 9y_{12} + 9y_{13} + 9y_{14} + 9y_{15} + 9y_{16} - 3y_1y_9 - 3y_2y_3 + 3y_2y_{10} - 3y_3y_{10} - 3y_5y_{15} + 3y_6y_7 - 3y_6y_9 + 3y_6y_{12} - 3y_6y_{13} + 3y_7y_{12} + 3y_8y_{11} + 3y_9y_{12} + 3y_9y_{14} + 3y_9y_{15} + 3y_{11}y_{14} + 3y_{11}y_{16}$$

$$x'_6 = 9y_6 + 9y_7 + 3y_9 + 9y_{11} + 9y_{12} + 9y_{13} + 9y_{14} + 9y_{15} + 9y_{16} - 3y_1y_9 - 3y_2y_3 + 3y_2y_{10} - 3y_3y_{10} - 3y_5y_{15} + 3y_6y_7 - 3y_6y_9 + 3y_6y_{12} - 3y_6y_{13} + 3y_7y_{12} + 3y_8y_{11} + 3y_9y_{12} + 3y_9y_{14} + 3y_9y_{15} + 3y_{11}y_{14} + 3y_{11}y_{16}$$

As described in section 4.2 the range of y_j is 0 to 1. In order to map back to the original engineering attribute ranges, the constraints are modified to include the transformation variable. The transformation variable will be given by the equation

$$tv_i = x_{iw} + \frac{(x_{ib} - x_{iw})}{\max x'_i} \qquad (5.11)$$

where tv_i: transformation variable for attribute i

x_{iw}: worst value of attribute i

x_{ib}: best value of attribute i

max x'_i: maximum value of attribute i in the normalized range of y_j

$i = 1, 2, 3, \ldots$; $j = 1, 2, 3, \ldots$

For example, from attribute x_1'

$$\max x'_1 = 3y_1 + 3y_2 + 1y_3 + 9y_4 + 1y_5 + 3y_8 + 1y_9 + 9y_{10} + 3y_{11} + 9y_{16} - 3y_1y_9 - 3y_2y_3 + 3y_2y_{10} - 3y_3y_{10} - 3y_5y_{15} + 3y_6y_7 - 3y_6y_9 + 3y_6y_{12} - 3y_6y_{13} + 3y_7y_{12} + 3y_8y_{11} + 3y_9y_{12} + 3y_9y_{14} + 3y_9y_{15} + 3y_{11}y_{14} + 3y_{11}y_{16}$$

subject to

$0 \le y_j \le 1$ for $j = 1, \ldots, 16$

The solution of this maximization is x'_1=62. Then, from Eq. 5.11 the transformation variable for x_1 is

$$tv_1 = 1.5 + \frac{(22 - 1.5)}{62}$$

Thus, applying the corresponding transformation variable to each constraint function of the solar lamp, the transformed constraints are as follow

Solar lamps

$$x_1 = 1.5 + \frac{(22 - 1.5)}{62} x'_1$$

$$x_2 = \frac{100}{72} x'_2$$

$$x_3 = 50 + \frac{(200 - 50)}{78} x'_3$$

$$x_4 = \frac{20}{38} x'_4$$

$$x_5 = 5 + \frac{(60 - 5)}{109} x'_5$$

$$x_6 = 0.4 + \frac{(6 - 0.4)}{99} x'_6$$

$0 \le y_j \le 1$ for $j = 1,\ldots,16$

Similarly, the constraints for the low voltage option are as follow

Low Voltage lamps

$$x_1 = 1.5 + \frac{(22 - 1.5)}{70} (9y_1 + 9y_2 + 9y_3 + 9y_4 + 3y_5 + 3y_8 + 3y_9 + 9y_{10} + 3y_{11} + 1y_{15} + 3y_1y_9 - 3y_2y_3 + 3y_2y_{10} - 3y_3y_9 - 3y_3y_{10} + 3y_5y_9 - 3y_5y_{10} + 3y_6y_7 + 3y_6y_{12} + 3y_7y_{12} + 3y_8y_{11} + 3y_8y_{15} - 3y_9y_{10} + 3y_{11}y_{15})$$

$$x_2 = \frac{100}{69} (9y_7 + 9y_{11} + 9y_{12} + 9y_{13} + 9y_{14} + 3y_1y_9 - 3y_2y_3 + 3y_2y_{10} - 3y_3y_9 - 3y_3y_{10} + 3y_5y_9 - 3y_5y_{10} + 3y_6y_7 + 3y_6y_{12} + 3y_7y_{12} + 3y_8y_{11} + 3y_8y_{15} - 3y_9y_{10} + 3y_{11}y_{15})$$

$$x_3 = 50 + \frac{(2000 - 50)}{75} (9y_2 + 1y_3 + 3y_4 + 3y_5 + 9y_8 + 3y_9 + 9y_{10} + 9y_{11} + 9y_{15} + 3y_1y_9 - 3y_2y_3 + 3y_2y_{10} - 3y_3y_9 - 3y_3y_{10} + 3y_5y_9 - 3y_5y_{10} + 3y_6y_7 + 3y_6y_{12} + 3y_7y_{12} + 3y_8y_{11} + 3y_8y_{15} - 3y_9y_{10} + 3y_{11}y_{15})$$

$$x_4 = \frac{20}{54} (9y_1 + 9y_2 + 9y_3 + 3y_5 + 3y_9 + 9y_{10} + 3y_1y_9 - 3y_2y_3 + 3y_2y_{10} - 3y_3y_9 - 3y_3y_{10} + 3y_5y_9 - 3y_5y_{10} + 3y_6y_7 + 3y_6y_{12} + 3y_7y_{12} + 3y_8y_{11} + 3y_8y_{15} - 3y_9y_{10} + 3y_{11}y_{15})$$

$$x_5 = 5 + \frac{(60-5)}{88}(3y_1 + 3y_2 + 1y_3 + 1y_4 + 3y_6 + 9y_7 + 3y_8 + 9y_9 + 3y_{10} + 9y_{11} + 9y_{12} + 9y_{13} + 9y_{14} + 3y_{15} + 3y_1y_9 - 3y_2y_3 + 3y_2y_{10} - 3y_3y_9 - 3y_3y_{10} + 3y_5y_9 - 3y_5y_{10} + 3y_6y_7 + 3y_6y_{12} + 3y_7y_{12} + 3y_8y_{11} + 3y_8y_{15} - 3y_9y_{10} + 3y_{11}y_{15})$$

$$x_6 = 0.4 + \frac{(6-0.4)}{87}(9y_7 + 9y_9 + 9y_{11} + 9y_{12} + 9y_{13} + 9y_{14} + 9y_{15} + 3y_1y_9 - 3y_2y_3 + 3y_2y_{10} - 3y_3y_9 - 3y_3y_{10} + 3y_5y_9 - 3y_5y_{10} + 3y_6y_7 + 3y_6y_{12} + 3y_7y_{12} + 3y_8y_{11} + 3y_8y_{15} - 3y_9y_{10} + 3y_{11}y_{15})$$

$0 \leq y_j \leq 1$ for $j = 1,\ldots,15$

The structure of the objective function for this mathematical model is nonlinear and the constraints are quadratic inequalities and simple bounds. So, a computational tool such as LINGO v12.0 can be used to compute the maximization function. The LINGO inputs and results are shown in the appendix III. The algorithm was solved in less than 1 second in a computer with a processor Intel® Pentium® M 1.60Ghz, 1Gb of RAM. The solution was found after 64 iterations with infeasibility of 1.13×10^{-13}. Optimal values of utility and optimal sets of part characteristics values are obtained from the calculation.

The optimal customer utility for the solar lamp is

$$\mathbf{Uc_{(s)} = U(x(y)) = 0.7967 \approx 0.80}$$

and the set of engineering characteristics

$$\mathbf{x_{k(solar)} = (\mathit{x_1, x_2, x_3, x_4, x_5, x_6})_{solar} = (8.44\ ,\ 0\ ,\ 575\ ,\ 0\ ,\ 8.53\ ,\ 0.4)}$$

Similarly, for low voltage the algorithm was solved in 1 second after 64 iterations and infeasibility equal to 0. The customer utility for the low voltage is

$$\mathbf{Uc_{(lv)} = 0.7557 \approx 0.76}$$

With the corresponding set of engineering characteristics

$$\mathbf{x_{k\ (lowvolt)} = (\mathit{x_1, x_2, x_3, x_4, x_5, x_6})_{lowvolt} = (10.93\ ,\ 0\ ,\ 594.05\ ,\ 8.09\ ,\ 12.56\ ,\ 0.98)}$$

Note that some of these values of part characteristics are not at their best

individual value, but the sets are the combination of values that provide the maximum utility of each design option, as measure by overall product quality.

5.3. Utility Perceived by Producer

The next step in the procedure is to calculate the utility perceived by the producer using the equation:

$$U_P = \frac{e^{\boldsymbol{\beta x'_k}}}{\sum_K e^{\boldsymbol{\beta x'_k}}} \qquad (5.12)$$

The vector of coefficient β is defined by the relative weight of engineering characteristics in the house of quality (Figure 5-1):

$$\beta = (0.25 , 0.05 , 0.20 , 0.24 , 0.22 , 0.03)$$

The vector of attributes, x_k, is approximated to the vector obtained from the optimization model of the utility perceived by customer:

$$x_{k(solar)} = (8.44 , 0 , 575 , 0 , 8.53 , 0.4)$$

$$x_{k(lowvolt)} = (10.93 , 0 , 594.05 , 8.09 , 12.56 , 0.98)$$

These vectors can be normalized respect to their best and worst value. For this, the values are interpolated between 1 for the best and 0 for the worst attribute value. The normalized attribute vectors are:

$$x'_{k(s)} = (0.34 , 0 , 0.27 , 1 , 0.94 , 1)$$

$$x'_{k(lv)} = (0.36 , 0 , 0.28 , 0.60 , 0.86 , 0.90)$$

Expanding and substituting in the Eq. 5.12 the utility to the producer for the solar

option is calculated:

$$U_{P_{(s)}} = \frac{e^{(0.25,0.05,0.20,0.24,0.22,0.03)(0.34,0,0.27,1,0.94,1)}}{e^{(0.25,0.05,0.2,0.24,0.22,0.03)(0.34,0,0.27,1,0.94,1)} + e^{(0.25,0.05,0.2,0.24,0.22,0.03)(0.36,0,0.28,0.6,0.86,0.90)}}$$

The result of performing the operations is

$$\mathbf{U_{P(s)} = 0.52}$$

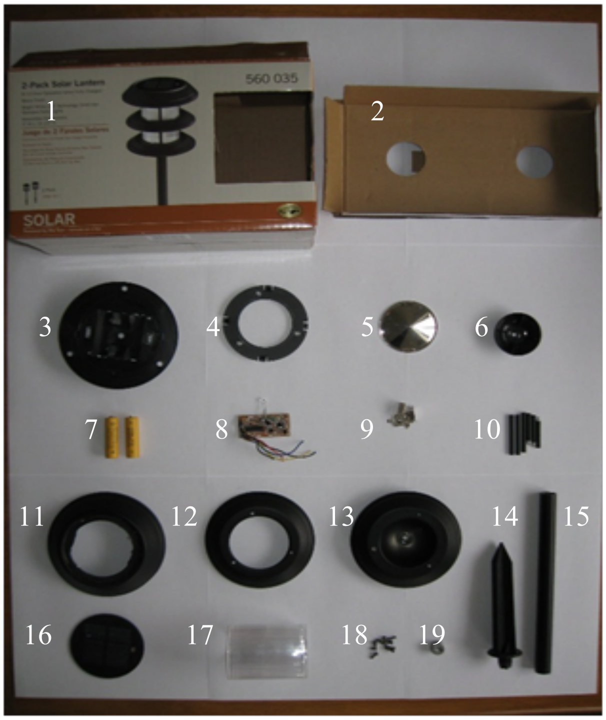
Similarly, the producer's utility for the low voltage option is calculated using Eq. 5.12.

$$\mathbf{U_{P(lv)} = 0.48}$$

5.4. Utility Perceived by the Environment

To estimate the utility perceived by the environment, the designer must first understand the environmental impact of the two available design options. Two lamps samples, one of each option, were disassembled and analyzed to determine the construction configuration, materials, and part weights.

Figure 5-7 and Figure 5-8 shows all the parts for each option, including their packaging material. Figure 5-9 and Figure 5-10 show the bill of materials resulting from the parts analysis. When evaluating the environmental impact of each option, it must be done considering the same operational conditions for both products. Unlike the solar option, low voltage lamps require an external module to obtain and convert the power to operate. For this reason the electrical transformer and distribution cable were added to the low voltage lamp bill of material.



1. Packaging Box
2. Packaging filling
3. Batteries housing
4. Top mounting plate
5. Reflector
6. Bottom fixture
7. Batteries
8. Circuit board (w LED)
9. Battery contactors
10. Side columns
11. Deflector
12. Deflector
13. Bottom plate
14. Ground stick
15. Pole
16. Solar panel
17. Screen
18. Screws
19. Threaded link
20. Steel cover
21. Coil frame
22. Circuit board
23. Contactor
24. Coil copper
25. Coil core metal
26. Thermal sensor
27. Plastic covers
28. Front case
29. Rear case
30. Insulated cable
31. Reflector
32. Connectors
33. Top deflector
34. Bulb

