Product Descriptors for Early Product Development: An Interface between Environmental Experts and Designers

by

Julie L. Eisenhard

Bachelor of Mechanical Engineering
Georgia Institute of Technology, 1998

Submitted to the Department of Mechanical Engineering in
Partial Fulfillment of the Requirements for the Degree of

Master of Science in Mechanical Engineering

at the
Massachusetts Institute of Technology
June 2000

©2000 Massachusetts Institute of Technology
All rights reserved

Signature of Author ....
Department of Mechanical Engineering
May 5, 2000

Certified by ....
David R. Wallace
Ester and Harold Edgerton Associate Professor of Mechanical Engineering
Thesis Supervisor

Accepted by ....
Ain A. Sonin
Chairman, Departmental Committee on Graduate Students

MASSACHUSETTS INSTITUTE
OF TECHNOLOGY
SEP 2 0 2000
LIBRARIES

ENG

Product Descriptors for Early Product Development: An Interface between Environmental Experts and Designers

by

Julie L. Eisenhard

Submitted to the Department of Mechanical Engineering
on May 5, 2000 in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Mechanical Engineering

Abstract

Sustainable development is not just about technological innovation, but rather about a radical shift in the way society thinks. The environmental effects of our choices and behavior must be internalized. In the context of product development, this internalization should occur in early product development under the guidance of an environmental expert.

During early product design phases there may be numerous concepts with significant differences, detailed information is scarce, and decisions must be made quickly. The overhead in developing parametric life-cycle assessment (LCA) models for a diverse range of concepts, and the lack of detailed information make the integration of environmental expertise through traditional LCA models impractical. Therefore, a new approach was developed to incorporate analytically based environmental assessment in early design stages.

Product descriptors are the communication interface between environmental experts and designers for this new model, called a learning surrogate LCA. Product descriptors are a set of keywords both understood by designers in relation to a preliminary product, and meaningful in an approximate environmental impact assessment of a product. This thesis develops a set of product concept descriptors for use in environmental assessment.

The chosen descriptor set was measurable by designers in conceptual design, and produced reasonable results when used to predict environmental impacts using an approximate model. Tests within the DOME integrated modeling environment have shown it is possible to predict the life-cycle energy consumption of a product. There is also a basis for the method to be used in predicting solid material, greenhouse effect, ozone layer depletion, acidification, eutrophication, winter smog, and summer smog.

Thesis Supervisor: David R. Wallace
Title: Ester and Harold Edgerton Associate Professor of Mechanical Engineering

Acknowledgements

There are many people I'd like to thank for contributing to this work, providing motivation for me to begin this work, or both. First, I sincerely thank the designers who took time out of their busy workdays to complete the survey: Allan Budris, Konrad Chan, Mike Elter, Nicolas Ganzon, Rachel Happe, Karl Hauenstein, Jared Judson, Darrell Kleinke, Richard Moberg, Jon Rossman, Kevin Ryczek, Ronald Scholl, Willaim Starks, Robert Stephens, Rich White, and Ted Wright. As well, I'd like to thank Renee Olson and Kikki Baumann for allowing me to bother them much more than once.

I thank the Alliance for Global Sustainability for providing funding for this work; it has been quite an experience for me—one that has opened up my eyes and mind. I thank David Wallace, my advisor, for having confidence in me to do this work, for offering just the right amounts of structure and flexibility—research support with allowance to go where the research takes me, and for his thorough editing capabilities. I am especially grateful to Inês Sousa for her mentorship, without which this research would never have gotten as far as it did. I also thank the rest of the CADLab crew for their many personalities: Johnny Chang, Juan Deniz, Ed Ferara, Maria Kamvysellis, Jaehyun Kim, Bill Liteplo, Jeff Lyons, Shaun Meredith, Stephen Smyth, and Priscilla Wang.

Thanks to Kevin Davis, my close and best friend, for supplying me with chocolate and his words of wisdom to get me through the last physical writing of this thesis. Finally, I'd like to thank members of my family, especially my mother and grandfather, for providing support and motivation without even knowing it.

Table of Contents

List of Figures

List of Tables

List of Acronyms and Symbols

ANN	Artificial Neural Network
Br	Bromine
CADLab	Computer-Aided Design Laboratory
Cd	Cadmium
CFC	Chlorofluorocarbons
CH_4	Methane
Cl	Chlorine
CO_2	Carbon Dioxide
COD	Chemical Oxygen Demand
Cr	Chromium
C_xH_y	Hydrocarbons
DfS	Design for Sustainability
DOME	Distributed Object-based Modeling Environment
EIME	Environmental Information and Management Explorer
FAL	Franklin Associates, Ltd.
Fl	Flourine
H_2O	Water
Hg	Mercury
ICV	Internal Combustion Vehicle
LCA	Life-Cycle Assessment
LCI	Life-Cycle Inventory
MIT	Massachusetts Institute of Technology
N/A	Not Applicable
N_2	Nitrogen
Ni	Nickel
NH_3	Ammonia
NO_x	Nitrous Oxides
N_{tot}	Total Nitrogen
PAH	Polycyclic Aromatic Hydrocarbon
Pb	Lead
PE	Polyethylene
PP	Polypropylene
RTI	Research Triangle Institute
SETAC	Society of Environmental Toxicology and Chemistry
SO_2	Sulfur Dioxide
SO_x	Sulfur Oxides
SPM	Solid Particle Material
TEAM	Tools for Environmental Analysis and Management
UNEP	United Nations Environmental Program
US	United States

1 Motivation

Un-sustainability is unintended; Industry intentions of 'going green' are on the whole undoubtedly good, but is real progress being made? John Ehrenfield (1998) suggests "few, if any, of the many new practices being touted as green or eco-efficient or some other manifestation of sustainability are in fact sustainable." He makes this point not because the corporate world isn't trying, but because he feels no one can truly make a difference until we realize within ourselves what sustainability is.

Indeed, there are many definitions of sustainability. Ehrenfeld (1998) merges many definitions and adds a deeper moral meaning to the word:

> Sustainability is a possible way of living or being in which individuals, firms, governments, and other institutions act responsibly in taking care of the future as if it belonged to them today, in equitably sharing the ecological resources on which the survival of the human and other species depends, and in assuring that all who live today and in the future will be able to satisfy their needs and human aspirations.

True sustainability results are not just about technological innovation, but about a radical shift in the way society thinks. The environmental effects of choices must be internalized. This is not an immediate act, but an ongoing growth in morality and a coordinated education process involving mentor, training method, and tyro.

This research presents an education process in a product development setting. The environmental expert takes the role of the mentor by means of a *learning surrogate life-cycle assessment model* and the traditional product designer plays the environmental novice. Just as traditional education does not mold all students to become a teacher, the product designer is not being molded into an environmental expert, he/she is simply learning about how design changes can affect the Environment in a holistic sense. The thesis mainly focuses on the method of education, and in particular presents new work on one of the interfaces between teacher and student, the *product descriptors*.

2 Introduction

The push for sustainable development has changed the way companies develop products. Traditional product designers are being asked to judge the environmental impact of the products they are developing. Not only is this an additional task for the designer, but it also is not necessarily something they are qualified to do. There is a need for design tools that support a team-oriented, distributed, multidisciplinary design process, and assist designers in balancing complex performance tradeoffs.

Work by Borland and Wallace (1999) included the modeling of a product's environmental performance in this type of integrated design setting. The approach formed a seamless link of parametric design models for integrated tradeoff analysis. However, it could not directly be applied to a similar setting in conceptual design where data are scarce and the pace is swift. This is unfortunate because early phases of the design process are widely believed to be the most influential and are the key to properly addressing the environmental impacts of products (Bhamra 1999).

Traditional life-cycle assessment (LCA), the environmental impact evaluation tool used previously (Borland and Wallace 1999), does not lend itself well to the conceptual phase. Traditional LCA is too data intensive, and hence too slow for this early phase. Also, a design change made at this stage of the process is usually much more than a minor refinement (Ulrich and Eppinger 1995); each change would require a new LCA model.

This thesis describes work and testing done in developing an environmental assessment tool for use in integrated conceptual design called a learning surrogate LCA. The tool facilitates an integrated systems approach to the design process, assesses environmental impact based only on information known in the conceptual phase, and supports complex design changes. The heart of the tool is an artificial neural network (ANN), which trains on product attributes and environmental impact data from pre-existing life-cycle assessment studies. The product design team queries the trained artificial model with new high-level product attribute data to quickly obtain an approximate environmental impact assessment for a new product concept. The designer can then use the calculated environmental performance, along with key performance measures from other models, in tradeoff analysis and concept selection.

There are four main parts to this thesis. First addressed is the context of the tool—the environment, in which the tool is used and the methodology, on which it is based. The surrogate model itself is then described on a high-level, introducing its main components—input, output, data structure, and neural net. The next sections detail these elements and describe the evolution of their development. Finally, discussion closes by merging the four parts into a whole and testing overall performance with respect to product descriptor input, the main focus of this thesis.

3 Background

The selection of product descriptors, the main focus of this paper, is only one part of a larger project—the learning surrogate LCA model. This background section will provide context for the overall surrogate tool by describing the product development environment, in which the tool will be used, and describing the LCA methodology, on which the tool is based. Some time is spent presenting the difficulties of traditional LCA processes, which directly lead to the development of the surrogate LCA tool.

3.1 Traditional Product Development

Product design or product development is the process of mapping customer, corporate and governmental requirements into a product that can be produced and marketed (Ulrich and Eppinger 1995). The process is interdisciplinary, time consuming, and involves many tradeoffs. Product design includes every technical aspect of the product, from the purchasing of components to manufacturing, assembly, service, and obsolescence. A successful product not only performs well for the company through high profit, low investment time, and improved future capability, but it also must be valued by the customer and follow government regulations.

3.1.1 The Development Process

Ulrich and Eppinger (1995) define five stages of product development for an *engineered*, *discrete*, *physical* product[1]: concept development, system-level design, detail design, testing and refinement, and production ramp-up. The process begins with a mission statement and ends with product launch. It should be noted that the end of the development process might change in the future with the inclusion of another stage—product take-back—as governments worldwide contemplate mandatory product take-back laws (Environmental Defense 1999). However, such an inclusion, although it will

---

[1] Engineered implies a product whose functional worth is at least semi-complex. Discrete products are individually distinct, rather than goods made in bulk, such as chemicals. A physical product is that which the buyer owns and can physically touch, unlike a service or software.

likely influence a company's value structure, would not alter the key activities within the previous five stages.

There are eight key activities during concept development. These activities are illustrated in Figure 1 (Ulrich and Eppinger 1995). Fundamentally important to the concept development process is that a great many decisions have been made by the end of the phase—everything from deciding the targeted market to selecting the most-likely-to-succeed concept for further development. A concept is described in terms of its form, function, and features. The concept that continues beyond this phase will also carry with it a set of specifications, an analysis of competitive products, and an economic justification of the project.

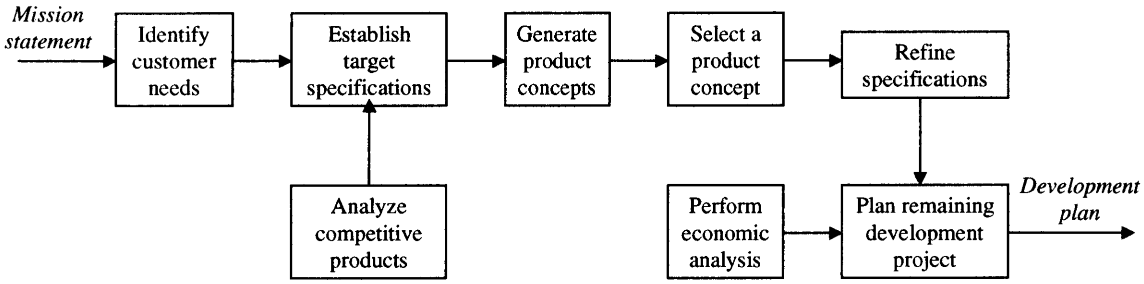


Figure 1: The Concept Development Phase.