Figure 5-7 Solar lamp parts and packaging

Figure 5-8 Transformer and low voltage lamp parts and packaging

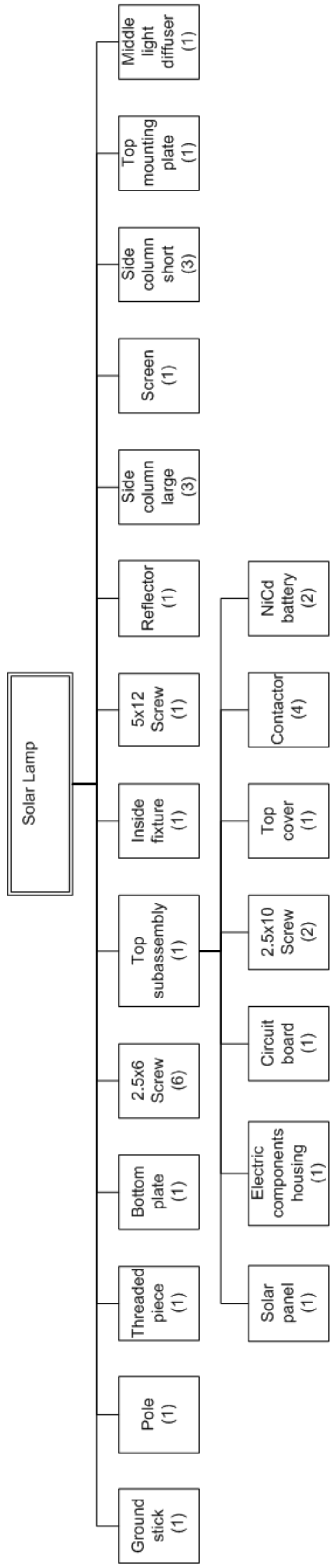


Figure 5-7 Solar lamp bill of material

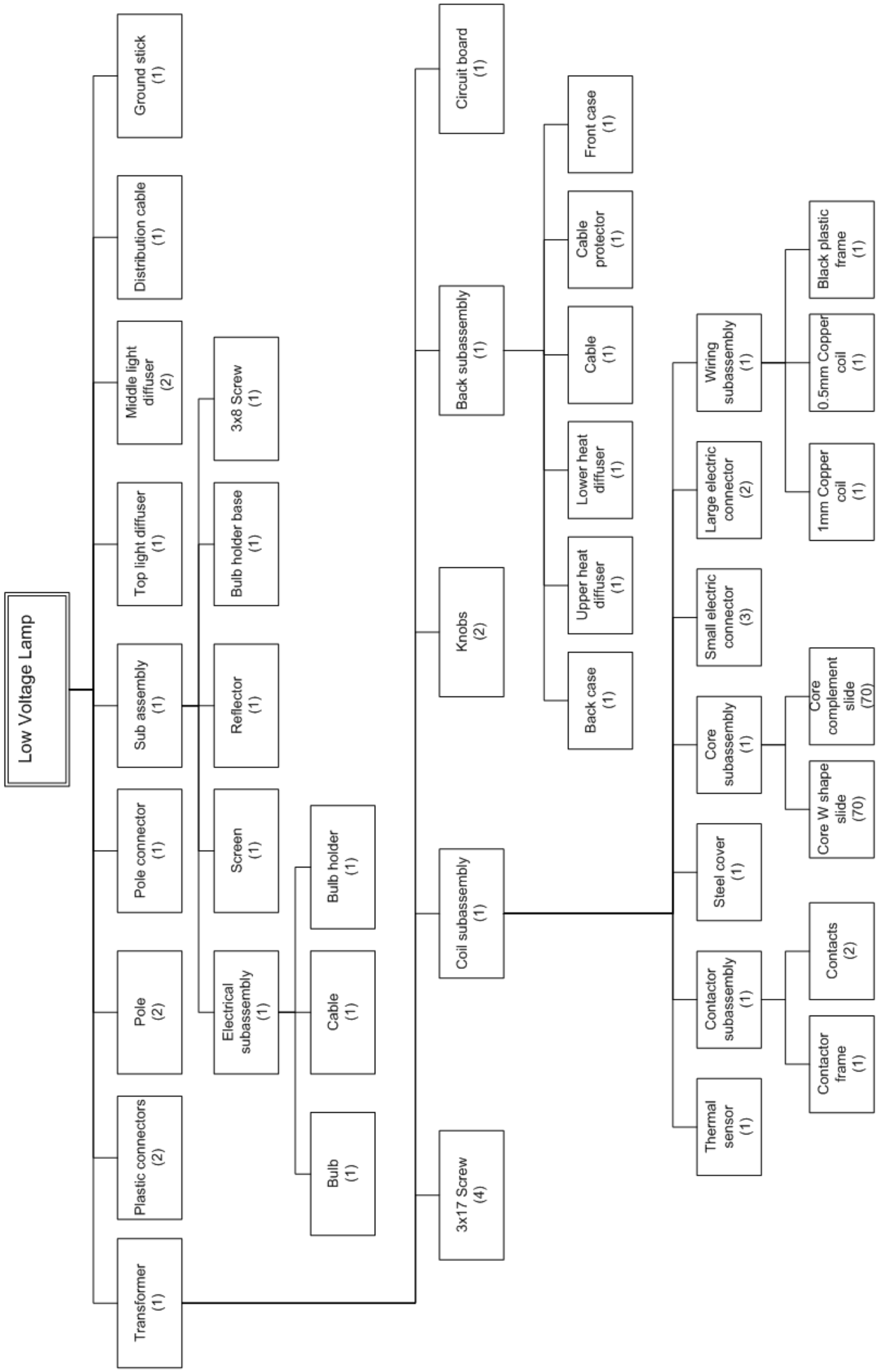


Figure 5-8 Low voltage lamp bill of materials

Table 5-7 Materials and processes inventory for solar and low voltage lampsshows the materials and processes inventory for both options. It is clearly visible that the amount of material contained in a low voltage lamp is significantly greater than the amount for the solar lamp. The transformer accounts for about 90% of the total weight. The illuminating unit weights only approximately 237g, comparable to the solar lamp which weight is approximately 278g including its power source.

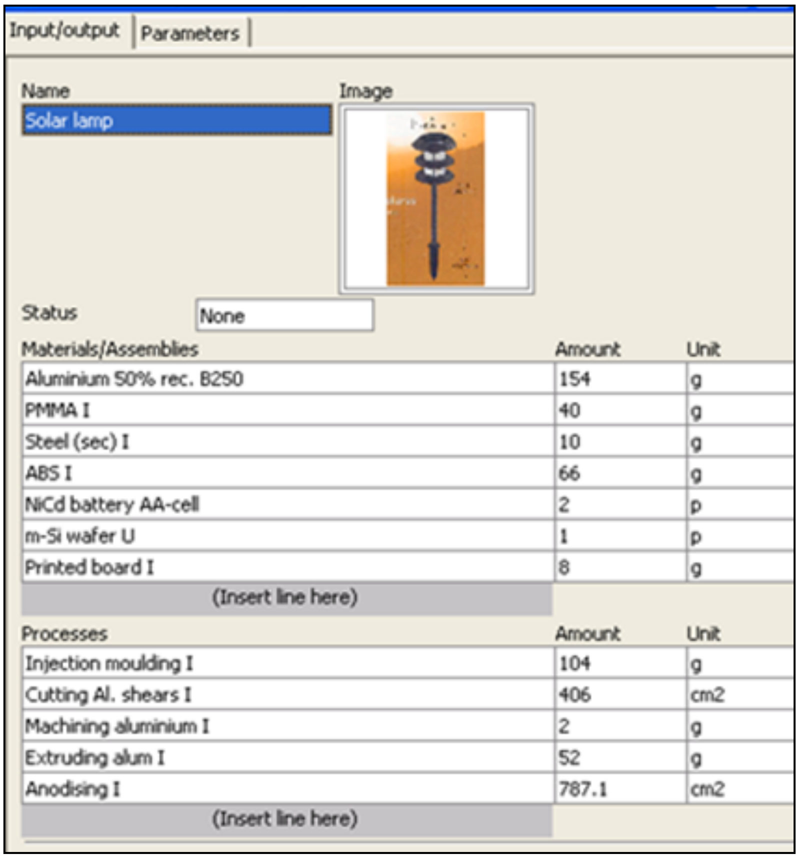
Table 5-7 Materials and processes inventory for solar and low voltage lamps

	Quantity		Units
Material/Assemblies	**Solar**	**Low Volt**	
Aluminiym 50% recyclable	154	132	g
PMMA	40	60	g
Steel	10	52	g
ABS	66	284	g
PE (LDPE)	--	474	p
NiCad battery AA-cell	2	--	p
m-Si wafer	1	1	g
Printed Board	8	34	g
Copper	--	617	g
Glass	--	2	g
PP	--	42	g
CuZn15	--	150	g
Cast Iron GG15	--	694	g

	Quantity		Units
Processes	**Solar**	**Low Volt**	
Injection moulding	104	384	g
Cutting, shears	406	3525	cm^3
Machining aluminum	2	--	g
Extruding aluminum	52	54	g
Anodizing	787	1045	cm^3

Once the part analysis is completed, the bill of material information is fed into a lifecycle analysis software such as SimaPro v7.2.4 to perform the assessment of the environmental impact of each option. Figure 5-11 and Figure 5-12 shows screenshots of the input windows for each product. Note that each unit of the low voltage lamp has its own input screen: lamp, transformer, and cable. (Figure 5-12b and c).

Eco-indicator 99 could be the methodology to assess the environmental impact, which is based on damages occurred to human health, ecosystem quality, and resources depletion. The main output is a single score that unifies all the damages on it. The environmental impact calculated by the program for the solar lamp is $X_{(s)}$= 2.28 eco-points. As for the low voltage lamp option the calculated environmental impact score is $X_{(lv)}$ = 5.82 eco-points. The impact of the low voltage lamp is greater than the impact of the solar lamp.



Input/output | Parameters

Name: Solar lamp

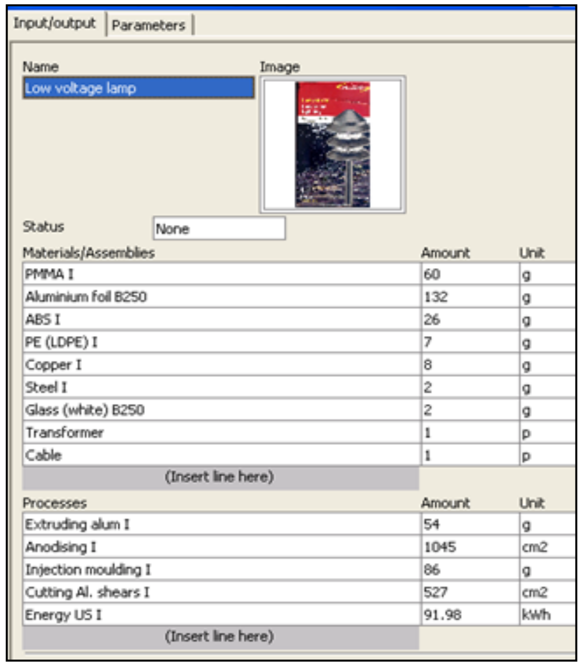
Image

Status: None

Materials/Assemblies	Amount	Unit
Aluminium 50% rec. B250	154	g
PMMA I	40	g
Steel (sec) I	10	g
ABS I	66	g
NiCd battery AA-cell	2	p
m-Si wafer U	1	p
Printed board I	8	g
(Insert line here)		

Processes	Amount	Unit
Injection moulding I	104	g
Cutting Al. shears I	406	cm2
Machining aluminium I	2	g
Extruding alum I	52	g
Anodising I	787.1	cm2
(Insert line here)		

Figure 5-11 Materials and process input in SimaPro for solar lamp.



Input/output | Parameters

Name: Low voltage lamp

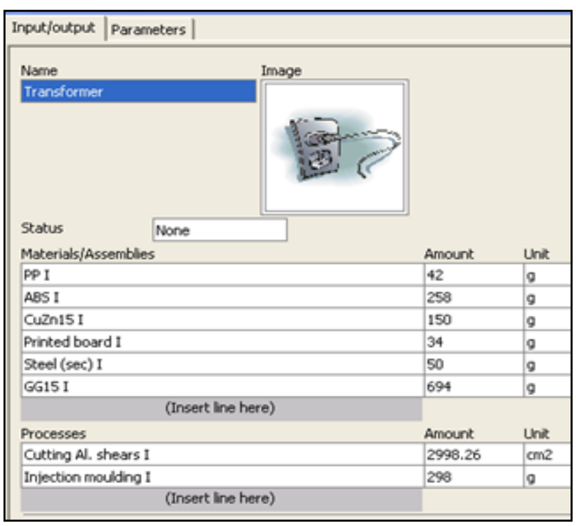
Image

Status: None

Materials/Assemblies	Amount	Unit
PMMA I	60	g
Aluminium foil B250	132	g
ABS I	26	g
PE (LDPE) I	7	g
Copper I	8	g
Steel I	2	g
Glass (white) B250	2	g
Transformer	1	p
Cable	1	p
(Insert line here)		

Processes	Amount	Unit
Extruding alum I	54	g
Anodising I	1045	cm2
Injection moulding I	86	g
Cutting Al. shears I	527	cm2
Energy US I	91.98	kWh
(Insert line here)		

(a)



Input/output | Parameters

Name: Transformer

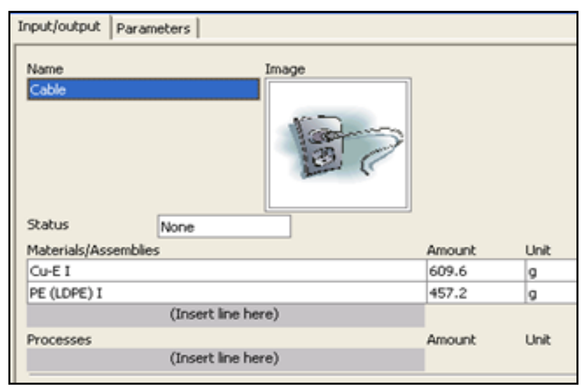
Image

Status: None

Materials/Assemblies	Amount	Unit
PP I	42	g
ABS I	258	g
CuZn15 I	150	g
Printed board I	34	g
Steel (sec) I	50	g
GG15 I	694	g
(Insert line here)		

Processes	Amount	Unit
Cutting Al. shears I	2998.26	cm2
Injection moulding I	298	g
(Insert line here)		

(b)



Input/output | Parameters

Name: Cable

Image

Status: None

Materials/Assemblies	Amount	Unit
Cu-E I	609.6	g
PE (LDPE) I	457.2	g
(Insert line here)		

Processes	Amount	Unit
(Insert line here)		

(c)

Figure 5-12 Materials and process input in SimaPro for low voltage lamp
(a) **Input for low voltage lamp.**
(b) Input for low voltage transformer. (c) Input for low voltage distribution cable

Figure 5-13 and Figure 5-14 shows the output impact network that visualizes the contribution of each material and/or processes to the score and the relation to each other.

Note that the main contribution in the solar lamp comes from the aluminum extruding process that requires large amounts of energy to complete. Furthermore, note that the main contributor for the low voltage impact is also the aluminum extruding and the cupper required for the distribution cable and coil inside the transformer. These main contributions impact mostly in the resources depletion category. Figure 5-15 shows a comparison of the two options impact by category. Note that approximately 60% of the impact falls into the resources depletion category.

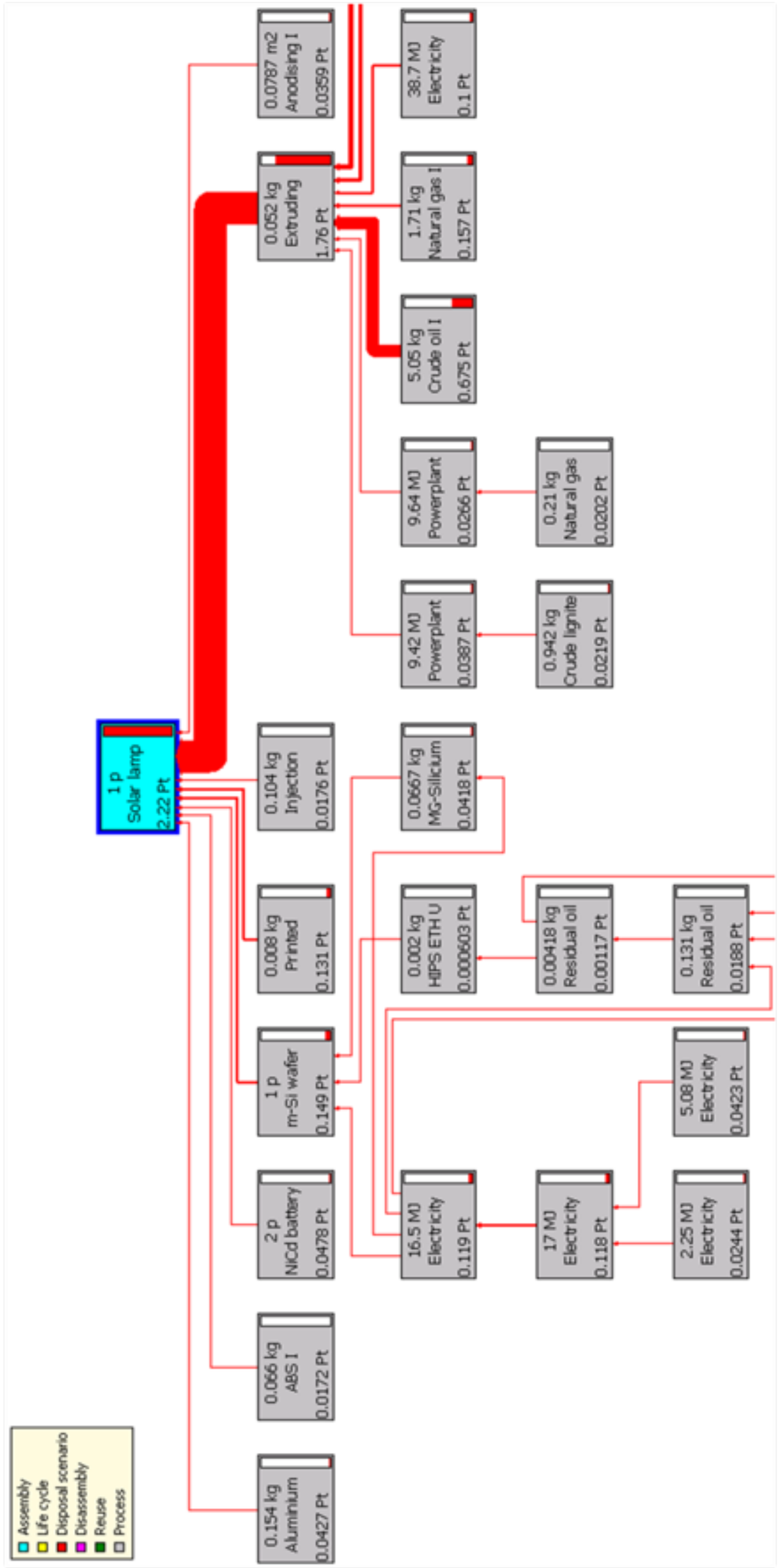


Figure 5-13 SimaPro assessment output for solar lamp

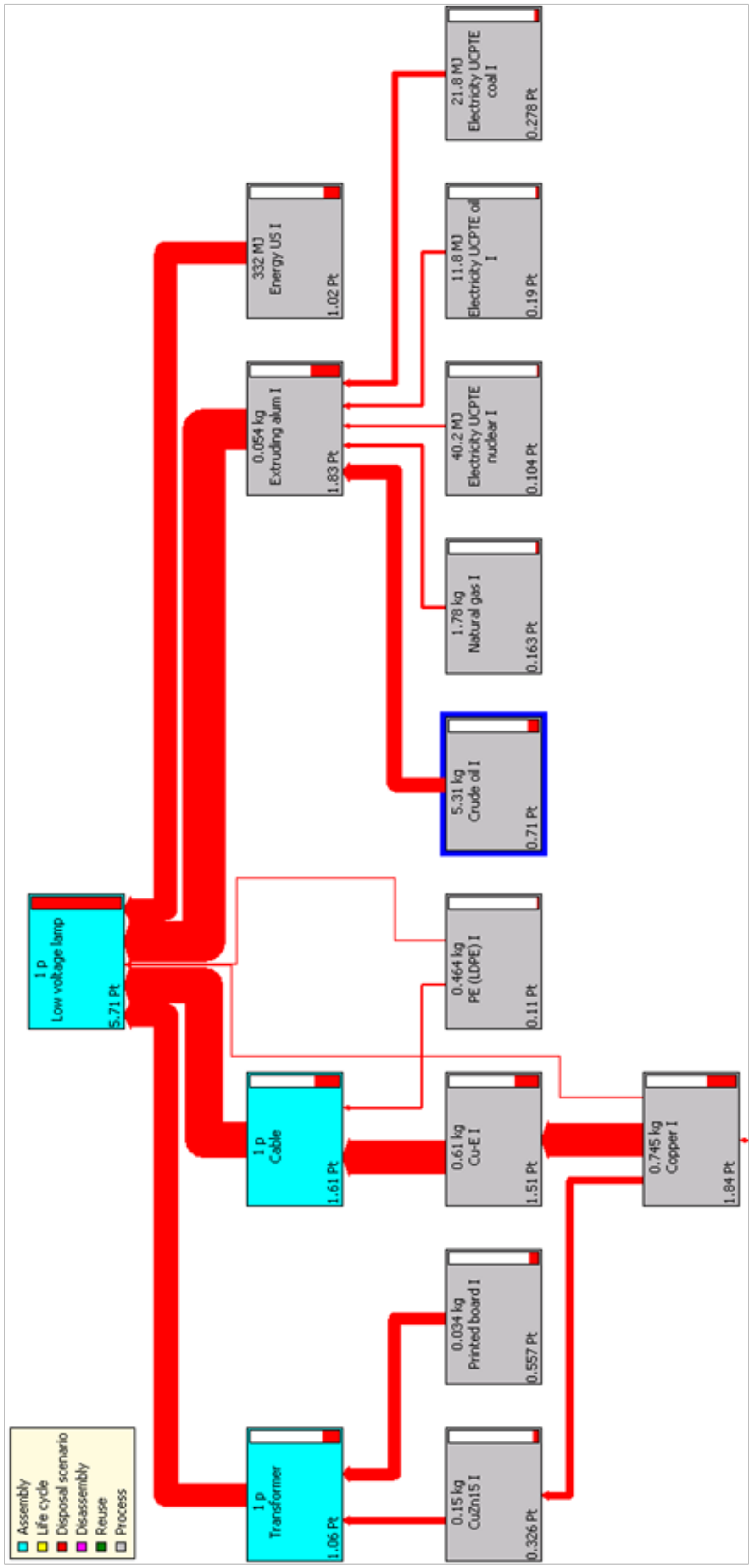


Figure 5-14 SimaPro assessment output for low voltage

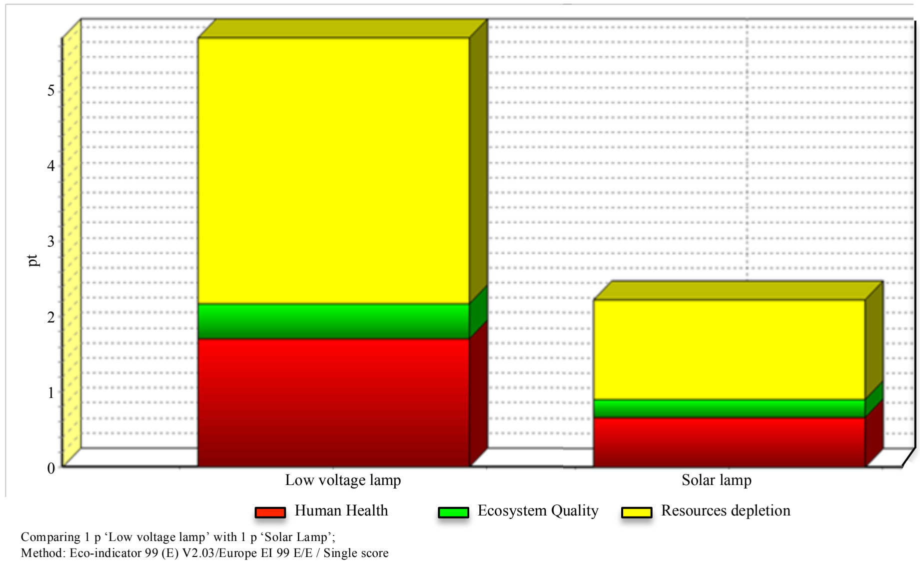


Figure 5-15 Comparison of environmental impact between low voltage and solar

Then the score of each alternative is mapped to estimate the utility each lamp has to the planet. As discussed in section 4.4, the utility to the planet can be defined by the function

$$U_e = \frac{1}{(IX+1)} \tag{5.13}$$

where:

U_e : utility of the design perceived by the planet (environment),

I: impact factor that is a function of the nature of the product

X: impact assessment of the design (obtained from LCA tools).

The factor *I* defines how much the utility to the planet drops as the product's environmental impact increases. It scales the different utility curves for each product family based on the nature of the products.

Since the factor *I* is not standardized yet and, since the compared products belong to the same product family, any value of *I* would be acceptable for the purposes of this case study. Suppose an impact factor *I* = 0.2. The planets utility function depicts the curve shown in Figure 5-16. Then, the utility to the planet for each option is calculated

using Eq. 5.13:

$$U_{e_{(s)}} = \frac{1}{(0.2*2.22+1)} \quad \rightarrow \quad \boldsymbol{U_{e(s)} = 0.69}$$

$$U_{e_{(lv)}} = \frac{1}{(0.2*5.82+1)} \quad \rightarrow \quad \boldsymbol{U_{e(lv)} = 0.46}$$

These results are also depicted in Figure 5-16. Comparing each other, the solar lamps presents a higher planet utility than the low voltage lamps base on the environmental impact that they generate.

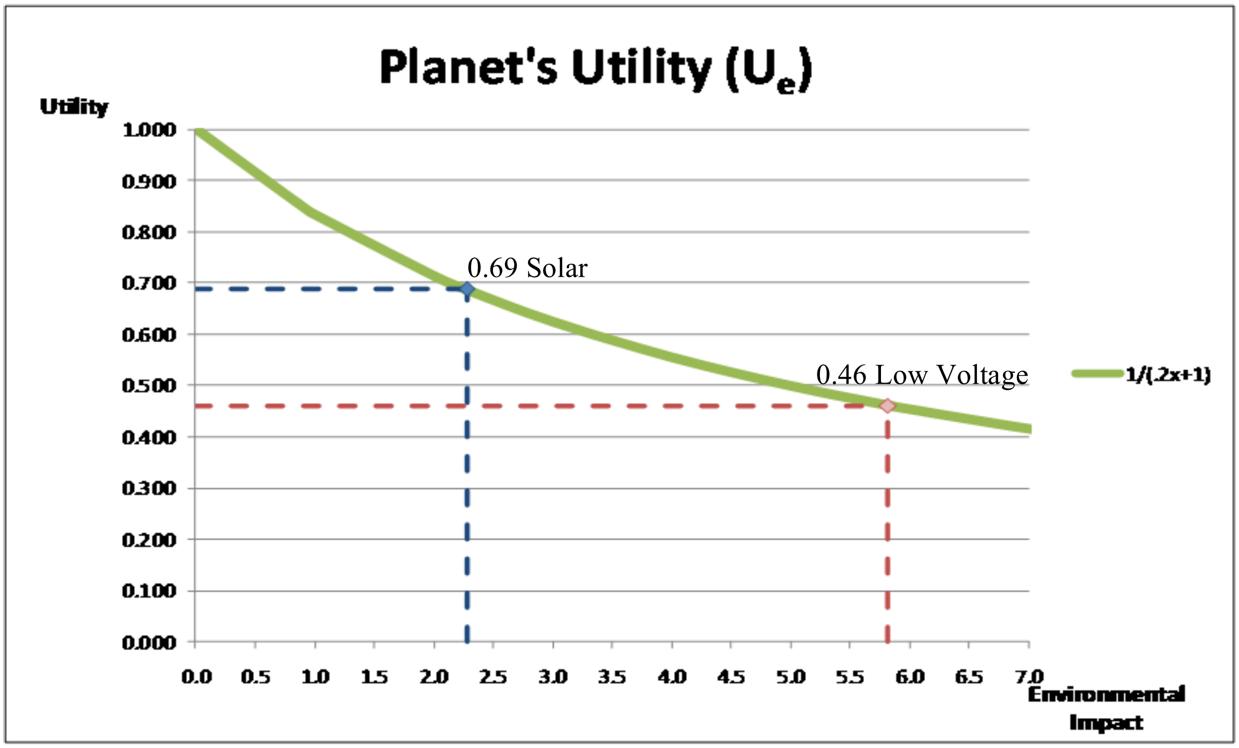


Figure 5-16 Planet utility function with I = 0.2

5.5. Global utility

Finally, the global utility of each design option is calculated with the equation

$$U_{Gk} = a_c U_c + a_p U_p + a_e U_e \tag{5.14}$$

where :

U_{Gk}: Global Utility of option k.

a: weight factor vector

$a = [a_c, a_p, a_e]$

$$a_c + a_p + a_e = 1 \tag{5.15}$$

U_c = Design utility perceived by customer

U_p = Design utility perceived by producer

U_e = Design utility perceived by planet (earth).

The weight factors vector a describes the importance of the stakeholder utilities respect to each other. They depict the design tendency that the designer possesses. A neutral global utility means that the designer assigns equal values of weight factor to each stakeholder (a_c, a_p, a_e) = (0.33, 0.33, 0.33). Assuming a neutral approach, the global utility of solar lamp is calculated using Eq. 5.14

$$U_{G_s} = 0.33 * 0.80 + 0.33 * 0.53 + 0.33 * 0.69$$

$$\boldsymbol{U_{G_s} = 0.67}$$

Similarly, the global utility of low voltage lamp is

$$U_{G_{lv}} = 0.33 * 0.76 + 0.33 * 0.49 + 0.33 * 0.46$$

$$\boldsymbol{U_{G_{lv}} = 0.57}$$

With the given values of utilities to the customer, producer, and planet, the solar powered light design option obtains the highest global utility. Moreover, in this case global utility for the solar option will always be higher than the low voltage lamp even for different values of weight factors *a* since the utilities for all stakeholders were higher in the solar option in every category.

5.6. Flexing the Model

Consider now a different situation. To better illustrate how the weight factors *a* affect the global utility, assume that the value of the customer utility for low voltage is

$$\mathbf{U_{c(lv)} = 0.85}$$

with set of part characteristics

$$\mathbf{(x_1, x_2, x_3, x_4, x_5, x_6)_{lv} = (17.6\ ,\ 95.65\ ,\ 1844,\ 14.44,\ 54.41,\ 0.4)}$$

The new utility to the producer is

$$\mathbf{U_{p(lv)} = 0.48}$$

The value of the utility to the planet is maintained because it depends on the environmental impact assessment

$$\mathbf{U_{e(lv)} = 0.46}$$

Under this scenario only the low voltage lamp utility to the customer $U_{c(lv)}$ is higher than the solar lamp utility to the customer $U_{c(s)}$.

Solar		**Low Volt**
$U_{c(s)} = 0.80$	<	$U_{c(lv)} = 0.85$
$U_{p(s)} = 0.53$	>	$U_{p(lv)} = 0.48$
$U_{e(s)} = 0.69$	>	$U_{e(lv)} = 0.46$

Using Eq. 5.14, the neutral global utilities for this scenario are

$$\boldsymbol{U_{G(s)} = 0.67} \quad > \quad \boldsymbol{U_{G(lv)} = 0.60}$$

The neutral global utility works as baseline values. Neutral global utility means that there is no preference for the customer, or the producer, or the planet (a_c=a_p=a_e= 0.33). So, for a designer with a neutral design tendency the solar option has the highest global utility between the two options.