System-level design mainly consists of definition of the product architecture. Product architecture is the division of a product into its basic physical building blocks in terms of what they do and how they interface with other functional elements. Defining the product architecture allows further development to be carried out on different portions of the product concurrently. Accompanying the product subdivision, a preliminary final assembly diagram is specified.

Detail design includes all activities in preparing the product for prototype testing. Key tasks are: complete specification of the geometry, materials, and tolerances of all new parts, identification of standard parts to be purchased from suppliers, establishing a process plan, and designing any needed tooling for new part production. The results of these key tasks are compiled in a product *control document*.

The testing and refinement phase builds and assesses several product prototypes. Prototypes are built with the same geometry and material properties as the actual product, but not with the intended production system. This allows the design team to evaluate product performance and reliability and tweak the product before production. Prototype evaluation mainly occurs internally, and then extends to tests with customers in their use environment.

The goal of production ramp-up is to iron out and bugs in the intended production system before full-scale production and product launch. During this time the work force is also trained on the final production and assembly processes. Only when the team feels all flaws have been addressed and settled is the product launched and distributed to market.

3.1.2 The Power of Non-Consensus

One of the key things to notice about the design process is that it is a process of forming a positive collective opinion among all stakeholders with regard to the product. Design occurs within or at the request of a single firm, whose goal is to make as many people's lives better as possible in order to yield a larger target market and more sales. Team members generally abide by firm values during the design process. However, the firm and the team know that they must also value outside opinions—those of consumers, regulators, and other stakeholders—to design a successful product.

The development process merges the opinions of all interested parties—achieves consensus—to form the final product. Failure to reach consensus results maximally may result in a sub-optimal product that sells, but leaves the door open for better competition. Failure to have approval of consumers results in low sales. Failure to have approval of regulators results in expensive mitigation or perhaps even a product that will never reach market. This is the power of non-consensus.

Reaching consensus also has power in its own right, in addition to a successful product. Shielding a particular stakeholder, or party, from non-objective decisions does not imply consensus. On the other hand, it may lead directly to wasted effort. If all parties are included in all decisions and there is consensus for each decision individually, the final product is much more likely to be a success. Furthermore, minimally the final product will not make a particular party entirely happy; however, the act of yielding consensus throughout the process waives the right to demand the process begin again. This is the power of consensus. This idea will become clearer in section 3.2.2—during a life-cycle assessment, it is important not only to include, but also to inform and mediate with all involved parties.

Consensus is recognized as a high priority in product development. With this in mind, an important effort should be made to include the Environment as an interested stakeholder in the minds of designers, just as important as the consumer or regulator. It is the theory of some (Susskind 2000) that environmental inclusion is an easier task for European designers versus American designers. Europe is more densely populated than the United States in most areas, so environmental impacts, such as loss of green space to landfill, may be felt more strongly there. Also, countries such as the Netherlands, who seem to be leading the way in widespread environmental initiatives, are also at low levels of elevation, suggesting a strong motivation to avoid global warming (to be discussed in section 4.3.1.3). However, no matter the country, the effort of inclusion should occur in the conceptual phase of design, as this is where stakeholder requirements are analyzed.

3.1.3 The Importance of the Conceptual Phase of Design

There are many reasons for including environmental considerations in the conceptual phase. To give the Environment a chance to shape collective opinion about the product is only one of them. The conceptual phase of product design is the most influential of all phases. It is during this phase when all the various stakeholder requirements evolve from an equal playing field to varying degrees of importance. It therefore becomes important to have the Environment represented as a stakeholder during this phase as well as to have an appropriate expert representing this view. If the

Environment is appropriately included, environmental requirements can then be used in a test for concept feasibility along with other requirements, such as performance specifics and price. This means the design team must be able to evaluate the approximate environmental performance of a wide range of solution concepts early in the design process.

Decisions that emerge from the conceptual phase are also most likely never to be changed to any significant degree. This resolved decisiveness is due to the large amount of resources—time, manpower, and money—needed to start over or make a change once a certain path has been chosen and ship deadlines are approaching. It is essential to include the Environment early to prevent environmental mistakes, which may not be corrected or mitigated later, from occurring in the first place. There are many good things that can come out environmental assessment in conceptual design. However, there are also several limiting factors to the phase as well.

Time is probably the least plentiful resource for the development cycle as a whole (Ulrich and Eppinger 1995). It can mean the difference between a product and a successful product by beating competition to the shelf. Therefore, time saving support tools are crucial throughout the product development process. In conceptual design, though, lack of information is as much a problem as lack of time. Without information no type of cost, environmental, or other functional performance evaluation can even begin.

Traditional product designers are not necessarily qualified to assess environmental information. Yet, government stakeholder importance seems to be slowly increasing as firms try to design for current and even future regulations and designers are being asked to judge the environmental impact of the products they are developing. In response, many different methods have been developed in attempting to internalize environmental concerns into the product development process.

3.2 Traditional Life-Cycle Assessment

Traditional Life-Cycle Assessment (LCA) is one of the more popular methodologies. It is "one of the most recognized and internationally accepted methods for examining environmental performance" (Consoli *et al.* 1993). This section describes the traditional LCA concept, its guiding principles and some of its weaknesses.

3.2.1 Goals and Applications

The application of LCA considers all the environmental detriments associated with a product's lifetime, from "cradle-to-grave". This approach envelops all activities related to the product including everything from raw material extraction, to production, to use, through disposal. Although these activities together may tell the full story of a product, it should be recognized that LCA simply represents the true physical system; it cannot claim to be unconditionally complete.

LCA can claim at least to portray as complete a picture as possible and more importantly, to be influential in changing the human thought process. It is an educational tool to begin training people to internalize the environmental consequences of the choices they make. In addition, the systematic steps for applying LCA frame an open, constructive discussion amongst those already concerned and those learning about environmental protection.

LCA can be applied in both the public and private sectors. Areas of application include: education, communication, product design, product research and development, pollution prevention, liability assessment and reduction, strategic planning, environmental program assessment and improvement, policy and regulation development, purchasing and procurement, labeling programs, market strategy development, and environmental performance evaluations (Barnthouse *et al.* 1997). Given this range, it is possible that a LCA study conducted for one application will be at least a helpful reference in another area.

3.2.2 Framework

There are four main steps to conducting a traditional LCA (Consoli 1993): goal definition and scoping, inventory analysis, impact assessment, and improvement assessment. These four main steps should, most importantly, be conducted in a transparent manner. This will ensure that the "non-objective judgments"[2] (Susskind 2000) inevitably made during the process are well documented, allowing for verification of the results and further exploration of applicability.

The goal definition and scoping part of an LCA is arguably the most important. What occurs in this step not only determines the direction and boundaries for the entire assessment, but also begins the documentation of human judgment. The integral elements of this first step of LCA are: defining the study's purpose, determining its scope, establishing the functional unit, and developing measures to ensure the quality of the study (Consoli 1993).

The study purpose clearly states the problem, or reason for the assessment, and identifies how the results intend to be used. Determination of the study scope lays out system boundaries (geographic and time frames), data requirements, assumptions, and limitations. The functional unit defines system performance and relates input and output data of the study; it is also essential in comparative studies. Finally, data quality goals are developed at this stage to later measure confidence in the individual data, the entire data set, and in the decisions made based on these data.

The performance of an inventory analysis is highly dependent on the system boundaries set in 'goal definition and scoping.' This stage inventories all of the energy and material inputs and outputs to the system under study, where the system boundaries indirectly specify what these inputs and outputs are. The result is a life-cycle inventory (LCI) list. For example, imagine some system contained within a black box (Figure 2).

---

[2] Non-objective judgments: those judgments made with some bias, where the bias may or may not be recognized.

Inventory analysis looks at the inputs and outputs related to the box, whereas the system boundaries define the dimensions of the box.

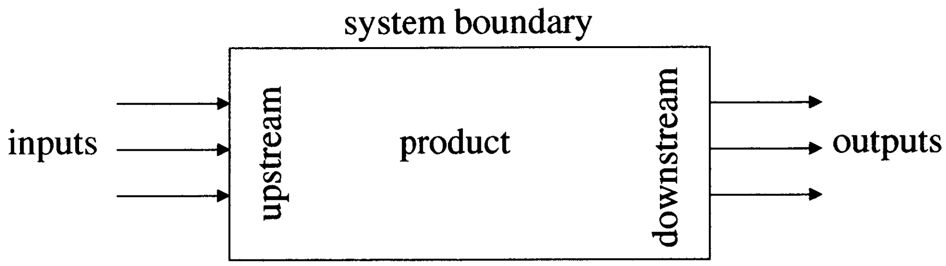


Figure 2: A black box model represents the defining parts of an inventory analysis.

The inputs and outputs are also made up of a series of "upstream" or "downstream" functions. The system boundary specifies which of these functions are included within the system boundary. For example, steel can be an input material to the black box while ignoring any processing functions that go along with its manufacturing or the system boundary can be 'drawn' to include the upstream extraction and processing operations, which mold the steel into a useable form. Further downstream from the product, methods of disposal may be included in the analysis. The degree to which an assessment looks down- or up-stream is dependent on the availability of data and the data requirements documented while determining the scope of the study.

Impact assessment evaluates the effects of those environmental burdens identified during inventory analysis. There are three parts to an impact assessment according to the Society for Environmental Toxicology and Chemistry—SETAC (Consoli 1993): classification, characterization, and valuation. Classification entails grouping the inventory data into *impact categories* (discussed in further detail in section 4.3.1) based on the type of effect yielded by the environmental burden. SETAC suggests the use of three general protection areas—resource depletion, human health, and ecological health—that can be broken down into specific impact categories.

Characterization involves aggregating and quantifying the impact categories specified during classification. There are a variety of different approaches to characterization due to the fact that this stage is one of the more subjective of a LCA. Normalization of the aggregated data within each category may be included in the characterization step in order to prepare the impact categories for valuation.

Valuation, a much more subjective process, takes characterization a step further. In this step, impact categories are weighted according to their perceived importance to increase comparability across categories. As can be imagined, the assignment of weightings could easily directly reflect the values of the parties involved in carrying out this process. It is therefore essential to maintain transparency of this task and to involve all stakeholders in the discussion.

Improvement assessment explores the assessed product by identifying, evaluating, and selecting ways in which to improve the product with respect to its environmental burden. In a way, this step allows the user to reflect on what was learned in the earlier stages of the LCA and to continue improving the product. If the product has already been produced this step can also be used to focus mitigation efforts.

It is recognized that this methodology contains many assumptions and non-objective judgments. However, this fact does not take away from the method's usefulness if conducted in a transparent manner. Maximum transparency can be achieved by opening up the process to all affected constituencies. The involvement of these groups will ensure that the study is adequate, credible, acknowledged, and not a wasted effort. Depending on the study, transparent documentation may also allow for the results, or at least the data, to be reused—increasing the applicability of the study. In this way, the documentation is a communication tool, allowing readers to understand the context and limitations of the study.

3.2.3 Limitations

The detailed LCA of a product provides insight into a product's potential impact on the environment, yet there are three main shortcomings to using the tool in design: time, data availability, and data quality. Detailed LCA requires a large amount of time—so much so that it is usually too slow for many product development cycles. Time is directly proportional to the amount of required data and therefore can be an indicator of data quality for an individual LCA study.

Time, data availability, and data quality are also problems when data from multiple LCA studies are pooled together to form an information, or knowledge, database. This type of database is one of two suggested solutions to increasing the accessibility of LCA (Linton 1999). The other solution—approximate LCA—is discussed in the next section.

Data, unfortunately, are not widely available for collection. Considering the number of products on the market, there have been very few LCA studies of products (Linton 1999), and those that are performed usually are not public information. The execution of a LCA study requires experienced staff—internal or contracted—that usually maintains ownership of the study.

When data can be obtained, there could be many problems with data quality on the whole. Although each study separately might be of high quality, differences among studies might lead to poor combined data quality. Defined system boundaries, the passage of time, and the context each study was performed under could all lead to differences across data (Linton 1999). As described in the previous section, system boundaries define how far up- and downstream in a product's life-cycle a study will cover. Differing system boundaries among collected data could mean some products will be wrongly portrayed in a better (or worse) 'environmental light'.

With the passage of time, new discoveries could be made, not only in terms of product innovation, but also in terms of the state-of-the-art in LCA and pollution prevention. This means that a certain product's impact assessed at one point in time could be different if conducted at another point in time. For a time difference of only five years, uncertainty in data can grow by as much as 70% (Linton 1999).

The context of a study includes the opinions of those conducting the study and the location used in assessing a product's use phase. As discussed in the previous section, opinions are a part of LCA no matter how structured the methodology and opinions will differ from expert to expert. Depending on a study's use location, different environmental impacts may be seen to be as more important and aggregated in such a way to reflect this.

3.3 Approximate Life-Cycle Assessments

Time is a major factor in preventing LCA implementation in product design. In order to reduce modeling time an obvious solution might be to perform a simplified assessment. Simplified assessments may be qualitative or quantitative, ranging from checklists, matrices, abridged LCA, and LCA streamlining, to a variety of other forms of approximate LCA.

Checklists are qualitative approaches that target distinct environmental design strategies such as material conservation, energy efficiency, and pollution prevention guidelines (Lindahl 1999). Although an excellent starting point to raise environmental awareness, checklists are quite general and their use lacks the thought process that may lead designers to new or subtle opportunities. Also, checklists do not readily support subtle tradeoff analysis.

Qualitative matrices (Allenby 1992) also promote life-cycle thinking. Matrices provide an illustrative means for evaluating tradeoffs and interactions among design criteria. However, their form limits the manipulation of information to assess new design strategies quickly when tradeoffs involve complex multi-objective functions.

Abridged LCA (Graedel *et al.* 1995) is a semi-quantitative matrix approach. Like qualitative matrices, it highlights only the most significant of concerns. An additional benefit to abridged LCA is its numerical basis, allowing for matrix manipulation and improved, but perhaps inconsistent, tradeoff analysis as the quantitative elements are based on heuristics.

LCA streamlining (SETAC 1999) refers to the design of LCA in terms of what is included in the study and what is not. SETAC views streamlining as "an inherent element of the of the scope-and-goal definition process" of an LCA, determining what is necessary to support its use. Streamlining removes portions of an LCA deemed non-critical to a specific 's environmental impact profile. SETAC has found that the more streamlined an LCA becomes, the less accurate its results.

In summary, these approximate methods will all significantly reduce the amount of time and information required for modeling. However, they do not work well in integrated design, as they are qualitative in nature or do not consider all of the information necessary for tradeoff analysis. Qualitative information, although easy to come by and understand, is difficult to include in complex, fast-paced tradeoff analyses, such as those found in conceptual integrated design. To increase the accessibility of LCA in product development, it is important to discover ways to maintain the rigor of the analyses while significantly reducing the in-use time required.

4 Learning Surrogate LCA Model

The learning surrogate LCA model proposed by Sousa *et al.* (1999) is a different approach to approximate LCA. Unlike the others, it does not require any LCA modeling at the time of use. Learning algorithms train artificial neural networks (ANNs) using high-level product attribute and corresponding environmental impact data from pre-existing life-cycle assessment studies. The product design team queries this trained artificial model with high-level product attribute data for a new concept to quickly obtain an approximate impact assessment for the design. The approach is illustrated in Figure 3.

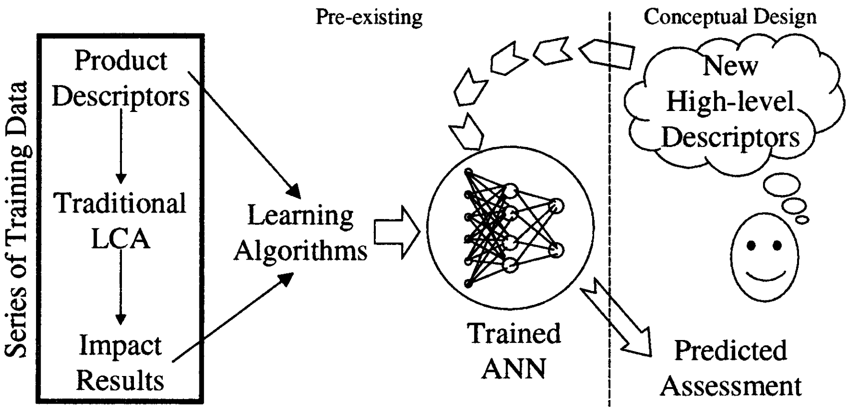


Figure 3: Learning Surrogate Model Concept.

4.1 The Overall Concept

The surrogate LCA model uses artificial neural network training algorithms to learn by example (Masters 1993). The learning process begins when the ANN is provided a set of product descriptors from previously analyzed existing products and corresponding full LCA results. The training algorithms adjust parameters within the network so that its output better models the actual impact results of the training data products. The process continues until the network converges. Effective learning requires a training set representing a reasonable distribution of products.

After the completion of training, the ANN is ready for use. Designers need to simply provide high-level descriptions of new product concepts to gain LCA predictions based upon trends inferred from the real products and LCA studies used as training data. A new model does not have to be constructed to analyze a new concept. However, the results of new detailed LCA studies should be continually added to enhance the training data set. This is an ongoing process (see Figure 4).

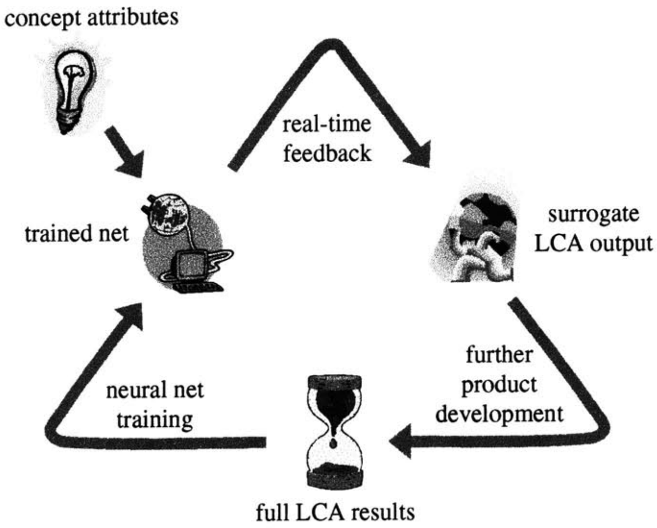


Figure 4: The surrogate model is only part of the ongoing process to assess a product's environmental impact.

The surrogate LCA model learns from detailed LCA studies, yet possesses a high-level interface allowing it to operate with the limited data available in conceptual design. It has the flexibility to learn and grow as new information becomes available, but does not require the creation of a new model to make LCA predictions for a new product concept. Also, it does not delay product development by supporting extremely fast comparison of the environmental performance of product concepts. At later stages of development, when fewer concepts are under consideration, a more detailed LCA approach can be applied.

4.2 Environmentally Conscious Integrated Design

No matter what type of LCA is implemented, an environmental expert should be brought in as part of the design team to integrate environmental assessment into the process. However, communication is often a barrier to integration as it takes time to establish and maintain adequate synchronization of information between designers and environmental analysts. Work by Borland *et al.* (1998) within the DOME (Distributed Object-based Modeling Environment) project (Abrahamson *et al.* 2000; Pahng *et al.* 1998) has demonstrated the effectiveness of a tool that both supports integrated environmentally conscious design and facilitates timely communication.

Ideally, the services of an environmental expert should be extended to the designer. A computer-based method to provide such an extension has been proposed (Borland and Wallace 1999; Borland *et al.* 1998) to provide designers with real-time environmental impact assessment based upon detailed parametric LCA models. The method allows for the evaluation of any number of simple, parametric variations in concept. Even so, it is still of limited value for conceptual design because of the amount of time and information needed to develop parametric LCA models for new design concepts. Once development is complete, the learning surrogate model can be exploited in DOME as a substitute for detailed LCA in conceptual design.

DOME allows the traditional designer and the environmental expert to collaboratively work together to develop a product design. Expertise is distributed, allowing each person to concentrate on the fields they know best. After the initial exchange of information, an interface is negotiated among all involved parties.

The negotiated interface is simply an agreement as to what data will be exchanged and in what form. The designer's model depends on some results from the environmental expert's model, for example an environmental performance indicator, and the surrogate life-cycle model requires inputs from other models and perhaps the environmental expert directly. The interface provides the opportunity for concurrent modeling while maintaining any proprietary data, models, or tools with the appropriate owner. Figure 5 illustrates how learning surrogate LCA will work in this environment.

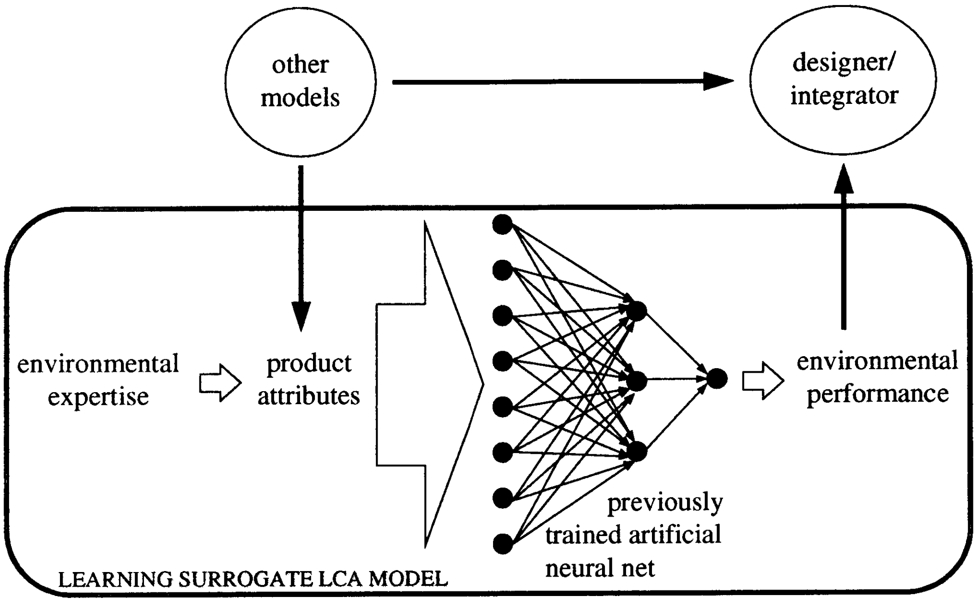


Figure 5: Learning surrogate LCA within integrated conceptual design.

After the interface is defined, the environmental expert will publish the appropriate inputs and outputs to the previously trained neural network as distributed objects on the Internet. The designer integrates these objects (along with those from other models) into their design and immediately gains the services of the environmental expert's surrogate life-cycle model.

The designer now has the ability to evaluate and compare the impacts of many diverse concepts. Moreover, this stage can take place completely without the environmental expert and continue only using the services already extended through the surrogate life-cycle model. For example, the designer changes the design by adding a part. The additional part is translated through the interface as an input to the life-cycle model, perhaps as added mass of a particular material. The result of the added mass is increased environmental impact of the design. A decision will have to be made on the importance of the added part with respect to its environmental impact.

Successful performance of the surrogate model depends on information. It is important to develop an appropriate form of the product attributes and surrogate results, as well as have sufficient training data available. The surrogate model can be thought of as a product, and in a way this is how its design was approached. Section 4.1 was a description of functional requirements that must now be transformed into something useful.