An environmentally conscious designer will assign a higher importance to the planet utility. So, considering the vector (a_c, a_p, a_e) = (0.3, 0.2, 0.5) and using Eq. 5.14 the global utilities are

$$\boldsymbol{U_{G(s)} = 0.69} \quad > \quad \boldsymbol{U_{G(lv)} = 0.58}$$

Again the solar option has higher global utility for an environmentally conscious designer with the given set of weight factors. On the other hand, an environmentally oblivious designer assigns lower or zero importance to the planet utility. For example, considering the vector (a_c, a_p, a_e) = (0.6, 0.4, 0.0) and using Eq. 5.14 the global utilities are

$$\boldsymbol{U_{G(s)} = 0.68} \quad < \quad \boldsymbol{U_{G(lv)} = 0.70}$$

The low voltage lamp has higher global utility for an environmental oblivious designer with the given set of weight factors.

To visualize and understand the effect of the weight factors in the global utility it is possible to plot the response surface for each option. The global utility surface is described by the plane function with normal vector (a_c, a_p, a_e). Clearing the factor a_c from Eq. 5.15, obtains

$$a_c = 1 - a_p - a_e \tag{5.16}$$

Substituting Eq. 5.16 into Eq. 5.14 yields to the equation of the global utility in function of a_p and a_e

$$U_G = U_c + a_p(U_p - U_c) + a_e(U_e - U_c) \quad (5.17)$$

Figure 5-17 depict the global utility surfaces for each design option. It is easy to identify in this figure what design option has higher global utility based on the design tendency. These observations are summarized in Table 5-8 Higher global utility among design option based on design tendency. The intersection line between the two planes (black dotted line) represents the sets of weight factors a_c, a_p, and a_e (a_c=1-a_p-a_e) to were the value of the global utility for both options are equal. The equation of this line is a_p= -3.5a_e + 0.7, shown in Figure 5-18. Any combination of weight factors outside of this line will result in a higher global utility for one of the options. The orange area represents higher global utility for solar option. The green area represents higher global utility for low voltage option.

Table 5-8 Higher global utility among design option based on design tendency

Design tendency		Higher global utility design option
Customer focused	$a_c\uparrow$, $a_p\downarrow$, $a_e\downarrow$	Low voltage
Producer focused	$a_c\downarrow$, $a_p\uparrow$, $a_e\downarrow$	Low voltage
Environmental conscious	$a_c\downarrow$, $a_p\downarrow$, $a_e\uparrow$	Solar
Neutral	$a_c = a_p = a_e$	Solar

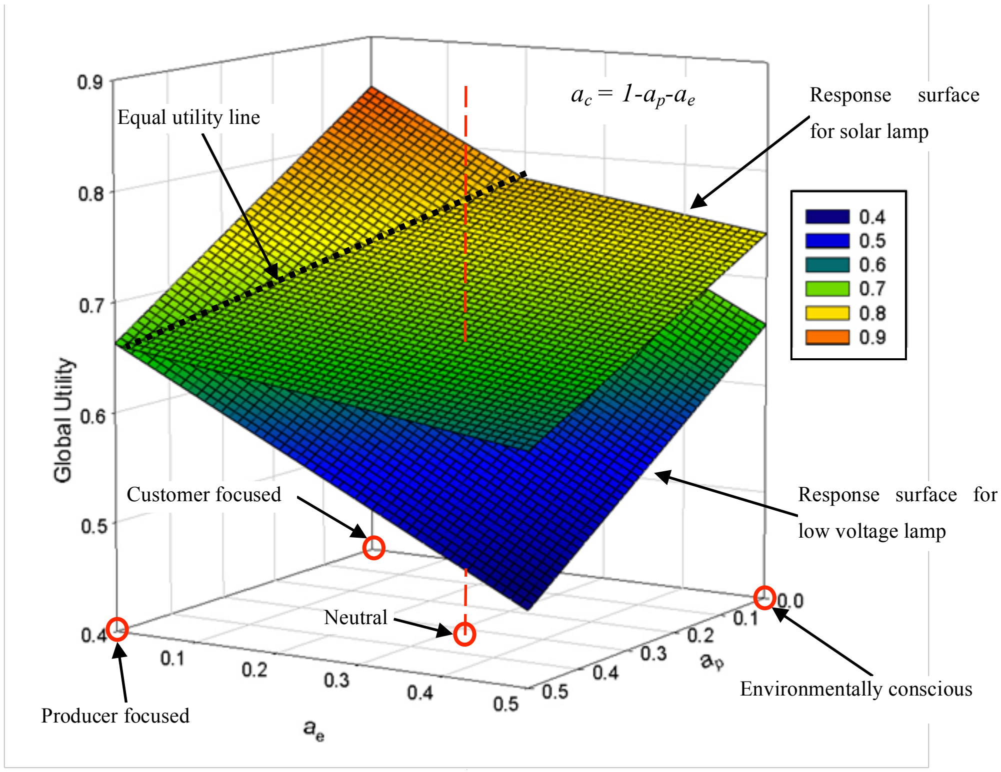


Figure 5-17 Response surfaces for solar and low voltage lamp respect to the weight factors

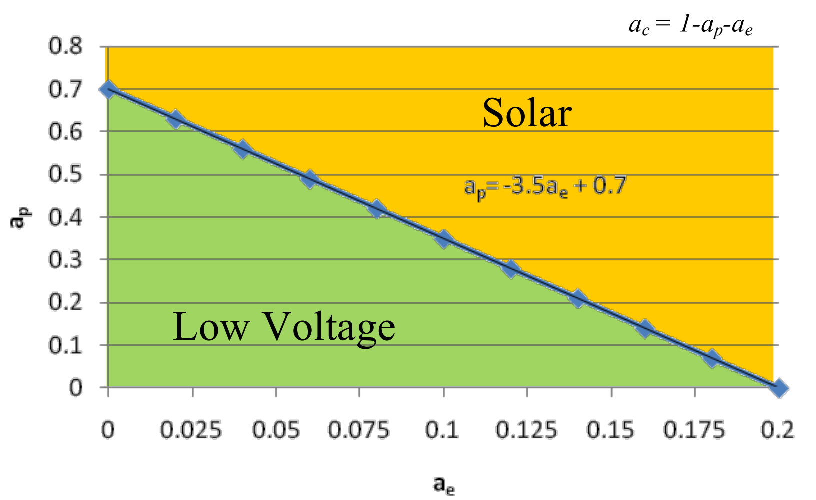


Figure 5-18 Line of equal global utility for solar and low voltage lamps

5.7. Redesign of existing product

One application for the proposed framework is to compare the global utility of different design options, as read in the previous section. This application can be used to identify the set of part characteristics that provide higher product utility and apply them to potential new designs.

Another application is the redesign of existing products. The framework can be used to identify the effect on the global utility when certain part characteristics are modified. So, the designer can predict how the product will perform out in the market before making decisions during design changes.

To exemplify this application consider the solar lamp. Suppose the designer wants to understand what would be the effect of changing the material of the lamp pole from aluminum to plastic ABS.

In previous sections the utility to the customer was calculated for the solar option. However, this utility value was maximized with optimal set of part characteristics. To redesign the lamp, the designer must understand the existing lamp's design condition and calculate the utilities for all the stakeholders with actual performance levels of part characteristics. Utility to the customer will be calculated using the same nonlinear function developed in section 5.2, with the difference that actual part characteristic performance level would be used instead of a boundary range. To simplify this example, the part performance levels will be equal to the value calculated in the maximization in section 5.2 but only levels related to the lamp pole will be equal to actual performance value. Thus, the lamp aluminum pole performances are

		Nominal	**Normalized**
Pole stiffness	$y_6 =$	255.45 Lb/in	0.85
Pole weight	$y_7 =$	0.0872 Lbs	0.84
Pole weight fraction	$y_{12} =$	12.2%	0.52

The utility to the customer is calculated with Eq. 5.1

$U_{c(s)}$ = (1/k) *((k*a1*(6.36E-04*x1^2 + 3.18E-02*x1 - 3.84E-02)+1) * (k*a2*(-2.67E-05*x2^2 + 1.22E-02*x2 + 3.17E-02)+1) * (k*a3*(1.79E-07*x3^2 + 1.42E-04*x3 - 8.31E-03)+1) * (k*a4*(-2.11E-03*x4^2 - 7.04E-03*x4 + 9.94E-01)+1) (k*a5*(8.83E-05*x5^2 - 2.32E-02*x5 + 1.08E+00)+1) * (k*a6*(-8.52E-03*x6^2 - 1.16E-01*x6 + 1.04E+00)+1) - 1);

x1 = 1.5+(22-1.5)/62 * (3*y1 + 3*y2 + 1*y3 + 9*y4 + 1*y5 + 0*y6 + 0*y7 + 3*y8 + 1*y9 + 9*y10 + 3*y11 + 0*y12 + 0*y13 + 0*y14 + 0*y15 + 9*y16 - 3*y1*y9 - 3*y2*y3 + 3*y2*y10 - 3*y3*y10 - 3*y5*y15 + 3*y6*y7- 3*y6*y9 + 3*y6*y12 - 3*y6*y13 + 3*y7*y12 + 3*y8*y11 + 3*y9*y12 + 3*y9*y14 + 3*y9*y15 + 3*y11*y14 + 3*y11*y16);

x2 = 100/72 * (0*y1 + 0*y2 + 0*y3 + 0*y4 + 0*y5 + 0*y6 + 9*y7 + 0*y8 + 0*y9 + 0*y10 + 9*y11 + 9*y12 + 9*y13 + 9*y14 + 3*y15 + 0*y16 - 3*y1*y9 - 3*y2*y3 + 3*y2*y10 - 3*y3*y10 - 3*y5*y15 + 3*y6*y7- 3*y6*y9 + 3*y6*y12 - 3*y6*y13 + 3*y7*y12 + 3*y8*y11 + 3*y9*y12 + 3*y9*y14 + 3*y9*y15 + 3*y11*y14 + 3*y11*y16);

x3 = 50+(2000-50)/78 * (0*y1 + 3*y2 + 1*y3 + 3*y4 + 0*y5 + 0*y6 + 0*y7 + 9*y8 + 9*y9 + 9*y10 + 9*y11 + 0*y12 + 0*y13 + 0*y14 + 0*y15 + 9*y16 - 3*y1*y9 - 3*y2*y3 + 3*y2*y10 - 3*y3*y10 - 3*y5*y15 + 3*y6*y7- 3*y6*y9 + 3*y6*y12 - 3*y6*y13 + 3*y7*y12 + 3*y8*y11 + 3*y9*y12 + 3*y9*y14 + 3*y9*y15 + 3*y11*y14 + 3*y11*y16);

x4 = 20/38 * (3*y1 + 3*y2 + 1*y3 + 0*y4 + 9*y5 + 0*y6 + 0*y7 + 0*y8 + 0*y9 + 0*y10 + 0*y11 + 0*y12 + 0*y13 + 0*y14 + 1*y15 + 1*y16 - 3*y1*y9 - 3*y2*y3 + 3*y2*y10 - 3*y3*y10 - 3*y5*y15 + 3*y6*y7- 3*y6*y9 + 3*y6*y12 - 3*y6*y13 + 3*y7*y12 + 3*y8*y11 + 3*y9*y12 + 3*y9*y14 + 3*y9*y15 + 3*y11*y14 + 3*y11*y16);

x5 = 5+(60-5)/109 * (3*y1 + 3*y2 + 1*y3 + 1*y4 + 3*y5 + 9*y6 + 9*y7 + 3*y8 + 9*y9 + 3*y10 + 9*y11 + 9*y12 + 9*y13 + 9*y14 + 9*y15 + 3*y16 - 3*y1*y9 - 3*y2*y3 + 3*y2*y10 - 3*y3*y10 - 3*y5*y15 + 3*y6*y7- 3*y6*y9 + 3*y6*y12 - 3*y6*y13 + 3*y7*y12 + 3*y8*y11 + 3*y9*y12 + 3*y9*y14 + 3*y9*y15 + 3*y11*y14 + 3*y11*y16);

x6 = .4+(6-.4)/99 * (0*y1 + 0*y2 + 0*y3 + 0*y4 + 0*y5 + 9*y6 + 9*y7 + 0*y8 + 3*y9 + 0*y10 + 9*y11 + 9*y12 + 9*y13 + 9*y14 + 9*y15 + 9*y16 - 3*y1*y9 - 3*y2*y3 + 3*y2*y10 - 3*y3*y10 - 3*y5*y15 + 3*y6*y7- 3*y6*y9 + 3*y6*y12 - 3*y6*y13 + 3*y7*y12 + 3*y8*y11 + 3*y9*y12 + 3*y9*y14 + 3*y9*y15 + 3*y11*y14 + 3*y11*y16);

y1 = 0;
y2 = 0;
y3 = 0;
y4 = 1;
y5 = 0;
y6 = 0.85;
y7 = 0.84;
y8 = 1;
y9 = 0;
y10 = 1;
y11 = 0;
y12 = 0.52;
y13 = 0;
y14 = 0;
y15 = 0;
y16 = 0;
a1 = 0.25;
a2 = 0.50;
a3 = 0.3;
a4 = 0.35;
a5 = 0.45;
a6 = 0.4;
k = -0.988265;

Solving the equation with the proposed methods, the customer utility of actual solar lamp is

$$\boldsymbol{U_{c(Al)} = 0.77}$$

with set of engineering characteristics

$$(x_1, x_2, x_3, x_4, x_5, x_6)_{\text{al pole}} = (10.02 , 23.64 , 694.46 , 2.51 , 20.98 , 1.8)$$

Subsequently, the performance level of the material substitution is calculated based on design requirements. Assuming a pole made of plastic ABS with performance level:

		Nominal	Normalized
Pole stiffness	$y_6 =$	62.4 lb/in	0.2
Pole weight	$y_7 =$	0.038 lb	0.23
Pole weight fraction	$y_{12} =$	5.3%	0.98

The customer utility is calculated using equation Eq. 5.1 but replacing aluminum pole by plastic ABS pole attributes levels. Solving the equation, the customer utility for the material substitution is

$$\boldsymbol{U_{c(ABS)} = 0.79}$$

with set of engineering characteristics

$$(x_1, x_2, x_3, x_4, x_5, x_6)_{\text{ABS pole}} = (8.91 , 17.07 , 610.06 , 0.74 , 15.64 , 1.2)$$

Then, the utility to the producer is calculated for both options, using the Eq. 5.12. The normalized vectors of engineering characteristics are

$$\text{x}_{k(al)} = (0.42 , 0.24 , 0.33 , 0.87 , 0.71 , 0.75)$$

$$\text{x}_{k(ABS)} = (0.36 , 0.17 , 0.29 , 0.96 , 0.81 , 0.86)$$

and the vector of coefficient set is

$$\beta = (0.25 , 0.05 , 0.20 , 0.24 , 0.22 , 0.03)$$

Therefore, the producer utility for aluminum pole alternative is

$$U_{P_{(Al)}} = \frac{e^{(0.25,0.05,0.20,0.24,0.22,0.03)(0.36,0.17,0.29,0.96,0.81,0.86)}}{e^{(0.25,0.05,0.20,0.24,0.22,0.03)(0.36,0.17,0.29,0.96,0.81,0.86)} + e^{(0.25,0.05,0.20,0.24,0.22,0.03)(0.25,0.05,0.20,0.24,0.22,0.03)}}$$

$$\boldsymbol{U_{p(Al)} = 0.49}$$

Similarly, the producer utility for the plastic ABS pole is

$$U_{P_{(Al)}} = \frac{e^{(0.25,0.05,0.20,0.24,0.22,0.03)(0.25,0.05,0.20,0.24,0.22,0.03)}}{e^{(0.25,0.05,0.20,0.24,0.22,0.03)(0.36,0.17,0.29,0.96,0.81,0.86)} + e^{(0.25,0.05,0.20,0.24,0.22,0.03)(0.25,0.05,0.20,0.24,0.22,0.03)}}$$

$$\boldsymbol{U_{p(ABS)} = 0.51}$$

Next, the utility to the planet is calculated. The environmental impact for the lamp with aluminum pole was assessed in section 5.4, which is 2.22 points. Therefore, the utility to the planet is

$$\boldsymbol{U_{e(Al)} = 0.69}$$

The impact is reassessed to reflect the changes due to the material substitution. Figure 5-19 shows screenshots in SimaPro where materials and processes are input for both options. Note the differences in the mass for aluminum and ABS and their respective processes due to the material substitution.