Practical use of the model involves designers and environmental experts directly, so the requirements of these stakeholder groups must be thoroughly attended to. Assuming what goes on inside the neural net is of no concern for these groups as long as the output is accurate, focus should be placed on the interface between these groups and the surrogate model. Section 4.3.2 reviews previous work (De Schepper 1999) in defining the output interface, or abbreviated life-cycle inventory (LCI) list. Section 1 describes the author's work in defining the input interface to the surrogate model, or product descriptors. Interaction between the environmental expert and traditional designer holds true in this situation—consensus is essential.

4.3 Output: The Abbreviated LCI List

This section focuses on the form of the output from the surrogate LCA. Normally the result of a LCA will be in the form of aggregated data at least to the level of environmental impact categories, at most down to a single number. However, even aggregating to environmental impact categories requires assumptions and non-objective judgments to be made. This section details the trade-offs that were balanced, and decisively selects an *abbreviated LCI list* as the output interface.

4.3.1 Categories of Environmental Impact

An environmental impact category represents an environmental problem, which is the aggregate of inflows and outflows (emissions and materials) from a product life-cycle. The inflows and outflows are determined through a life-cycle inventory, or LCI. There are many different levels of generality, at which the impact categories can be defined. Impacts are generally grouped into three broad categories: resource depletion, human health, and ecological health (Consoli 1993). Some of the more specific problems within these main categories are described below to give a sense of the type and significance of information a designer is faced with when given LCA results. The problems are described in such a way as to allow identification of the major emissions and materials contributing to the problem. Table 1 provides a listing of the specific environmental impact categories detailed in the next sections.

Table 1: Categories of Environmental Impact.

Greenhouse effect	Winter smog
Ozone layer depletion	Summer smog
Acidification	Pesticides
Eutrophication	Energy
Heavy metals	Solid material
Carcinogens	

4.3.1.1 Resource Depletion

Resource depletion ultimately results in social and/or economic problems depending on the particular resource under discussion. Resources can take the form of minerals, fossil fuels and uranium, renewable and non-renewable materials, and available physical space. If the potential for depletion is not heeded, key resources may become scarce and possibly non-existent.

4.3.1.2 Human Health

Toxins, ozone layer depletion, summer smog, and winter smog can affect human health. Toxic substances such as heavy metals, carcinogens, and pesticides directly result in failing human health. Heavy metals include lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), and mercury (Hg) (Brezet *et al.* 1997).

Depletion of the ozone layer, or stratospheric ozone, will lead to increasing risk of skin cancer as the ozone offers significant protection against the Sun's high energy UV radiation. Depletion over Europe is estimated at 5 to 10 percent, while over the South

Pole it is estimated to be between 30 and 50 percent[3]. Ozone depletion occurs due to the presence of halide substances such as chlorine (Cl), fluorine (Fl), and bromine (Br) compounds. These compounds reach high levels of the atmosphere through the extremely slow diffusion processes of substances such as CFC and trichloroethylene. (Brezet *et al.* 1997)

Summer smog results in severe health problems and agricultural damage. Summer smog is particularly harmful for asthma patients, children, and the elderly as it acts corrosively toward lung tissue. Summer smog is due to tropospheric ozone close to the Earth's surface. This ozone is formed by a complex reaction of hydrocarbons (C_xH_y), nitrous oxides (NO_x), and sunlight (Brezet *et al.* 1997).

Winter smog can be quite deadly. For example, in the winter of 1952, 4000 people died from the smog in London. Winter smog occurs due to dust (SPM), soot, and sulphur dioxide (SO_2) emissions. (Brezet *et al.* 1997)

4.3.1.3 Ecological Health

Toxins, the greenhouse effect, acidification, and eutrophication affect ecological health. Toxins such as pesticides and heavy metals (also harmful to humans) affect the health of the Environment.

Intensified greenhouse effect results in global warming, steadily increasing the average global temperature and changing climates all over the world. The greenhouse effect acts like a blanket around the Earth, holding in radiation captured from the Sun and emitted from the Earth. Entirely without this blanket, the Earth would be about 30°C colder (Brezet *et al.* 1997), but minimally enhanced coverage or thickness is also devastating to many ecosystems. Increased levels of atmospheric gases such as water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrogen (N_2), and chlorofluorocarbons (CFCs) enhance the greenhouse effect (Brezet *et al.* 1997).

---

[3] Ice crystals in the atmosphere above this region enhance ozone breakdown.

Acidification negatively impacts many ecosystems indirectly. Acidification falls upon the Earth in the form of acid rain. When the rain is absorbed into the ground, its acidity causes trace chemicals within the soil to dissolve, allowing once settled toxins to flow into the roots of plants, into the bellies of water life, and into our water supply. Acidification is caused mainly by the emission of sulfur (SO_x), nitrous oxide (NO_x), and ammonia (NH_3) (Brezet *et al.* 1997).

Eutrophication is mainly a fluvial problem, directly impacting the environment within a river, lake, or sea. Certain substances behave as a fertilizer toward plant life and can sometimes push growth beyond a sustainable level. The result of unbalanced growth is the disappearance of rare plant species and the suffocation of fish, yielding a loss of biodiversity, as only the strongest will survive. The same substances that cause acidification, contribute to eutrophication.

Although some level of information can be extracted from surrogate model results in the form of environmental problems, in some cases the aggregation level is already too much. For example, in Japan it is useful to know results and how they relate to CO_2 emissions directly rather than the greenhouse effect.

4.3.2 Optimized Model Functionality

A life-cycle inventory is a full list of all impact substances associated with a product. The LCI data is the most objective and informative form of environmental performance to an environmental expert. Subjectivity increases as these data are classified and aggregated to compute environmental impact categories and single environmental indicators (as would be more comprehensible to the typical designer). Ideally the surrogate LCA would predict inventory data so that different impact assessment schemes might be then applied to bring the data to the designer's level. Clearly it would be difficult to predict all inventory data associated with a detailed LCA using the surrogate LCA approach. Therefore, an *abbreviated LCI list* was tested (De Schepper 1999) for its ability to predict environmental impact categories.

The model's output left in the form of an abbreviated LCI list will optimize model functionality. This should allow for no direct emission data to be lost, as well as provide easy aggregation to environmental impact categories. Output in this form will also allow for the environmental expert and designer to make the necessary assumptions and non-objective judgments 'together' in order to further characterize and manipulate the data to the appropriate form for their needs.

4.3.3 Accuracy of Approximate Results

The De Schepper (1999) study tried to identify the components of the abbreviated LCI list, consisting of only key LCI elements, which could be linked to the impacts in Table 1 as a full LCI would. This investigation is illustrated in Figure 6. The goal is to then map the simplified inventory list back to derive an appropriate list of high-level product attributes that can be provided by designers in the conceptual phase of design.

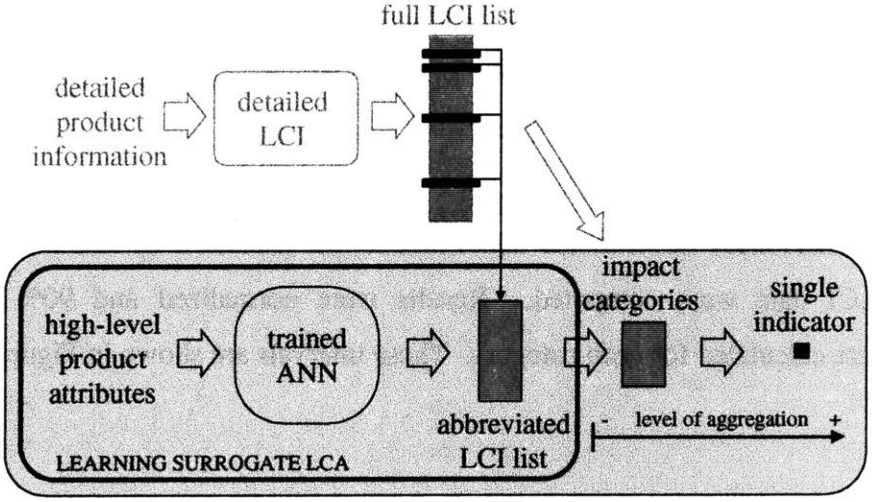


Figure 6: Can the learning surrogate LCA model's results for conceptual design compare to those of detailed LCA?

The full list of LCI elements used to calculate impacts originated from the Eco-Indicator '95 approach (Pre Consultants 1999). Impacts predicted using the full LCI list were used as a baseline to validate impacts predicted using the abbreviated LCI list, on which the surrogate modeling approach will focus. The approximate LCI listing, or abbreviated LCI list (Table 2), proposed included only materials that accounted for the majority of environmental impacts.

Table 2: The Abbreviated LCI List.

Energy	Cr	CO_2	CH_4
Solid Material	Ni	SO_2	COD
CFC	PAH	NO_x	N_{tot}
Pb	SPM	C_xH_y	Halon
Cd			

With the two LCI lists defined, existing results from 20 LCA studies using complete LCI data were compared with results achieved using the abbreviated list (De Schepper 1999). The 20 LCA studies were conducted on a range of products and their variations, including: 2 vacuum cleaners, a mini-vacuum cleaner, a washing machine, a heater, 3 coffeemakers, 2 juicemakers, 2 chairs, 4 radios, a showerhead, a plastic crate, and 2 bags. The test resulted in predictions for the Table 1 impact categories with respect to both the abbreviated and full lists. The detailed inventory data for the 20 products tested were obtained from LCA studies conducted at TU Delft (DfS Group 1994-1997), published studies in the SimaPro 4 User's Manual (1999), and a study by PA Consulting Group (UK Ecolabeling Board 1992).

The differences between the numerical results produced by the abbreviated and complete LCI data were computed. Results were normalized and 90% confidence intervals were calculated for each category. These intervals are shown in Figure 7.

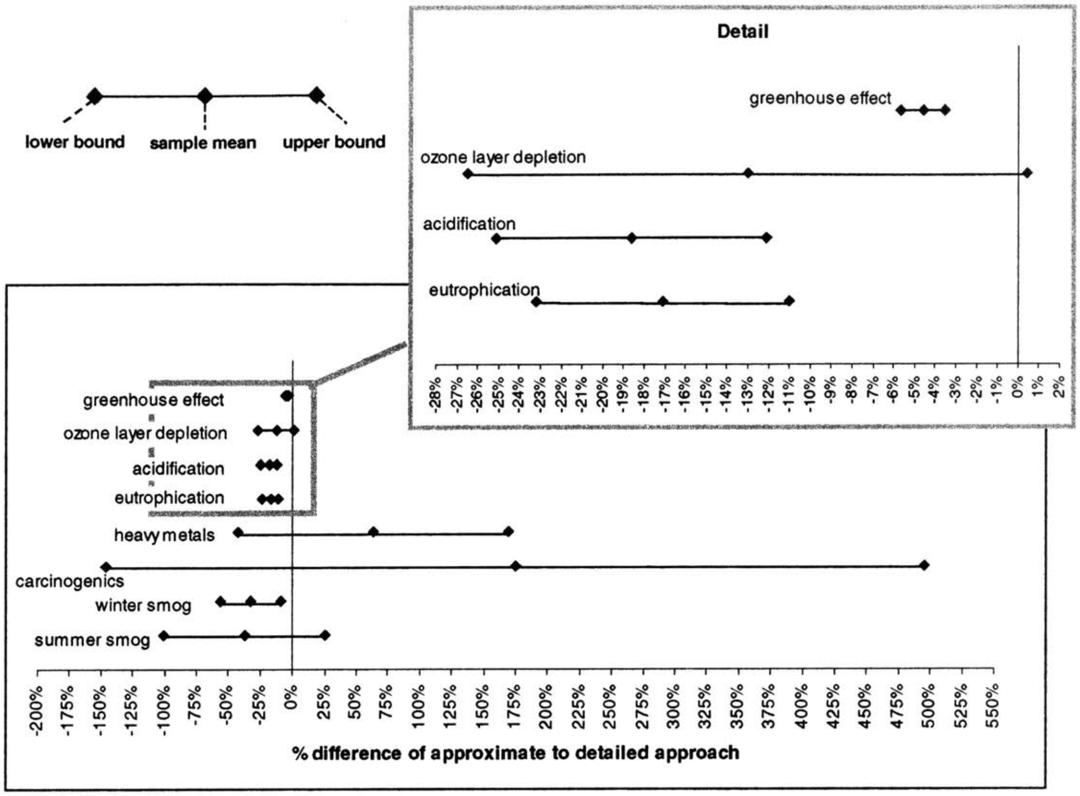


Figure 7: Normalized Data 90% Confidence Intervals.