The results generated by the software shows that the environmental impact with the material substitution is reduced to 0.867 points. Figure 5-20 shows the impact comparison by category between the two pole options. The major decrease is in the resources impact category, reduced by 38%. This reduction could be achieved because the aluminum extrusion process requires larger amounts of energy than the plastic molding. So, most of the fuel consumed to extrude the aluminum pole was removed and replaced by less energy consuming molding process (Figure 5-21 and Figure 5-22).

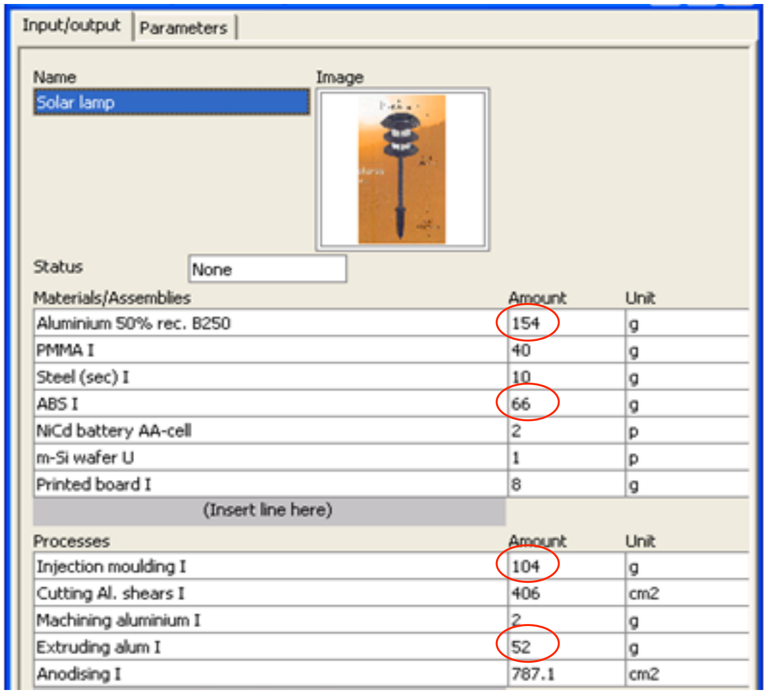
Again, the utility to the planet is given by Eq. 5.13

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

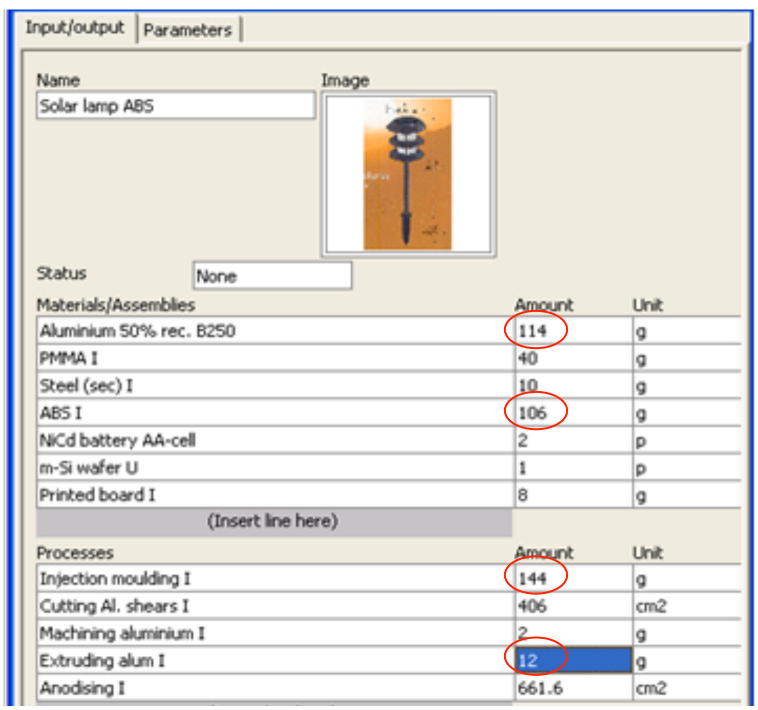
where I is the impact factor (I=0.2) and X is the impact score.

Thus, the utility to planet of the ABS pole option is

$$\boldsymbol{U_{e(ABS)} = 0.85}$$



(a)



(b)

Figure 5-19 Materials and process input in SimaPro.
(a) **Input for lamp with aluminum pole. (b) Input for lamp w ABS pole.**

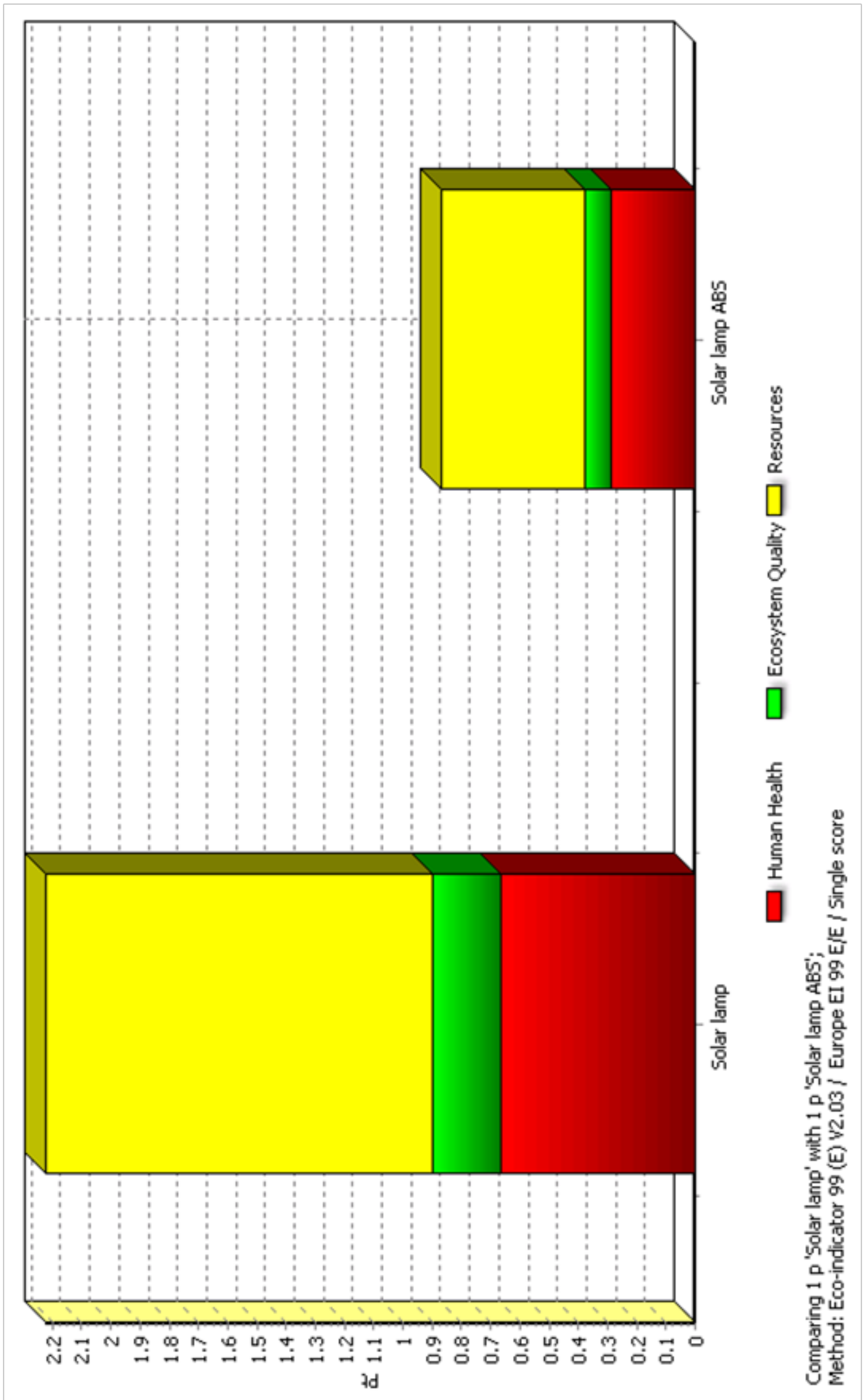


Figure 5-20 Comparison of environmental impact between lamp with aluminum and ABS pole

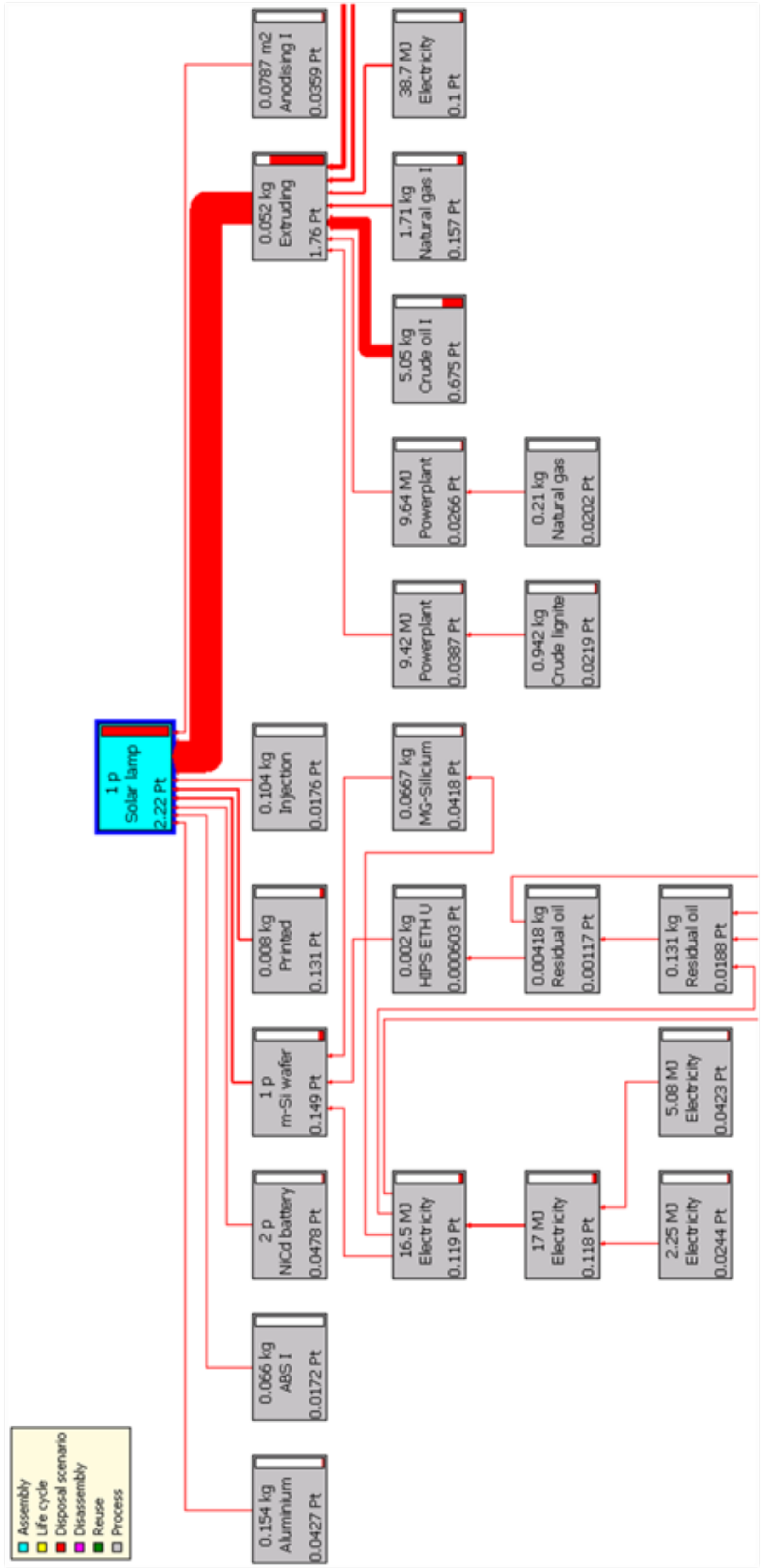


Figure 5-21 SimaPro assessment output for lamp with aluminum pole

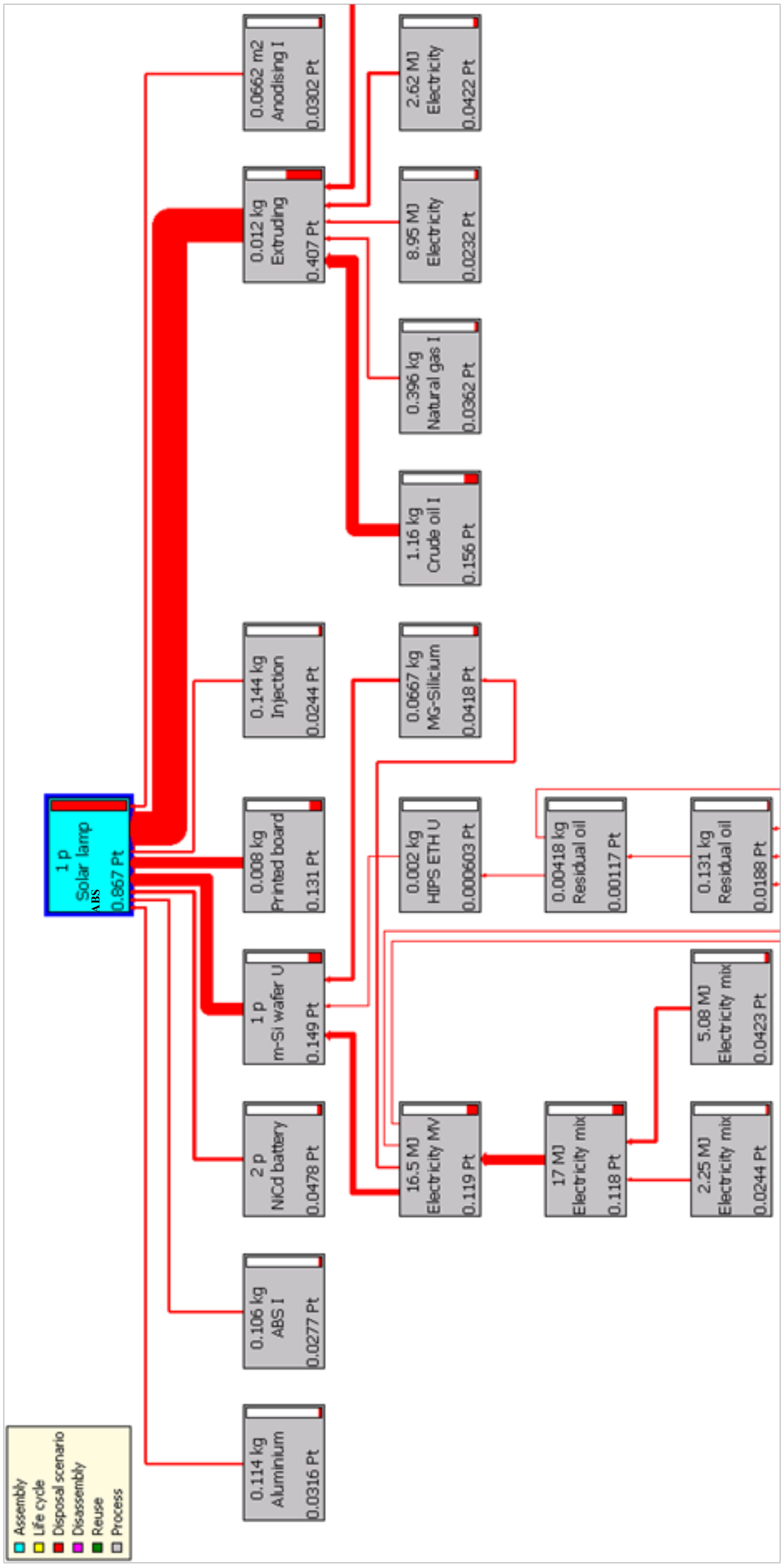


Figure 5-22 SimaPro assessment output for lamp with ABS pole

Finally, the global utility for both options are calculated. Using Eq. 5.14 and assuming neutral design tendency the global utilities are

Aluminum pole: $U_{G_{Al}} = 0.33 * 0.77 + 0.33 * 0.49 + 0.33 * 0.69$

$$\boldsymbol{U_{G_{Al}} = 0.65}$$

ABS pole: $U_{G_{Al}} = 0.33 * 0.79 + 0.33 * 0.51 + 0.33 * 0.85$

$$\boldsymbol{U_{G_{abs}} = 0.70}$$

For a neutral design tendency this material substitution represents an improvement in the design, since the global utility increased for the ABS pole instead compared to aluminum. A response surface is plotted in Figure 5-23 to visualize the global utilities for this material substitution with different design tendencies. From this plot can be noted that as the global utility for the aluminum pole option increases the design tendency leans towards the customer, but not enough to exceed the utility of the ABS pole alternative. On the other hand, the global utility increases for the ABS pole option as the design tendency leans towards the utility to the planet, and the highest utility can be achieved.

Thus, the proposed framework can aid the designers in the decision making process for a existing product redesign, by providing useful information about the effect in each stakeholder of the potential changes.

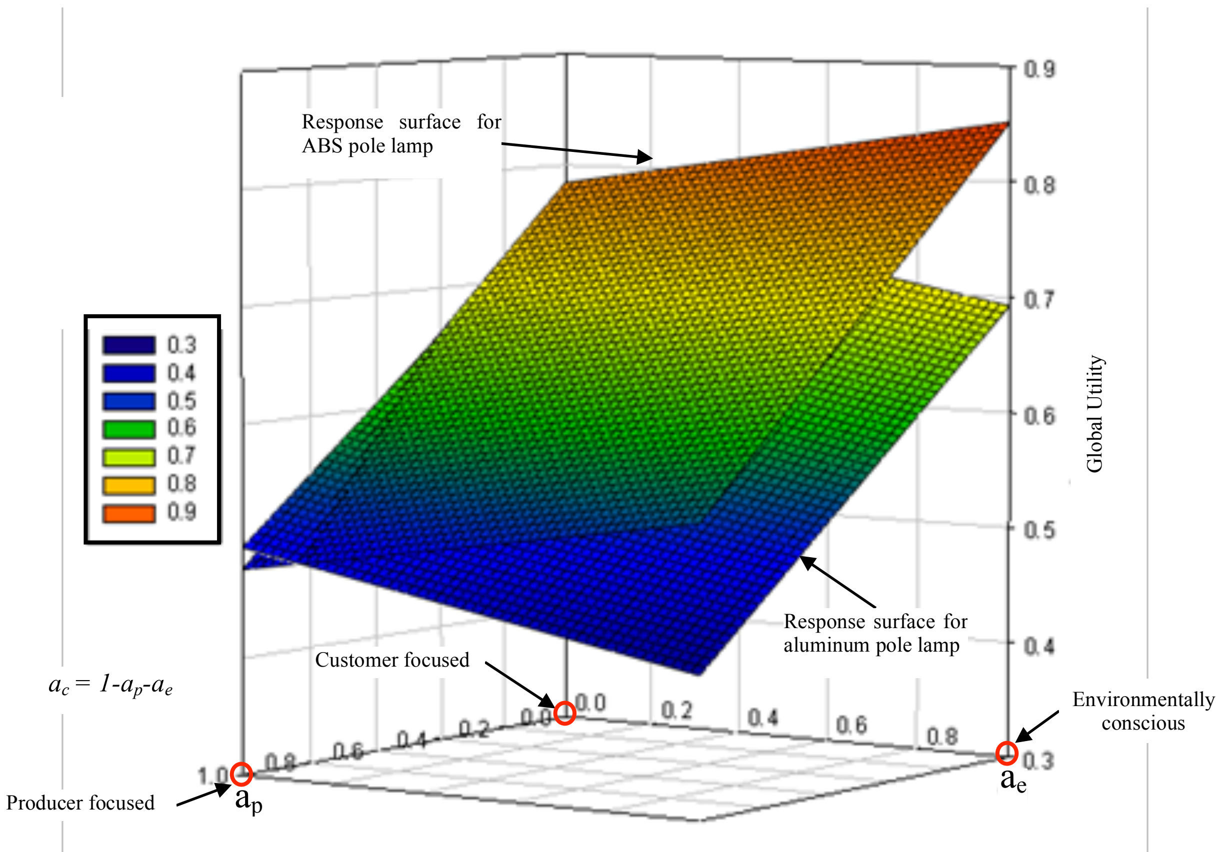


Figure 5-23 Response surfaces for lamps with Aluminum and ABS pole

5.8. Sensibility analysis

A sensibility analysis for this methodology was performed to observe the robustness of the methodology. Monte Carlo simulation was used to complete the analysis. As mentioned before, the framework is driven mostly by customer requirements, therefore customer utility. For this reason, the simulation was focused in the results from the utility to the customer of the solar design option.

10,000 pseudo random numbers were generated between the upper and lower boundaries of each part characteristic x_i. Then, the customer utility for each random combination of part attributes was calculated. The average and standard deviation of all the customer utilities were finally calculated (Table 5-9 Monte Carlo sensibility simulation

with upper and lower limits of x_i).

Table 5-9 Monte Carlo sensibility simulation with upper and lower limits of x_i

	X_1	X_2	X_3	X_4	X_5	X_6	
UPPER	22	100	2000	20	60	6	
LOWER	1.5	0	50	0	5	0.4	
	$a_1 = 0.25$	$a_2 = 0.5$	$a_3 = 0.3$	$a_4 = 0.35$	$a_5 = 0.45$	$a_6 = 0.4$	K = -0.988265

	X_1	X_2	X_3	X_4	X_5	X_6	$Ux_1=$	$Ux_2=$	$Ux_3=$	$Ux_4=$	$Ux_5=$	$Ux_6=$	$U_{c(s)}$
OPTIMAL	8.44	0.00	575.00	0.00	8.53	0.40	0.28	0.03	0.13	0.99	0.89	0.99	0.80

Monte Carlo	Average	0.732305
	Std Dev	0.084264

For these wide ranges of part characteristics the customer utility averaged 0.732 with standard deviation of 0.084. Observe that there is a noticeable difference between the utility for the optimal set and the average ($\Delta \approx 0.0677$). However, this calculation does not consider the constraints imposed by the relationship and correlation matrixes in the house of quality II. Hence, a new simulation is executed, but this time the values of the upper and lower limits of part characteristics are constrained to ±10% the optimal value (Table 5-10 Monte Carlo sensibility simulation with ±10% of optimal x_i values.).

Table 5-10 Monte Carlo sensibility simulation with ±10% of optimal x_i values.

	X_1	X_2	X_3	X_4	X_5	X_6	
10% up	9.284	0	632.5	0	9.383	0.44	
10% down	7.596	10	517.5	2	7.677	0.4	
	$a_1 = 0.25$	$a_2 = 0.5$	$a_3 = 0.3$	$a_4 = 0.35$	$a_5 = 0.45$	$a_6 = 0.4$	K = -0.988265

	X_1	X_2	X_3	X_4	X_5	X_6	$Ux_1=$	$Ux_2=$	$Ux_3=$	$Ux_4=$	$Ux_5=$	$Ux_6=$	$U_{c(s)}$
OPTIMAL	8.44	0.00	575.00	0.00	8.53	0.40	0.28	0.03	0.13	0.99	0.89	0.99	0.80

Monte Carlo	Average	0.801748
	Std Dev	0.003904

This time the customer utility averaged 0.802 with standard deviation of 0.004.

Many of the random sets of part characteristics values resulted in customer utility of 0.80, which is equal to the value of the utility of optimal set of part characteristics. The simulation was performed again, but this time using a random set of attributes that resulted in utility of 0.80. The boundaries for the random numbers were again ±10% of

the new random set value Table 5-11 Monte Carlo sensibility simulation with random set of attributes with U_c= 0.8.

Table 5-11 Monte Carlo sensibility simulation with random set of attributes with U_c= 0.8

	X_1	X_2	X_3	X_4	X_5	X_6	Ux_1=	Ux_2=	Ux_3=	Ux_4=	Ux_5=	Ux_6=	$U_{c(s)}$
10% up	3.510	1.313	1848.664	1.815	8.356	2.564							
10% down	2.872	1.074	1512.544	1.485	6.837	2.098							
	a_1 = 0.25	a_2 = 0.5	a_3 = 0.3	a_4 = 0.35	a_5 = 0.45	a_6 = 0.4	K = -0.988265						
OPTIMAL	3.19	1.19	1680.60	1.65	7.60	2.33	0.07	0.05	0.74	0.98	0.91	0.72	0.80

Monte Carlo	Average	0.798016
	Std Dev	0.006602

The averaged customer utility for the optional set of characteristics resulted in 0.798 with standard deviation of 0.007.

These small differences between the optimal utility and the random optimal set and the optional set shows the robustness of the methodology to estimate the customer utility of the design options. Therefore, due that the customer utility drives the methodology proposed in this work, the framework is robust.

6. Conclusions

In the modern society, designers face the challenging task of satisfying the needs of customers that tends to demand more environmentally friendly products but keeping good quality standards. Also, must consider the interest of the producer that faces the challenge of balancing environmental responsibility with the profitability of the products. This framework is a step forward into the complex task of integrating multiple lifecycle stages into the design process. 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.

Quality function deployment and multiattribute utility analysis are implemented to estimate the utility of design options with respect to the customer preferences. QFD translates the voice of the customer into technical requirements and communicates them through all the phases of the product development. Although this work focused in the first two matrices of the quality function deployment, developing the full QFD process is recommended. This way, other lifecycle stages such as Design for Manufacturing are also included in the design process. Multiattribute utility analysis provides to the QFD a more mathematical sound and, it is the key tool for the proposed framework when estimating the utility seen by the customer.

Logit, which is a model commonly used in business to estimate consumer demands, is implemented to estimate the utility perceived by the producer. The function was integrated in the framework and aligned with the optimal set of design attributes obtained from the QFD. Since the QFD observes a strong relationship with the customer preferences, the utility perceived by the producer is ultimately driven also by customer preferences. This fact shows the importance that customer has over the success of any design option.

A function that depicts the utility perceived by the environment is introduced in this work. The function combines the environmental impact with an impact factor related to the nature of the product. It relies in the use of LCA tools to obtain the environmental

impact score. Eco-indicator 99 was the LCA tool utilized in this work; however, the function is flexible enough to allow that any other LCA methodology could be used, as long as it provides any kind of score that can be incorporated in the function.

A global utility is also introduced. It combines all stakeholders' utilities into one equation. Single utility weight factors let designer contemplate different design tendencies such as environmentally friendly, producer and customer oriented. By integrating the three key stakeholders into one framework allows designing for multiple lifecycle stages such as Design for Quality, Design for manufacture and, Design for Environment.

In overall, this work presents a robust framework that allows:

1. decision makers to select options that are environmentally sound and also aligned with the business objectives
2. estimate products utility for customers, producers, and planet for existing products
3. predict impact on utility caused by design changes
4. assist as a decision making tool in the design process.

7. Future work

The following future work is proposed:

- Standardize the impact factor criteria for the environment's utility function. Define values of I for specific family of products.
- Develop additional consumer product cases;
- Validate the framework with industry data;
- Investigate the feasibility of substituting the optimal attribute set in the producer's utility with single attribute utility functions;
- Investigate the usability of the framework with regenerative products (positive environmental impact balance).

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9. APPENDICES

9.1. APPENDIX I: Assessment of Utility Function

(Excerpt from Thurston et. al., "Multiattribute Design Optimization and Concurrent Engineering", 1993)

Define attributes ranges

The decision maker is asked to define attribute ranges, based on his/her own estimates of the best or upper (u_i) and worst or lower (l_i) values of attribute levels that they anticipate being faced with or offered. The initial response for an attribute such as cost would normally be '0 cost to infinite cost'. This response is refined by asking the decision-maker to temper his or her estimate of the lower limit to that below which they could not tolerate going despite highly desirable levels of the other attributes. The upper limit is tempered to an optimistic yet realistic estimate of performance levels that alternative system potentially offer and that they would be interested in. 'Interest' is defined as the willingness to pay in terms of performance in another attribute in order to achieve the upper limit. For example, plastic automobile parts can offer extremely high levels of corrosion resistance with optimistic estimates as high as fifty years. However, other constraints such as the designed services life of the vehicle (ten to fifteen years) limit the value of a fifty-year corrosion resistance guarantee, so the decision-maker places an upper limit of fifteen years on corrosion resistance. The decision-maker is not 'interested' in improving corrosion resistance to greater than fifteen years; any level of corrosion resistance above fifteen years has equal value in that application. He/she is not willing to 'pay' in terms of any other attribute in order to go from, say, sixteen to fifty years, since both values are outside the range. When attribute levels are greater than the upper limit of the defined range, the 'single attribute utility function '$U_i(x_i)$ for attribute x_i is assigned a value of 1. In a sense, beyond the defined range the attribute us a binary characteristic: below the minimum range the system is unacceptable and above it the decision maker is indifferent to changes.