It was concluded that certain impact categories—energy[4], solid material[4], greenhouse effect, and ozone layer depletion—were well represented by the abbreviated list while others—acidification, eutrophication, winter smog, and summer smog—were reasonably suited to the simplified LCI. Heavy metals, carcinogens, and pesticides[5] were not likely to be predicted.

Additionally, products were ranked from most to least detrimental within each impact category according to their LCA results for that category. Within each category, the rankings resulting from the full and abbreviated lists were compared. The goal of this analysis was to identify any trends in the approximate approach's ability to rank products appropriately with respect to their environmental impacts.

---

[4] The energy and solid material categories were identical in the two lists.

The surrogate tool's ability to appropriately rank products is important if the tool is used independent of the integrated model. For the 20 products studied, the energy, solid material, greenhouse effect, and summer smog impact categories were identically rank ordered. The acidification, eutrophication, heavy metals, and winter smog categories had discrepancies, but they were minor, limited to a shift of no more than two places (e.g. from 3rd to 5th most detrimental product). The ozone layer depletion and carcinogens categories contained more deviations—up to a shift of six places. The carcinogens impact category produced the least consistent results, having only nine matches and the largest shift in product ranking (Café Sima from 13th to 7th), yet the first six products were ranked identically. This is illustrated in Table 3.

Table 3: Rankings for the carcinogens category produced the least consistent of all ranking results.

decreasing detriment

Carcinogens	
Detailed approach	*Approximate approach*
Washing Machine	Washing Machine
Heater	Heater
Vacuum Cleaner 2	Vacuum Cleaner 2
Vacuum Cleaner 1	Vacuum Cleaner 1
Café Pro+	Café Pro+
Café Comfort	Café Comfort
Mini Vacuum Cleaner	Café Sima
Radio 1	Mini Vacuum Cleaner
Juice Squeezer 1	Juice Squeezer 1
Juice Squeezer 2	Radio 1
Oak Chair	Juice Squeezer 2
Silver Chair	Oak Chair
Café Sima	Silver Chair
Radio 3	Showerhead
Radio 2	Radio 3
Radio 4	Radio 4
Paper Bag	Radio 2
PP Crate	PP Crate
Showerhead	PE Bag
PE Bag	Paper Bag

Results of the ranking analysis seem to suggest that the tool could be independently useful in conceptual design by determining the most environmentally detrimental of concepts. These concepts could then be easily filtered out of the

---

[5] No material impacts in the study were allocated to the pesticide category. Any such allocation was deemed highly dependent on product and therefore pesticides may not be a useful impact category to use in a more generically based learning surrogate model.

development process or improved. Both the ranking and the numerical accuracy tested in the statistical analysis are important in conceptual integrated design.

The goal now is to develop an appropriate set of high-level product descriptors that can be used to query the learning surrogate model. For this purpose, product attributes were systematically selected to relationally link with the abbreviated list of LCI data to later be tested with a full-blown surrogate model trial.

5 Product Descriptors as an Interface for Integration

This section focuses on the determination of the set of design properties, or *product descriptors*, which all products possess, that will allow the surrogate model to fulfill its functional requirements. Three rules were applied to this search: 1) the descriptor values must be known, or easily quantified in conceptual design; 2) the set must not be so large as to create excessive complications in the neural network architecture of the surrogate model; and 3) the descriptors should be independent of each other, yet fully represent the elements of the abbreviated LCI list.

To select the ideal interface for the identified stakeholders to interact with, an extensive list of possible descriptors was compiled. Narrowing of the list occurred in several phases: grouping the general descriptors, identifying whether the descriptors are known in conceptual design, and identifying relationships among descriptors and between descriptors and the abbreviated list to eliminate redundancy and ensure completeness. The ways in which these phases were completed are discussed in the next sections.

5.1 General Descriptors

All apparent properties of a product derive from a class of more basic properties, which Hubka (1982) terms *design properties.* All products possess the same set of design properties; they only vary in degrees of embodiment or measure. Product properties, including effectual performance, depend on these design characteristics. In particular they depend on the form, size, material, manufacturing methods, surface properties, tolerances, arrangement, etc. of the elements. Hubka identifies this fact and states, “this basic regularity permits us to consider the process of designing as a search for appropriate design properties.” (1982).

The process of environmentally conscious design, then, requires a set of basic properties, extended from those of traditional design. When this set is defined meaningfully—sufficient enough to distinguish among concepts and to encompass all areas of environmental impact, yet concise and known at the conceptual phase of design—any product could be thoroughly described from an environmental viewpoint.

5.1.1 Environmentally Meaningful Descriptors from Experts

Descriptors were extracted from ecodesign checklists and design improvement strategies in the literature (Alting and Legarth 1995; Fiksel 1996; Brezet and Hemel 1997; Sfantsikopoulos and Pantelis 1997; Hanssen 1999; Clark and Charter 1999). For example, checklist questions like "What type of energy is required when using the product?" suggest *in use energy consumption* and *in use energy source* as possible attributes characterizing a product's use phase. "Low energy consumption" and "clean energy source" are ecodesign strategies that also suggest these product attributes.

Other work (Rombouts 1998; Mueller and Besant 1999) has been done in defining environmentally meaningful product features. Rombouts (1998) derived a list of product features from the Ecodesign Checklist composed by Brezet and Hemel (1997). Mueller and Besant (1999) modeled what they termed life-cycle parameters as functions of design parameters. For example, mass, material composition, and efficiency were directly dependent on the power of a standard motor.

Interviews with experts complemented information found in the literature. A common view (Baumann 2000) was that environmental product descriptors at the conceptual stage are few, simple, and expressed in a product-specific language. For example, in the automotive industry frequently used environmental terms are *weight* and *fuel consumption*. Also, different levels of information are available and used at the early stage of product design, depending on the purpose of the design (improvement or innovation) and on the product requirements given (Potts 2000).

5.1.2 Environmentally Meaningful Descriptors from Designers

Product designers' perspective on environmentally meaningful attributes was added through an on-line survey (see Appendix B: The On-line Survey). Sixteen practicing designers working on a wide range of products (see chart on disciplines represented in Appendix C: Complete Survey Results) selected as many attributes as they felt were environmentally important. Results in Figure 8 show the percent responses for each attribute out of all responses given.

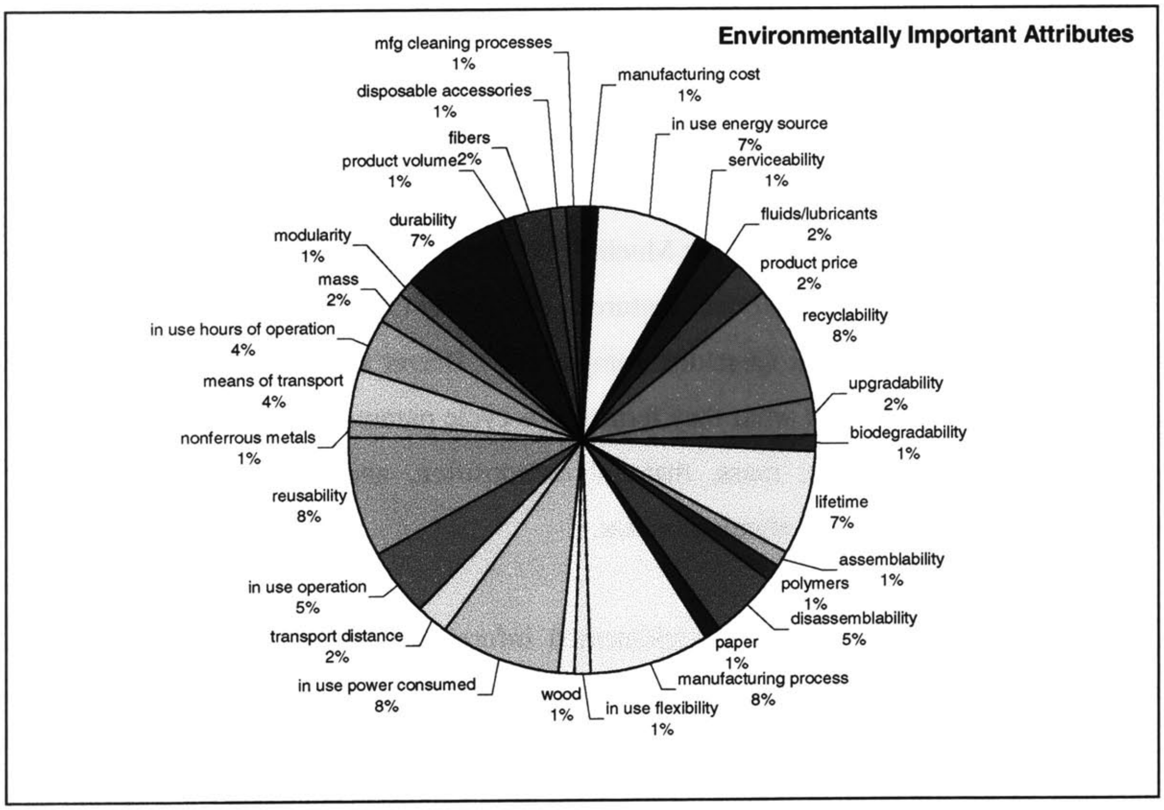


Figure 8: Attributes deemed environmentally important by product designers.

These results are interesting because they differ from what environmental experts perceive as environmentally important. In general these results support heavily the need for environmentally conscious integrated design, where environmental experts and designers work together. It can be inferred that although designers realize that they can make environmentally preferable choices, they still lack the expertise to appropriately make these decisions—for example *product price* was deemed as (minimally) important as *mass*. Although perhaps designers see *product price* in limiting how environmentally friendly a product can be, this attribute would not be listed by an environmental expert—in many cases costs are reduced by good environmental decisions (McAloone *et al.* 1998)—while *mass* would top the list.

Through these combined sources an initial product descriptor set was composed (Table 4). Some attributes are most clearly defined in a qualitative manner (e.g. *in use energy source* as electric, solar, none, etc.). Values for qualitative variables could be of three types (Fienberg 1980): dichotomous (yes/no), non-ordered polytomous (green/red/blue), or ordered polytomous (low/medium/high). Definitions of all variables and examples of discrete choices for each can be found in Appendix A: Product Descriptor Definitions.

Table 4: Initial Product Descriptor Set.

Mass	Lifetime	Serviceability
Volume	Use time	In use flexibility
Materials (various)	Mode of operation	Recycled content
Durability	Additional consumables	Recyclability
Distribution mass	In use energy source	Biodegradability
Distribution volume	In use power consumption	Disassemblability
Transport distance	Modularity	Reusability
Transportation means	Upgradeability	

5.2 Organizational Grouping

Given an extensive initial list of descriptors it was organizationally advantageous to group the attributes. This also guided the process of theoretically thinking about relationships among descriptors and with the abbreviated LCI list. Grouping was based on the methodology of Hubka and Eder (1982), which is built on the recognized phases of the life-cycle and the nature and purpose of technical systems. The defined groups include: general design; elementary design; functional; operational; distribution; and end-of-life attributes (Table 5).

Table 5: Organizational descriptor groupings.