After the attribute bounds $(u_i\ ,l_i)$ have been determined, the 2n optimization problems described in Section 11.2 are solved to obtain the (possibly) more restrictive bounds (x_{il},x_{iu}) on the attribute levels which reflect the constraint.

Determine single attribute utility functions and scaling constants

Two types of valuations or preferences of the design decision maker must be assessed. One is the imputed worth of varying levels of each attribute in isolation, expressed in the single attribute utility function for each attribute $U_i(x_i)$.The other relates to the trade-off between attributes the designer is willing to make. This information takes the form of the scaling factors a_i, and as discussed in Kirkpatrick et al. (1983), should not be confused with concepts of relative importance of attributes or weighting factors.

Figure 9-1 is an example of the type of 'lottery' question used to determine the scaling constants a_i. The value of a_i is equal to the utility where x_i is at the best level, x_{iu}, and all if the other attributes are at their worst levels; at this point $U(x_{1l}, \ldots, x_{iu}, \ldots, x_{nl})= a_i$. The 'certain alternative' shown on the left in Figure 9-2 represents an alternative with attributes at the levels shown for certain, and the lottery on the right represents an alternative in which there is uncertainty as to the attribute levels of an alternative. The lottery shows a probability p of 60% that weight will be 100lb and cost will be \$10,000, and probability 1-p of 40% that weight will be 400lb and the cost will be \$90,000. When a user responds to the query 'Which do you prefer, the certainty, the lottery, or are you indifferent?' that he or she prefers the certainty, the value of p is increased to a more desirable value which is half-way between the previous level and the last level at which the decision maker preferred the lottery. The value of p at which the decision-maker is indifferent between the 'certain alternative' and the lottery is thus obtained by iteration between extreme values of p. The multiattribute utility of the situation where all the attributes are at their best or most desirable levels x_u is set equal to 1, and where they are at their worst or least desirable levels x_l set equal to 0. The value of ai is then determined by

$$U(x_{1l}, \ldots, x_{iu}, \ldots, x_{nl}) = p\, U(x_u) + (1-p)U(x_l) \tag{9.1}$$

$$U(x_{1l}, \ldots, x_{iu}, \ldots, x_{nl}) = p(1) + (1 - p)(0) \tag{9.2}$$

$$U(x_{1l}, \ldots, x_{iu}, \ldots, x_{nl}) = p \tag{9.3}$$

Where $a_i = p$ since $U(x_{1l}, \ldots, x_{iu}, \ldots, x_{nl})= a_i$. .

For each value of *p* indicated in Column 1, indicate the decision-maker's preference for the certainty or the lottery with an X. Which do you prefer?

p	Certainty	Lottery
0%	X	
10%	X	
20%	X	
30%		
40%		
50%		
60%		
70%		
80%		
90%		
100%		

Check: For which value of p is the decision-maker indifferent between the certainty and the lottery?

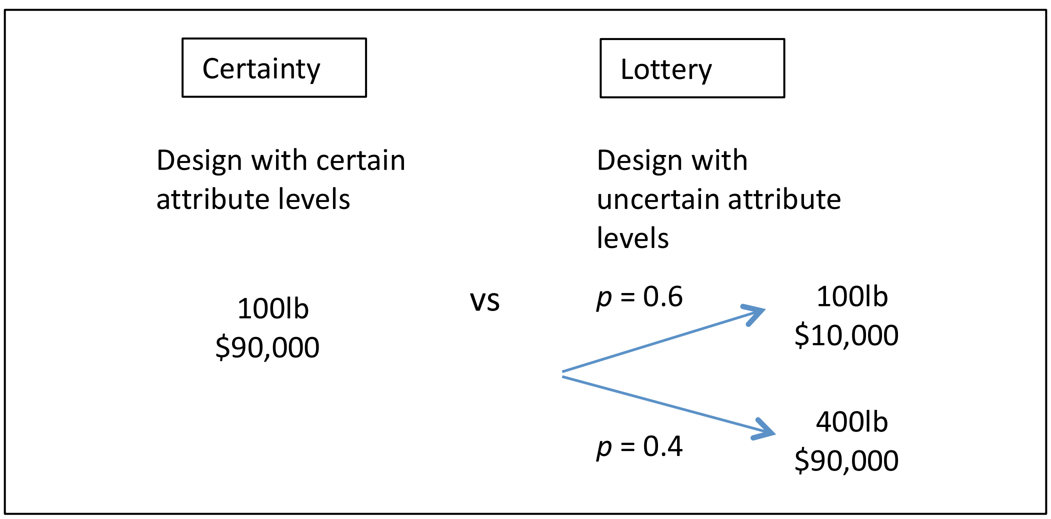

Figure 9-1 Lottery question to assess scaling constant a_i for weight

Points which determine the single attribute utility function for each attribute are assessed using a similar type of lottery question, except only one attribute is considered as shown in Figure 9-2. The designer is asked to imagine that two alternative designs are being considered, each alike in every respect except that 'certain' alternative's performance level for attribute xi is known with certainty to be some value x, while the

lottery alternative represents a design alternative in which there is uncertainty as to the attribute level. The lottery in Figure 9-2 shows a probability p of 60% that weight will be 100lb and probability 1 – p of 40% that weight will be 400lb. When the indifference point is reached, the relative value placed on the certainty equivalent as determined by the following equation is one point on the single attribute utility function.

$$U(x_{1l}, \ldots, x_{iu}, \ldots, x_{nl}) = p\, U_i(x_{iu}) + (1-p)U_i(x_{il}) \quad (9.4)$$

$$U(x_{1l}, \ldots, x_{iu}, \ldots, x_{nl}) = p(1) + (1 - p)(0) \quad (9.5)$$

$$U(x_{1l}, \ldots, x_{iu}, \ldots, x_{nl}) = p \quad (9.6)$$

For each value of w indicated in Column 1, indicate the decision-maker's preference for the certainty or the lottery with an X. Which do you prefer?

w	Certainty	Lottery
100lbs	X	
150lbs	X	
200lbs		
250lbs		
300lbs		X
350lbs		X
400lbs		X

Check: For which value of w is the decision-maker indifferent between the certainty and the lottery?

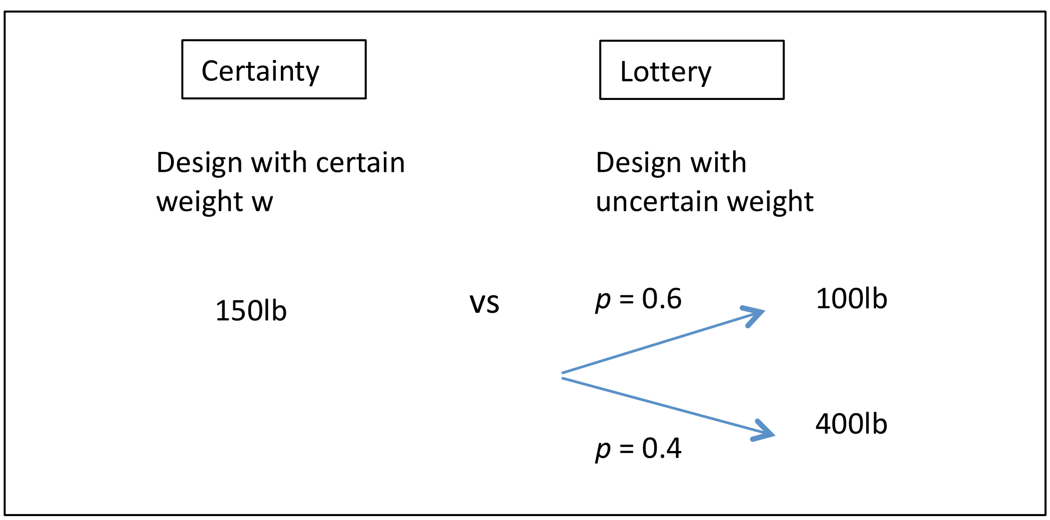

Figure 9-2 Lottery question to assess single attribute utility $U_i(x_i)$ for weight

The ‘certainty equivalent’ method just described to obtain indifference statements from the design decision-maker to determine the single attribute utility functions and scaling constants is discussed in greater detail by Dyer (1990) and Clausing and Pugh (1991). It can be performed by the analyst either manually or with the aid of a computer-based assessment program. When the assessment is performed manually, it is recommended that the analyst quickly sketch the single attribute utility function data points on a grid scald from 0 to 1 during the survey to check for inconsistencies. The shape of the curve reflects the decision maker’s non-linear valuation of changes in attributes levels.

9.2. APENDIX II: Scaled Pair Comparison

(Excerpt from Shillito, M. Larry, "Acquiring, Processing, and Deploying the Voice of Customer", 2001)

Pair Comparison

Description

Pair comparison is a highly discriminatory rating-ranking technique used to set a priority order and a relative magnitude to a number of related items. The method presents items to be judge in all possible pairs and then asks for judgment about each pair. A scale is created as each item is weighted against every other item and a relative zero point results. The list of items will be ranked in order of merit. Pair comparison provides a method of more accurately setting a priority order and relative magnitude of a number of related factors than arbitrary ranking. The process can be used to rate both positive criteria, like importance, quality, reliability, etc., and negative criteria like cost, maintenance, downtime, etc.

Method

1. Generate a list of items to be ranked and establish a framework for the comparisons Prepare a matrix or a graph to accommodate all of the entries being considered. Items to be evaluated are arrayed against themselves in a triangular matrix

Technique 2 – Scaled Pair Comparison

1. Design a set of preference weightings to reflect different degrees of importance.
2. Compare items in pairs until each item is compared with all other items. In each comparison, the rater must decide which of the two items is more important. The appropriate letter signifying the more important items is recorded in the cell representing the intersection of the two items. In addition, a numerical weight chosen from the rating scale is also entered along with the letter. See Table 9-1.
3. Total the numerical score for each concern. The item with the highest total score represents the concern with the overall greatest importance.

To express each component as a percentage of importance of all of the items, sum the total for each component row and divide this sum into each individual component score. An average value of component importance for a group of raters is obtained by averaging the value of all of the individual components ratings.

In Table 9-1, a zero occurs from item "B". Many times people and computers have difficulty working with zero. This can easily be eliminated by adding 1 to each row total score for each item and summing the new totals. Likewise, a new percentage importance is calculated based on these new totals. This conversion could also have been used in Table 9-1

Usage

1. The process is useful in those applications where a high degree of subjectivity is present but where a need for one-to-one pair-wise comparison is essential.
2. It is useful for prioritizing items that are extremely close in importance and therefore difficult to separate and rank.
3. A zero score should not be included in the rating scale. It makes it too easy to avoid making a decision and cheat to get the process finished faster.

Table 9-1 Scaled pair comparison

B	C	D
A 3	A 3	A 3
	C 3	D 2
		C 1

	Total Row Rating	Converted Ratings	Rating %
A	9	10	53
B	0	1	5
C	4	5	26
D	2	3	16
Total=		19	100

A	Camara is easy to load
B	Can be artistic with my camara
C	Camara is durable
D	Can tell all adjustments are correct

Criteria
1- Slightly more important
2- Reasonably more important
3- Much more important

9.3. APENDIX III: Case Study Input and Results

Lingo input file for Solar Lamp

```
MODEL:

[Customer_Utility_Solar_Lamp]

max = (1/k) * ((k*a1*(6.36E-04*x1^2 + 3.18E-02*x1 - 3.84E-02)+1) * (k*a2*(-2.67E-05*x2^2
+ 1.22E-02*x2 + 3.17E-02)+1) * (k*a3*(1.79E-07*x3^2 + 1.42E-04*x3 - 8.31E-03)+1) *
(k*a4*(-2.11E-03*x4^2 - 7.04E-03*x4 + 9.94E-01)+1) * (k*a5*(8.83E-05*x5^2 - 2.32E-02*x5 +
1.08E+00)+1) * (k*a6*(-8.52E-03*x6^2 - 1.16E-01*x6 + 1.04E+00)+1) - 1);

x1 = 1.5+(22-1.5)/62  * (3*y1 + 3*y2 + 1*y3 + 9*y4 + 1*y5 + 0*y6 + 0*y7 + 3*y8 + 1*y9 +
9*y10 + 3*y11 + 0*y12 + 0*y13 + 0*y14 + 0*y15 + 9*y16 - 3*y1*y9 - 3*y2*y3 + 3*y2*y10 -
3*y3*y10 - 3*y5*y15 + 3*y6*y7- 3*y6*y9 + 3*y6*y12 - 3*y6*y13 + 3*y7*y12 + 3*y8*y11 +
3*y9*y12 + 3*y9*y14 + 3*y9*y15 + 3*y11*y14 + 3*y11*y16);


x2 = 100/72 * (0*y1 + 0*y2 + 0*y3 + 0*y4 + 0*y5 + 0*y6 + 9*y7 + 0*y8 + 0*y9 + 0*y10 +
9*y11 + 9*y12 + 9*y13 + 9*y14 + 3*y15 + 0*y16 - 3*y1*y9 - 3*y2*y3 + 3*y2*y10 - 3*y3*y10 -
3*y5*y15 + 3*y6*y7- 3*y6*y9 + 3*y6*y12 - 3*y6*y13 + 3*y7*y12 + 3*y8*y11 + 3*y9*y12 +
3*y9*y14 + 3*y9*y15 + 3*y11*y14 + 3*y11*y16);


x3 = 50+(2000-50)/78  * (0*y1 + 3*y2 + 1*y3 + 3*y4 + 0*y5 + 0*y6 + 0*y7 + 9*y8 + 9*y9 +
9*y10 + 9*y11 + 0*y12 + 0*y13 + 0*y14 + 0*y15 + 9*y16 - 3*y1*y9 - 3*y2*y3 + 3*y2*y10 -
3*y3*y10 - 3*y5*y15 + 3*y6*y7- 3*y6*y9 + 3*y6*y12 - 3*y6*y13 + 3*y7*y12 + 3*y8*y11 +
3*y9*y12 + 3*y9*y14 + 3*y9*y15 + 3*y11*y14 + 3*y11*y16);


x4 = 20/38 * (3*y1 + 3*y2 + 1*y3 + 0*y4 + 9*y5 + 0*y6 + 0*y7 + 0*y8 + 0*y9 + 0*y10 +
0*y11 + 0*y12 + 0*y13 + 0*y14 + 1*y15 + 1*y16 - 3*y1*y9 - 3*y2*y3 + 3*y2*y10 - 3*y3*y10 -
3*y5*y15 + 3*y6*y7- 3*y6*y9 + 3*y6*y12 - 3*y6*y13 + 3*y7*y12 + 3*y8*y11 + 3*y9*y12 +
3*y9*y14 + 3*y9*y15 + 3*y11*y14 + 3*y11*y16);


x5 = 5+(60-5)/109 * (3*y1 + 3*y2 + 1*y3 + 1*y4 + 3*y5 + 9*y6 + 9*y7 + 3*y8 + 9*y9 + 3*y10
+ 9*y11 + 9*y12 + 9*y13 + 9*y14 + 9*y15 + 3*y16 - 3*y1*y9 - 3*y2*y3 + 3*y2*y10 - 3*y3*y10
- 3*y5*y15 + 3*y6*y7- 3*y6*y9 + 3*y6*y12 - 3*y6*y13 + 3*y7*y12 + 3*y8*y11 + 3*y9*y12 +
3*y9*y14 + 3*y9*y15 + 3*y11*y14 + 3*y11*y16);


x6 = .4+(6-.4)/99 * (0*y1 + 0*y2 + 0*y3 + 0*y4 + 0*y5 + 9*y6 + 9*y7 + 0*y8 + 3*y9 + 0*y10
+ 9*y11 + 9*y12 + 9*y13 + 9*y14 + 9*y15 + 9*y16 - 3*y1*y9 - 3*y2*y3 + 3*y2*y10 - 3*y3*y10
- 3*y5*y15 + 3*y6*y7- 3*y6*y9 + 3*y6*y12 - 3*y6*y13 + 3*y7*y12 + 3*y8*y11 + 3*y9*y12 +
3*y9*y14 + 3*y9*y15 + 3*y11*y14 + 3*y11*y16);

y1 >= 0;
y1 <= 1;
y2 >= 0;
y2 <= 1;
y3 >= 0;
y3 <= 1;
y4 >= 0;
y4 <= 1;
y5 >= 0;
y5 <= 1;
y6 >= 0;
y6 <= 1;
y7 >= 0;
y7 <= 1;
y8 >= 0;
y8 <= 1;
y9 >= 0;
y9 <= 1;
```

```
y10 >= 0;
y10 <= 1;
y11 >= 0;
y11 <= 1;
y12 >= 0;
y12 <= 1;
y13 >= 0;
y13 <= 1;
y14 >= 0;
y14 <= 1;
y15 >= 0;
y15 <= 1;
y16 >= 0;
y16 <= 1;


x1 >= 1.5;
x1 <= 22;
x2 >= 0;
x2 <= 100;
x3 >= 50;
x3 <= 2000;
x4  = 0;

x5 >= 5;
x5 <= 60;
x6 >= .4;
x6 <= 6;

DATA:

a1 = .25;
a2 = .50;
a3 = .3;
a4 = .35;
a5 = .45;
a6 = .4;

k = -0.988265;

ENDDATA

END
```