Group Name	*Associated Attributes*
General design	biodegradability, durability
Elementary design	material content, recycled content
Functional	mass, volume
Operational	lifetime, use time, energy source, mode of operation, power consumption, in use flexibility, upgradeability, serviceability, modularity, additional consumables
Distribution	distribution mass, distribution volume, means of transport, transport distance
End-of-life	recyclability, reusability, disassemblability

5.3 Level of Information in Conceptual Design

A survey was distributed with the purpose of gathering data on the type of information that is known and available during conceptual design. Survey participants were those members of the design team deeply involved in product development during its early phases. Participants were those presented in section 5.1.2.

Participants were asked to evaluate the level of information at which attributes are known in conceptual design. If the designer was able to specify or estimate an attribute in a qualitative or quantitative sense, "specified" was selected. If the designer could not specify the attribute, but would be able to rank concepts with respect to the attribute, "ranked" was selected. If the designer would know whether or not the product contained (e.g.) polymers, but could not estimate the percentage or rank a concept among others with respect to polymers, "binary" was selected. If the attribute cannot be known in conceptual design, "unknown" was selected. Finally, if the attribute did not apply to the class of products designed by the participant, "N/A" was selected. Results assessing operational descriptors are provided in Figure 9. All other results are provided in Appendix C: Complete Survey Results.

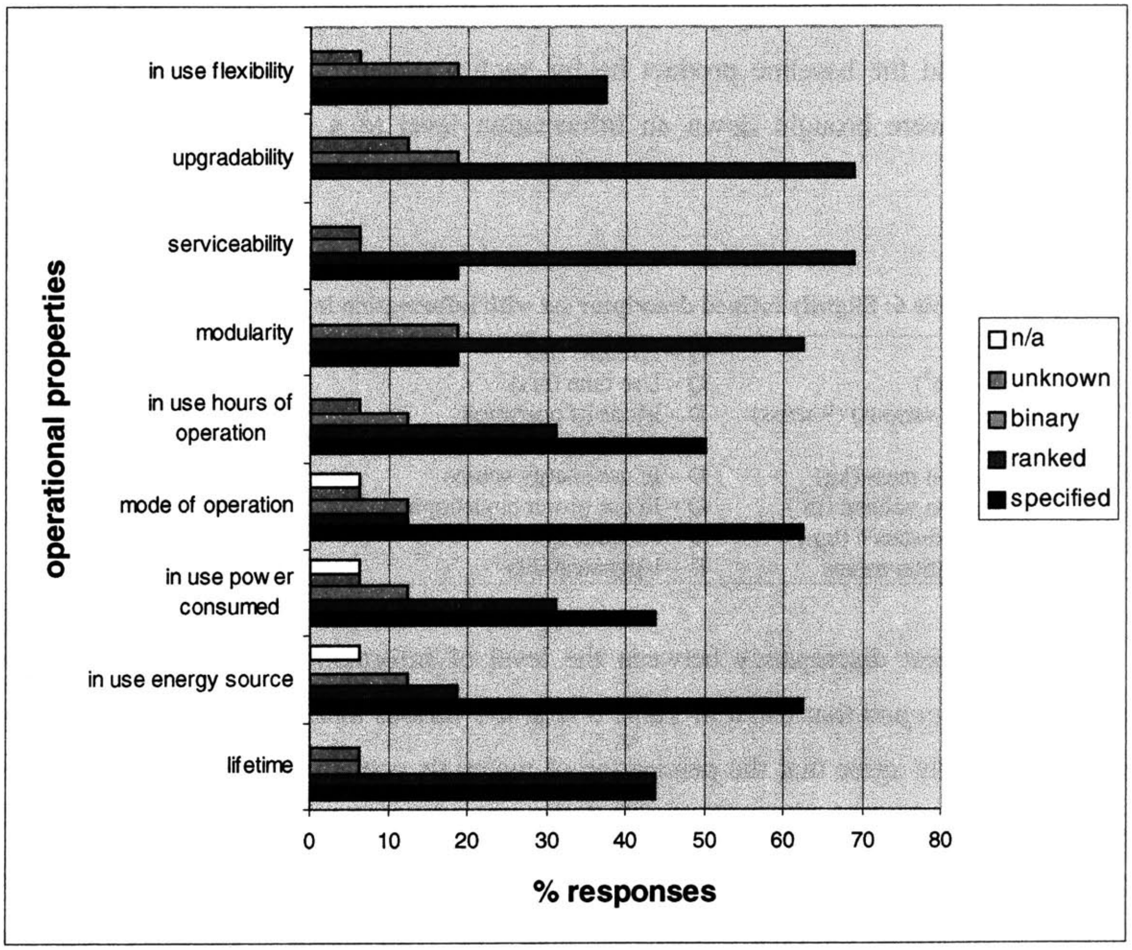


Figure 9: Survey results for operational properties.

These results indicate the level of information that a typical designer can reasonably be asked to provide in conceptual design. For example, *in use energy source* and *mode of operation* can be readily specified, whereas *upgradeability* and *serviceability* are more likely to be provided in terms of the current concept with respect to other concepts.

From the responses indicated by designers, a slightly refined descriptor set was composed (Table 6). In the table, *Q* signifies a quantitative variable, D a discrete variable, and *B* a binary variable (a discrete variable with only two choices). It was identified that although some variables were indicated to be known at a level in which they could be ranked, a ranking system would be difficult to implement within the neural net—what would the baseline product be for such a system? Therefore, all attributes rank-specified were brought down an information level to a binary, or dichotomous, variable.

Table 6: Slightly refined descriptor set with information level indicated.

Q – Mass (kg)	Q – Lifetime (hrs)	B – Serviceability
Q – Volume (m^3)	Q – Use time (hrs)	B – In use flexibility
Q – Materials (various) (%mass)	D – Mode of operation	B – Recycled content
B – Durability	B – Additional consumables	B – Recyclability
Q – Distribution mass (kg)	D – In use energy source	B – Biodegradability
Q – Distribution volume (m^3)	Q – In use power consumption (W)	B – Disassemblability
Q – Transport distance (km)	B – Modularity	B – Reusability
D – Transportation means	B – Upgradeability	

The largest discrepancy between the level of information said to be known in conceptual design and that listed in Table 6 is in the various materials. Overall, designers did not uniformly agree that the percentage of materials contained in a concept could be specified. However, excluding the times "N/A" was selected, on the average "specified" was indicated about 26% of the time. Because material content is an important part of a full LCI, it should be explored further why such a low percentage of designers stated the attributes could be specified. Meanwhile, current research will reflect the importance of material content by accepting quantitative information for those descriptors.

5.4 Information in Existing LCA

It was also identified that the descriptors must be used in existing assessments in order to have access to data for the training database. Attributes such as material content can be easily extracted from a LCA; however some of the binary attributes may not even be discussed in a detailed LCA. This could result in possibly inconsistent estimates entering the training database for some of the binary variables, leading to poor predictions for the surrogate model when queried.

In attempting to avoid inconsistencies, many of the attributes were analyzed more thoroughly. For example, *upgradeable* products can also be thought of as *reusable*—the parts that are not upgraded are reused to form an improved product. As well, if a product is *reusable* or *serviceable*, it can be thought of as having an extended *lifetime*. *In use flexibility* and *modularity*, although able to convey impact information at very high level, are difficult to capture in a single product's LCA. Also, while in practice the ranked attribute *disassemblablity* may provide meaningful information, collapsing the variable to a dichotomy will carry little meaning. Binary information does not convey the degree to which something can be disassembled, just that it is or is not disassembled; therefore, there will be little variation from concept to concept with regard to *disassemblablity*. Table 7 displays the revised product descriptor set.

Table 7: Revised descriptor set with regard to information captured in LCA.

Q – Mass (kg)	Q – Lifetime (hrs)	D – In use energy source
Q – Volume (m^3)	Q – Use time (hrs)	Q – In use power consumption (W)
Q – Materials (various) (%mass)	D – Mode of operation	B – Recycled content
B – Durability	B – Additional consumables	B – Recyclability
Q – Distribution mass (kg)	Q – Transport distance (km)	B – Biodegradability
Q – Distribution volume (m^3)	D – Transportation means	

5.5 Redundancy and Abbreviated LCI List Coverage Testing

The next step was to eliminate redundancy and ensure complete life-cycle coverage within the descriptor set. Product descriptions and detailed inventory data for 48 products (Table 8) were compiled for use in analysis of descriptor redundancy and life-cycle coverage. These data were obtained from thirty LCA studies conducted at TU Delft (DfS Group 1994-1997), six published studies in the SimaPro 4 User's Manual (1999), a study by PA Consulting Group (UK Ecolabeling Board 1992), and eleven nonproprietary studies conducted by the Research Triangle Institute (RTI) (Sharma 1996a; Sharma 1996b; Peters 1996) and Franklin Associates Ltd (FAL) (1990; 1994).

Table 8: Products used in the correlation tests.

Quantity	*Product*	*Quantity*	*Product*
3	Vacuum cleaner	3	Diaper system
3	Coffeemaker	2	Antifreeze
10	Television	2	Newsprint
5	Refrigerator	2	Shop towel
1	Washing machine	2	Coating
4	Radio	1	Vacuum dustbag
2	Juice maker	1	Coffee filter
1	Heater	3	Bag/crate
1	Showerhead	2	Chair

5.5.1 Quantitative Descriptors

First order relations among product attributes and between product attributes and abbreviated LCI elements were identified using correlation tests. Linearity and bivariate normality in the data was assumed to check for general trends; however, the probable existence of nonlinear or multivariate relationships among descriptors as well as the concept of dependence without correlation should be noted.

Bivariate Pearson product-moment correlations were computed and correlation tests to 95% statistical significance were performed (SPSS 1999). The Pearson correlation coefficient, r, is computed by

$$r = \sum_{i=1}^{N} \frac{(x_i - \overline{x})(y_i - \overline{y})}{(N-1)s_x s_y} \qquad (1)$$

where N is the number of data points and $\overline{x}$ and s_x are, respectively, the mean and standard deviation of variable x, and likewise for variable y. If the correlation significance, or *p*-value, was less than 5% (0.05), then independence was rejected and x and y show linear correlation.

Although relationships identified through correlation testing were linear and first order, some interesting results were recognized. For example, mass and distribution mass were found to be highly correlated as hypothesized. On the other hand, mass did not directly affect many of the abbreviated LCI list elements as expected (Table 9). However, in probing the data further, it was discovered that indeed the heavy influence of product mass was true for the 33 durable products among the data. This led to further data analysis and the idea of a product categorization system to improve the neural net's results, which is explained in section 5.6.

Table 9: Mass vs. Abbreviated LCI list elements. Highlighted results indicate correlation.

Abbreviated LCI list elements	*All products*		*Durable products*	
	r	*p-value*	*r*	*p-value*
energy	.348	.015	.771	.000
solid material	.663	.000	.752	.000
CFC	-.024	.874	.441	.006
Pb	-.015	.919	.715	.000
Cd	-.047	.749	.644	.000
Cr	-.04	.788	.689	.000
Ni	-.036	.806	.695	.000
PAH	-.027	.855	.603	.000
SPM	.948	.000	.507	.001
CO_2	.485	.000	.719	.000
SO_2	.835	.000	.550	.000
NO_x	.629	.000	.730	.000
C_xH_y	.969	.000	.854	.000
COD	-.077	.601	-.041	.806
N Total	.165	.262	.843	.000
Halon	-.041	.78	.718	.000
CH_4	-.036	.809	.689	.000

The continued non-correlation between mass and COD may be attributed to three outliers in the data set. There are various reasons why these data do not seem to fit with the set, including the LCA system boundaries for these products may be inconsistent with the other data.