Lingo input for Low Voltage Lamp

```
MODEL:


[Utility_Low_Volt_Lamp]        max = (1/k) *((k*a1*(6.36E-04*x1^2 + 3.18E-02*x1 - 3.84E-
02)+1) * (k*a2*(-2.67E-05*x2^2 + 1.22E-02*x2 + 3.17E-02)+1)
                             * (k*a3*(1.79E-07*x3^2 + 1.42E-04*x3 - 8.31E-03)+1) *
(k*a4*(-2.11E-03*x4^2 - 7.04E-03*x4 + 9.94E-01)+1)
                             * (k*a5*(8.83E-05*x5^2 - 2.32E-02*x5 + 1.08E+00)+1) *
(k*a6*(-8.52E-03*x6^2 - 1.16E-01*x6 + 1.04E+00)+1) - 1);



x1 = 1.5+(22-1.5)/70  * (9*y1 + 9*y2 + 9*y3 + 9*y4 + 3*y5 + 0*y6 + 0*y7 + 3*y8 + 3*y9 +
9*y10 + 3*y11 + 0*y12 + 0*y13 + 0*y14 + 1*y15
                      + 3*y1*y9 - 3*y2*y3 + 3*y2*y10 - 3*y3*y9 - 3*y3*y10 + 3*y5*y9 -
3*y5*y10 + 3*y6*y7 + 3*y6*y12 + 3*y7*y12 + 3*y8*y11
                      + 3*y8*y15 - 3*y9*y10 + 3*y11*y15 );

x2 = 100/69          * (0*y1 + 0*y2 + 0*y3 + 0*y4 + 0*y5 + 0*y6 + 9*y7 + 0*y8 + 0*y9 +
0*y10 + 9*y11 + 9*y12 + 9*y13 + 9*y14 + 0*y15
                      + 3*y1*y9 - 3*y2*y3 + 3*y2*y10 - 3*y3*y9 - 3*y3*y10 + 3*y5*y9 -
3*y5*y10 + 3*y6*y7 + 3*y6*y12 + 3*y7*y12 + 3*y8*y11
                      + 3*y8*y15 - 3*y9*y10 + 3*y11*y15 );

x3 = 50+(2000-50)/75  * (0*y1 + 9*y2 + 1*y3 + 3*y4 + 3*y5 + 0*y6 + 0*y7 + 9*y8 + 3*y9 +
9*y10 + 9*y11 + 0*y12 + 0*y13 + 0*y14 + 9*y15
                      + 3*y1*y9 - 3*y2*y3 + 3*y2*y10 - 3*y3*y9 - 3*y3*y10 + 3*y5*y9 -
3*y5*y10 + 3*y6*y7 + 3*y6*y12 + 3*y7*y12 + 3*y8*y11
                      + 3*y8*y15 - 3*y9*y10 + 3*y11*y15 );

x4 = 20/54           * (9*y1 + 9*y2 + 9*y3 + 0*y4 + 3*y5 + 0*y6 + 0*y7 + 0*y8 + 3*y9 +
9*y10 + 0*y11 + 0*y12 + 0*y13 + 0*y14 + 0*y15
                      + 3*y1*y9 - 3*y2*y3 + 3*y2*y10 - 3*y3*y9 - 3*y3*y10 + 3*y5*y9 -
3*y5*y10 + 3*y6*y7 + 3*y6*y12 + 3*y7*y12 + 3*y8*y11
                      + 3*y8*y15 - 3*y9*y10 + 3*y11*y15 );

x5 = 5+(60-5)/88      * (3*y1 + 3*y2 + 1*y3 + 1*y4 + 0*y5 + 3*y6 + 9*y7 + 3*y8 + 3*y9 +
3*y10 + 9*y11 + 9*y12 + 9*y13 + 9*y14 + 3*y15
                      + 3*y1*y9 - 3*y2*y3 + 3*y2*y10 - 3*y3*y9 - 3*y3*y10 + 3*y5*y9 -
3*y5*y10 + 3*y6*y7 + 3*y6*y12 + 3*y7*y12 + 3*y8*y11
                      + 3*y8*y15 - 3*y9*y10 + 3*y11*y15 );

x6 = .4+(6-.4)/87     * (0*y1 + 0*y2 + 0*y3 + 0*y4 + 0*y5 + 0*y6 + 9*y7 + 0*y8 + 9*y9 +
0*y10 + 9*y11 + 9*y12 + 9*y13 + 9*y14 + 9*y15
                      + 3*y1*y9 - 3*y2*y3 + 3*y2*y10 - 3*y3*y9 - 3*y3*y10 + 3*y5*y9 -
3*y5*y10 + 3*y6*y7 + 3*y6*y12 + 3*y7*y12 + 3*y8*y11
                      + 3*y8*y15 - 3*y9*y10 + 3*y11*y15 );

y1 >= 0;
y1 <= 1;
y2 >= 0;
y2 <= 1;
y3 >= 0;
y3 <= 1;
y4 >= 0;
y4 <= 1;
y5 >= 0;
y5 <= 1;
y6 >= 0;
y6 <= 1;
y7 >= 0;
y7 <= 1;
y8 >= 0;
y8 <= 1;
Y9 >= 0;
```

```
Y9 <= 1;
Y10>= 0;
Y10<= 1;
Y11>= 0;
Y11<= 1;
y12 >= 0;
y12 <= 1;
Y13 >= 0;
Y13 <= 1;
Y14>= 0;
Y14<= 1;
Y15>= 0;
Y15<= 1;

x1 >= 1.5;
x1 <= 22;
x2 >= 0;
x2 <= 100;
x3 >= 50;
x3 <= 2000;
x4 >= 0;
x4 <= 20;
x5 >= 5;
x5 <= 60;
x6 >= .4;
x6 <= 6;

DATA:

a1 = .25;
a2 = .50;
a3 = .3;
a4 = .35;
a5 = .45;
a6 = .4;
k  = -0.988265;

ENDDATA

END
```

Lingo solution for Solar Lamp

```
Local optimal solution found.
  Objective value:                              0.7967561
  Infeasibilities:                              0.000000
  Total solver iterations:                            64

  Model Class:                                       NLP

  Total variables:                     21
  Nonlinear variables:                 20
  Integer variables:                    0

  Total constraints:                   49
  Nonlinear constraints:                7

  Total nonzeros:                     145
  Nonlinear nonzeros:                  95

                                Variable           Value        Reduced Cost
                                       K      -0.9882650            0.000000
                                      A1       0.2500000            0.000000
                                      X1        8.443548            0.000000
                                      A2       0.5000000            0.000000
                                      X2        0.000000            0.000000
                                      A3       0.3000000            0.000000
                                      X3        575.0000            0.000000
                                      A4       0.3500000            0.000000
                                      X4        0.000000            0.000000
                                      A5       0.4500000            0.000000
                                      X5        8.532110            0.000000
                                      A6       0.4000000            0.000000
                                      X6       0.4000000            0.000000
                                      Y1        0.000000            0.000000
                                      Y2        0.000000        0.2055255E-02
                                      Y3        0.000000            0.000000
                                      Y4        1.000000            0.000000
                                      Y5        0.000000        0.8168462E-02
                                      Y6        0.000000            0.000000
                                      Y7        0.000000            0.000000
                                      Y8        1.000000            0.000000
                                      Y9        0.000000            0.000000
                                     Y10        1.000000            0.000000
                                     Y11        0.000000            0.000000
                                     Y12        0.000000        0.7861321E-02
                                     Y13        0.000000            0.000000
                                     Y14        0.000000            0.000000
                                     Y15        0.000000        0.1925980E-01
                                     Y16        0.000000            0.000000

                                     Row    Slack or Surplus      Dual Price
             CUSTOMER_UTILITY_SOLAR_LAMP       0.7967561            1.000000
                                       2        0.000000        0.2426047E-02
                                       3        0.000000        0.1317459E-02
                                       4        0.000000        0.2309254E-04
                                       5        0.000000       -0.7973437E-03
                                       6        0.000000       -0.3431011E-02
                                       7        0.000000       -0.1718428E-01
                                       8        0.000000       -0.4046213E-02
                                       9        1.000000            0.000000
                                      10        0.000000            0.000000
                                      11        1.000000            0.000000
                                      12        0.000000       -0.1030443E-02
                                      13        1.000000            0.000000
                                      14        1.000000            0.000000
                                      15        0.000000        0.7220143E-02
                                      16        0.000000            0.000000
```

17	1.000000	0.000000
18	0.000000	-0.2432956E-01
19	1.000000	0.000000
20	0.000000	-0.7861321E-02
21	1.000000	0.000000
22	1.000000	0.000000
23	0.000000	0.2408571E-02
24	0.000000	-0.1249934E-01
25	1.000000	0.000000
26	1.000000	0.000000
27	0.000000	0.7221536E-02
28	0.000000	0.000000
29	1.000000	0.000000
30	0.000000	0.000000
31	1.000000	0.000000
32	0.000000	-0.7861321E-02
33	1.000000	0.000000
34	0.000000	-0.7861321E-02
35	1.000000	0.000000
36	0.000000	0.000000
37	1.000000	0.000000
38	0.000000	-0.1946482E-02
39	1.000000	0.000000
40	6.943548	0.000000
41	13.55645	0.000000
42	0.000000	0.000000
43	100.0000	0.000000
44	525.0000	0.000000
45	1425.000	0.000000
46	0.000000	-0.1015696E-05
47	3.532110	0.000000
48	51.46789	0.000000
49	0.000000	0.000000
50	5.600000	0.000000

Lingo solution for Low Voltage Lamp

```
Local optimal solution found.
  Objective value:                              0.7557288
  Infeasibilities:                              0.000000
  Total solver iterations:                            61

  Model Class:                                       NLP

  Total variables:                    21
  Nonlinear variables:                18
  Integer variables:                   0

  Total constraints:                  49
  Nonlinear constraints:               7

  Total nonzeros:                    135
  Nonlinear nonzeros:                 78
```

Variable	Value	Reduced Cost
K	-0.9882650	0.000000
A1	0.2500000	0.000000
X1	10.93235	0.000000
A2	0.5000000	0.000000
X2	0.000000	0.000000
A3	0.3000000	0.000000
X3	594.0524	0.000000
A4	0.3500000	0.000000
X4	8.092401	0.000000
A5	0.4500000	0.000000
X5	12.55784	0.000000
A6	0.4000000	0.000000
X6	0.9793103	0.000000
Y1	0.000000	0.000000
Y2	1.000000	0.000000
Y3	1.000000	0.000000
Y4	1.000000	0.000000
Y5	0.2006207	0.000000
Y6	0.1823853	0.7078916E-02
Y7	0.1823853	0.000000
Y8	0.1817944	-0.2250184E-02
Y9	1.000000	0.000000
Y10	1.000000	0.000000
Y11	0.2710510	-0.9272927E-02
Y12	0.000000	0.000000
Y13	0.000000	0.000000
Y14	0.5190504	0.000000
Y15	0.000000	0.000000

Row	Slack or Surplus	Dual Price
UTILITY_LOW_VOLT_LAMP	0.7557288	1.000000
2	0.000000	0.000000
3	0.000000	0.000000
4	0.000000	0.000000
5	0.000000	0.000000
6	0.000000	0.000000
7	0.000000	0.000000
8	0.000000	0.000000
9	1.000000	0.000000
10	1.000000	0.000000
11	0.000000	0.000000
12	1.000000	0.000000
13	0.000000	0.000000
14	1.000000	0.000000
15	0.000000	0.000000
16	0.2006207	0.000000
17	0.7993793	0.000000

18	0.1823853	0.000000
19	0.8176147	0.000000
20	0.1823853	0.000000
21	0.8176147	0.000000
22	0.1817944	0.000000
23	0.8182056	0.000000
24	1.000000	0.000000
25	0.000000	0.000000
26	1.000000	0.000000
27	0.000000	0.000000
28	0.2710510	0.000000
29	0.7289490	0.000000
30	0.000000	0.000000
31	1.000000	0.000000
32	0.000000	0.000000
33	1.000000	0.000000
34	0.5190504	0.000000
35	0.4809496	0.000000
36	0.000000	0.000000
37	1.000000	0.000000
38	9.432348	0.000000
39	11.06765	0.000000
40	0.000000	0.000000
41	100.0000	0.000000
42	544.0524	0.000000
43	1405.948	0.000000
44	8.092401	0.000000
45	11.90760	0.000000
46	7.557837	0.000000
47	47.44216	0.000000
48	0.5793103	0.000000
49	5.020690	0.000000