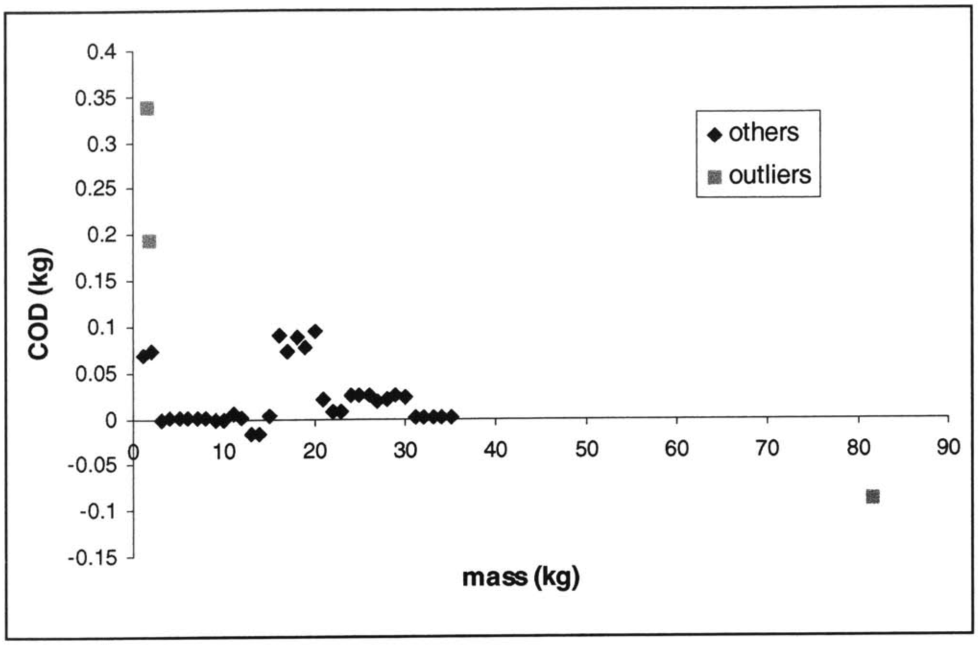


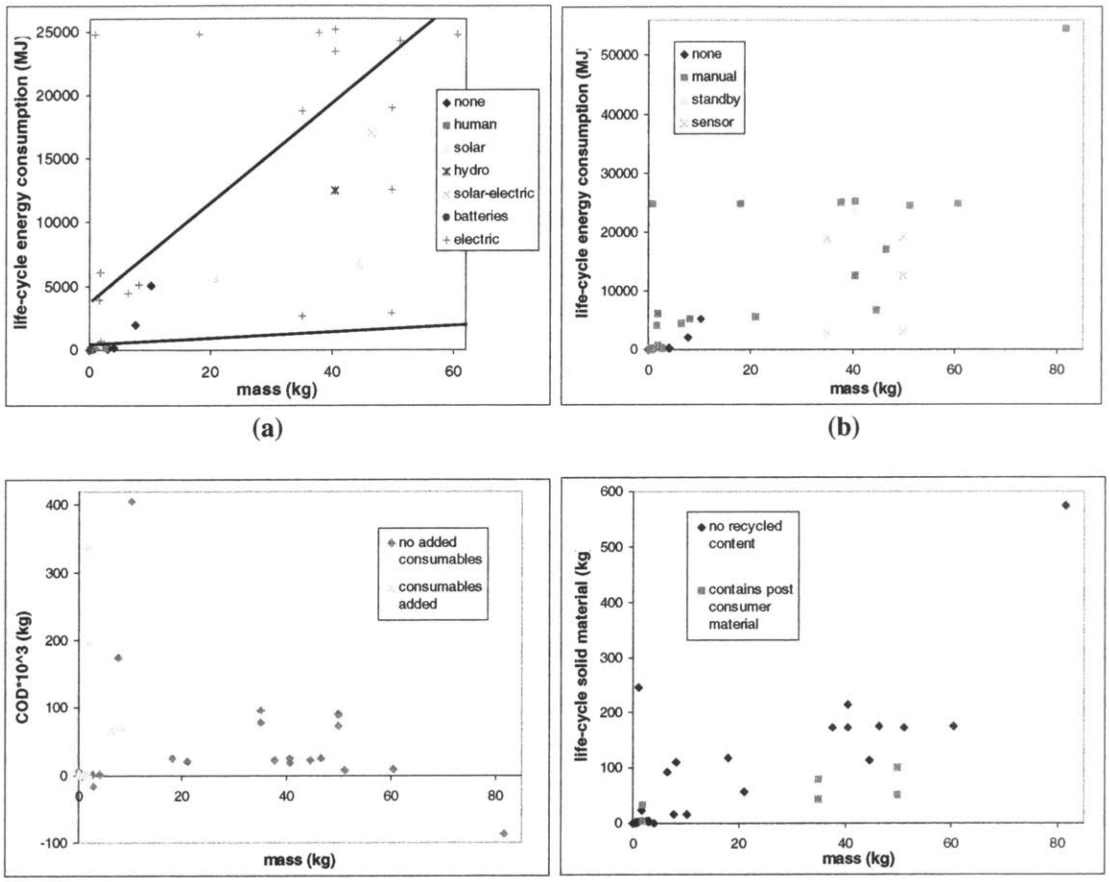
Figure 10: Scatter plot of mass vs. COD with outliers identified.

Overall correlation results did not reduce the length of the product descriptor list by much, but it did help to identify the need for filtration techniques to enter into the process and areas of concern for neural net testing. Further refinements in data analysis, using non-linear methods, could be done in later stages using more data points.

5.5.2 Qualitative Descriptors

It was identified that qualitative descriptors could not be analyzed by correlation tests in the same way as the quantitative attributes. Redundancy among dichotomous, or binary, variables was as easy as scanning the data. Life-cycle coverage testing was done through scatter plots (Devore 1995). The affect of discrete variables on abbreviated LCI results, in general, brought products to a higher or lower level of impact.

In Figure 11, plot (a) shows that electric energy source products exhibit substantially higher life-cycle energy values. Plot (b) displays products containing energy saving components such as a sensor control device consuming less energy through the life-cycle than those products without the device. Plot (c) demonstrates that product LCAs taking into account the use of additional consumables showed a trend in producing larger COD values. Plot (d) indicates products avoiding the use of strictly virgin materials have lower values for solid material impact.



(a) (b)

(c) (d)

Figure 11: Effects of several qualitative attributes on the abbreviated LCI list.

Overall, product features seem likely to provide adequate life-cycle coverage; correlations are evident for all LCI elements with at least one product attribute. In addition, it is believed that the neural net will learn other non-linear or multi-attribute relationships, such as the effect of *recyclability* and *material content* on solid material effluents, which are difficult to illustrate well in either correlation tests or scatter plots.

Given these final descriptor test results, the descriptor set was revised one last time. It is presented below in its fullest (Table 10). It should be noted that *durability* was removed from the list in favor of using it as a classification category to aid in ANN architecture complexity reduction (described in the next section). Also, included in the list, but not thoroughly tested are: *volume*, *biodegradability*, *transport distance*, and *transportation means*.

Table 10: The final product descriptor set.

Q – Mass (kg)
Q – Volume (m^3)
Q – Ceramics (%mass)
Q – Fibers (%mass)
Q – Ferrous metals (%mass)
Q – Nonferrous metals (%mass)
Q – Polymers (%mass)
Q – Wood (%mass)
Q – Paper/Cardboard (%mass)
Q – Chemicals (%mass)
Q – Other materials (%mass)
B – Recycled content
B – Additional consumables
B – Recyclability
B – Biodegradability
Q – Lifetime (hrs)
Q – Use time (hrs)
D – Mode of operation
D – In use energy source
Q – In use power consumption (W)
Q – Transport distance (km)
D – Transportation means

5.6 Surrogate Model Architecture Complexity Reduction

The system may learn faster and more effectively if the "learning space" is narrowed, or filtered, in a preliminary stage. A preliminary classification of products into general categories can potentially lead to more specific relationships between product attributes and LCI elements of the abbreviated list, such as indicated by the results in the previous sections. Other research (Reuleaux 1904; Hanssen 1996; Rombouts 1998) using similar approaches support this technique. However, a classification method used in conjunction with the surrogate model will focus on conceptual design and the possibility of going beyond qualitative rankings to predict an approximate environmental impact.

Reuleaux (1904) was the first to recognize the identicalness among various properties of different products and to form a classification system. Never before were products thought to share anything in common. Reuleaux began categorizing machine elements—the beginning of Kinematics—with respect to shared properties, something that was previously thought to be impossible. Rombouts (1998) used a case-based approach to enhance searches in expert systems for ranking ecodesign strategies.

Products can be subjected to a preliminary filtration process based on classes that potentially create common dominant environmental impacts. These classes, or categories, would then lead certain groups of product attributes to dominate in causing certain environmental impacts when appropriate measures of the attributes are used to query the surrogate model. Hanssen's (1996) work is used in support of this hypothesis.

A classification system by Hanssen (1996) focused on a product's application phase. Classification criteria included: chemical transformation, energy conversion, and mobile vs. stationary products. For each class of product, the results of 18 different LCA studies were used to analyze the most significant environmental impacts, as well as the contribution of different life-cycle phases to the impacts.

Each product class exhibited relationships with different environmental impacts. Depletion of fossil fuel resources, global warming, and acidification levels were most significant for stationary products with and without energy conversion and for mobile products with energy conversion. Photochemical oxidation and toxicity were most strongly tied with products being chemically transformed and mobile products with energy conversion. Solid waste generation was significant for mobile products without energy conversion.

For all product classes, the most important life-cycle stages were raw material production and use. Both life-cycle phases showed conversion of fossil energy to electricity, process energy, heat, or transportation as a dominating factor. Production, distribution, and production of packaging were of very low relevance in most product types.

Raw material production was the dominant life-cycle stage for products being chemically transformed, stationary products without energy conversion, and mobile products without energy conversion. The use phase was important for products being chemically transformed, stationary products with energy conversion, and mobile products with energy conversion. Waste generation was relevant for products being chemically transformed, and stationary products with energy conversion.

Given these findings (Hanssen 1996), the classification technique described below seems likely to achieve its purpose. The general categories of products presented below combined with the product descriptor set will fully characterize a product concept (see Figure 12). For each category definition, negation leads to opposite trends in the way product attributes generate impacts.

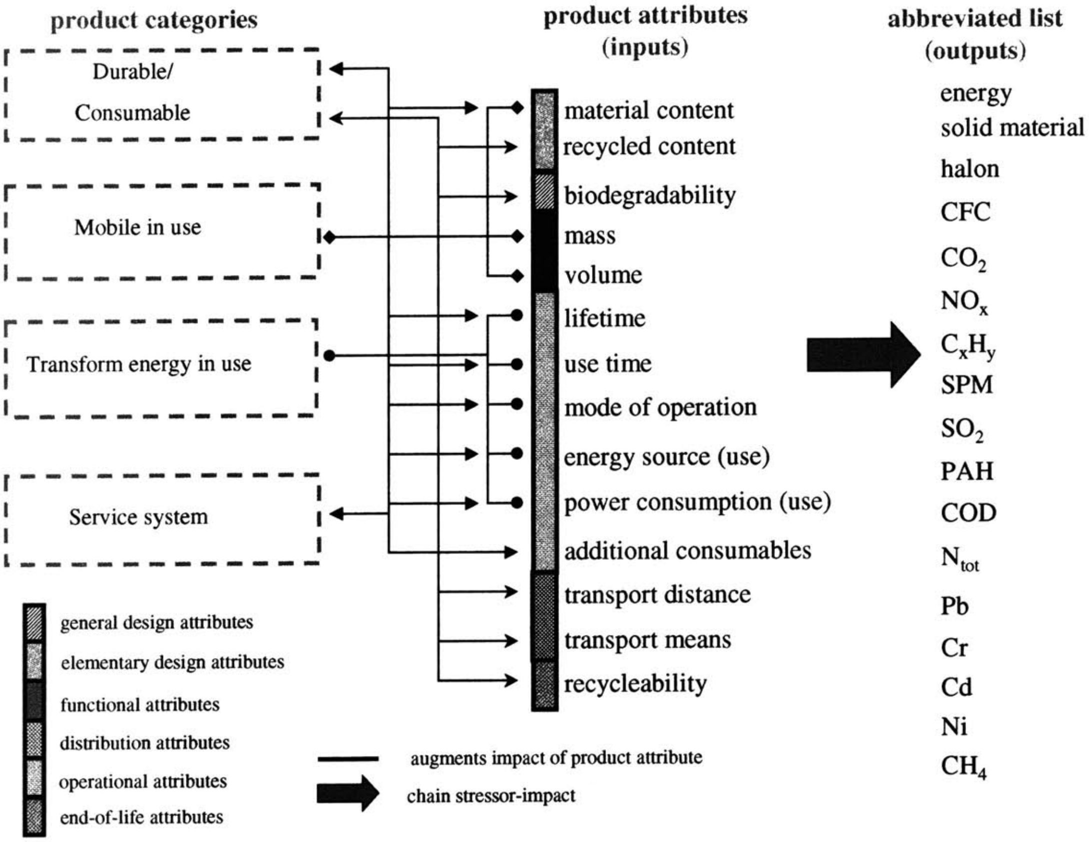


Figure 12: Product categories and corresponding relations with product attributes.

5.6.1 In Use Energy Transformation

The majority of environmental impacts caused by this type of product, frequently estimated at more than 90%, are related to energy conversion for consumption during the use phase (Alting and Legarth 1995; Hanssen 1999). Consequently, lifetime, use time, mode of operation, energy source and power consumption are dominant product attributes in causing significant environmental impacts.

5.6.2 In Use Mobility

Mass, volume, and material content indirectly affect the dominating impact of increased emissions and energy consumption for this type of product. The weight and size of a product in part determine the emissions and energy consumption generated by the transportation activity.

5.6.3 Durability

Durable products are expected to create higher flows in the use/reuse stage than consumable products. Therefore, all of the operational attributes—lifetime, use time, in use energy source, mode of operation, and power consumed—will contribute most significantly to environmental impact. Consumable products, on the other hand, are expected to produce higher flows upstream and downstream from the use phase. Thus, material content and the distribution attributes—distribution mass, distribution volume, means of transport, transport distance—will dominate in causality of environmental impact.

5.6.4 Service System

A product sold as part of a service system is expected to create higher flows in the use/reuse stage and significantly reduce upstream and downstream flows. Dominant product attributes are the same as those mentioned for durable goods. However, as services, these products potentially have typical ranges of impacts that are distinct (and likely less) from those caused by durable products. For example, a leased copier has a different life-cyle than one purchased by the customer.

6 The Surrogate Model as a Whole

With research on the product descriptors complete, testing of the surrogate model as a whole could begin. This entails compiling a database, using the database to train the neural net, and querying the model with a concept description it has never seen. Section 6.1 describes the process of compiling the database. Training and querying of the model are discussed in section 6.2.

6.1 Training Data

Given that data is collected from existing LCA studies it is important, as described in section 3.2.2, to introduce the origin of the data as well as test results. Data were compiled for 158 products of varying types; however, complete information could not be found for some descriptors—volume, biodegradability, transport distance, and transportation means—and life-cycle energy was the only abbreviated LCI list element with results from every product. Hence, the database was used in its most possible complete form for the 158 products.

Product information came from many different sources. In addition to those sources listed for the 48 products above were Keoleian (1997; 1998), Schuckert (1996), and data generated using TEAM® (Ecobilan 1996) based on EIME databases. The combination of many different sources made neural net performance testing also a test of data compatibility, as this is one of the limitations with multi-source data described in section 3.2.3.

Since data was difficult to collect due to proprietary issues, it was important that as much information as possible could be extracted from the collected data. Categorical (discrete) data sometimes contains more information than it appears (Fienberg 1980). Whenever possible, categorical data should be put in an ordered form. The importance of this statement was recognized during surrogate model testing.

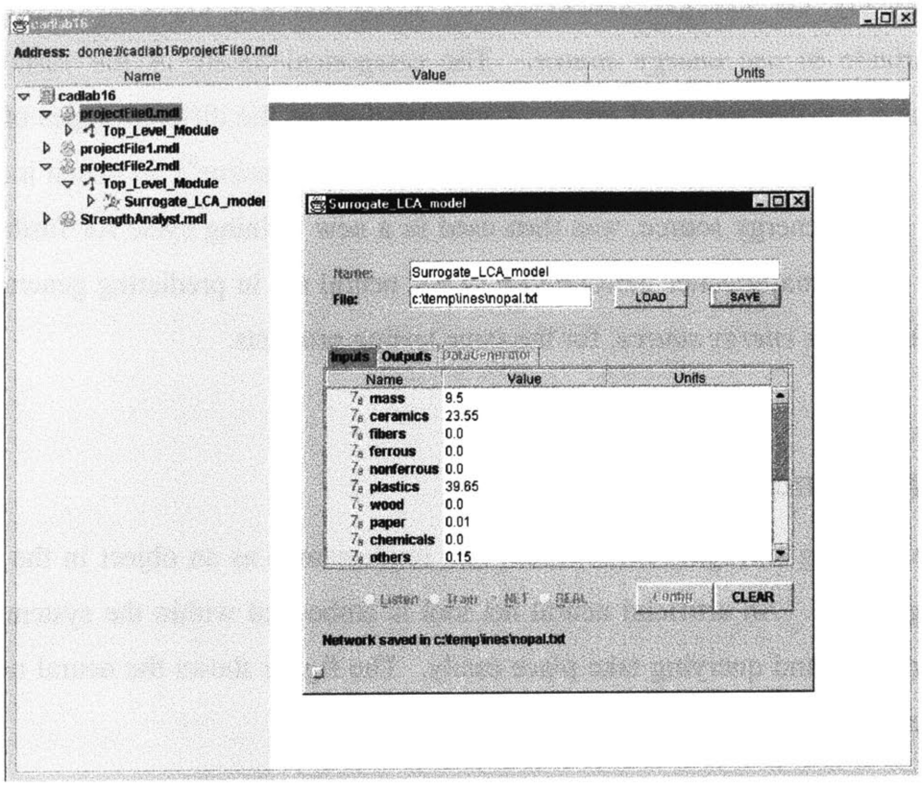
Originally, the surrogate model was not consistent with expected trends for the discrete variable *in use energy source*. The categorical nature of the variable was identified as a possible source of error. A new labeling of the different types of energy sources on a scale from zero (no energy source) to seven (gasoline[6]), to match increasing complexity of the energy source, was then used in a new training cycle for further tests. This led to substantially better performance of the neural net in predicting general trends when varying *in use energy source*, for the same testing products.

6.2 Performance

The learning surrogate LCA model was implemented as an object in the DOME system (Figure 13). An artificial neural net tool is embedded within the system (Deniz 2000), so training and querying take place easily. The figure shows the neural net being queried; the descriptor values have been entered as inputs.

---

[6] The scale was based only on those data in the training set. Other energy sources were not considered in the scale.



Address: dome://cadlab16/projectFile0.mdl

Name: Surrogate_LCA_model

File: c:\temp\ines\nopal.txt

Name	Value	Units
mass	9.5	
ceramics	23.55	
fibers	0.0	
ferrous	0.0	
nonferrous	0.0	
plastics	39.65	
wood	0.0	
paper	0.01	
chemicals	0.0	
others	0.15	

Network saved in c:\temp\ines\nopal.txt

Figure 13: The neural net as a DOME object.

A multiple input (descriptors), single output (life-cycle energy), feedforward, two-layer ANN with back propagation training (Bose 1996) was used. The hidden layer consisted of fifteen neurons. The network trained for 2 million epochs, which required 32 minutes on a 233 MHz Pentium® II processor.

The trained neural network was evaluated to assess the model's: absolute accuracy; precision in predicting relative differences; and ability to generalize trends. Tests were performed using six products with known LCA results, on which the ANN had *not* been trained. The six descriptor sets corresponding to these products were completely new to the network, simulating a new product concept description.

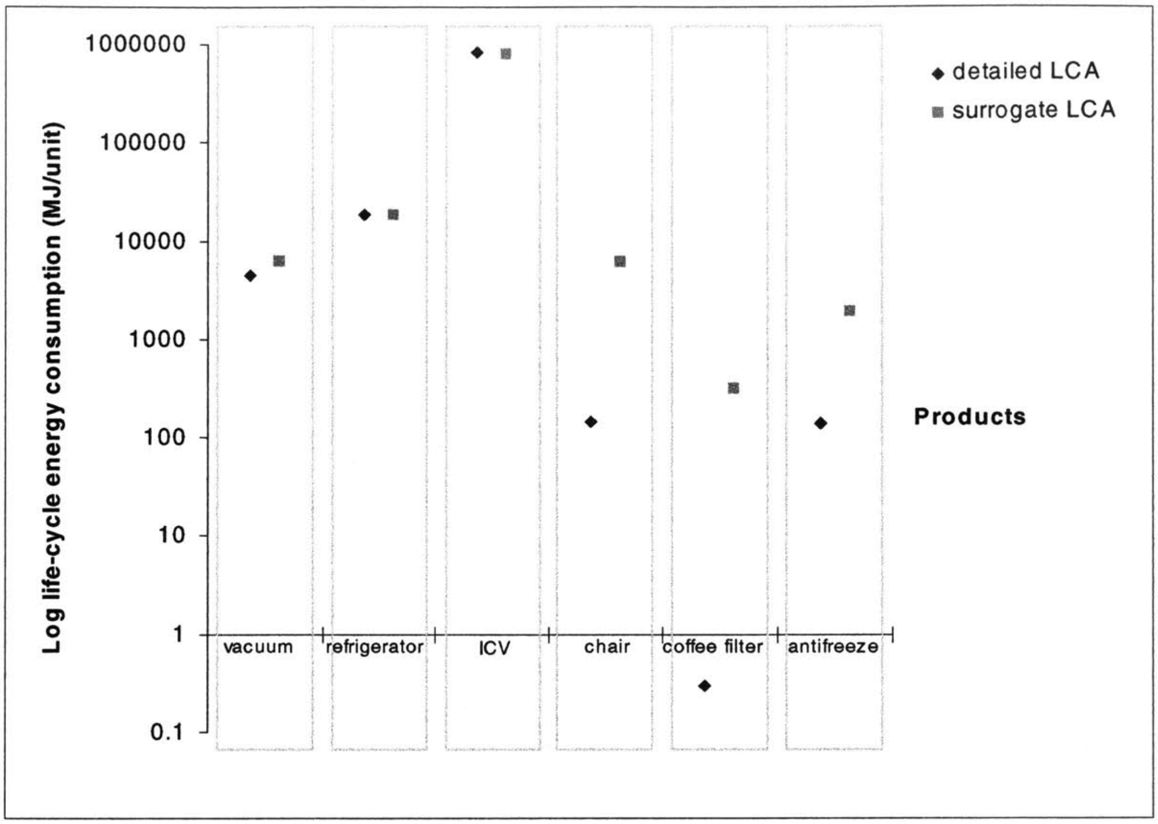


Figure 14: Accuracy comparisons for six products between the general surrogate LCA prediction and the detailed LCA result.

For durable goods like the vacuum cleaner, refrigerator and internal combustion vehicle (ICV) the life-cycle energy predictions were between 0.4 and 41 percent off of their targeted values (Figure 14). Given that the accuracy of life-cycle energy assessment from real LCA is typically ± 30 percent, (UK Ecolabeling Board 1992) these results seem satisfactory. The general surrogate model's accuracy was poor for products with small true values of life-cycle energy, as is exemplified by the results for the chair, coffee filter, and 1 gallon of antifreeze in Figure 14—with respective detailed LCA energy results of 149 MJ, 0.301 MJ, and 140 MJ.

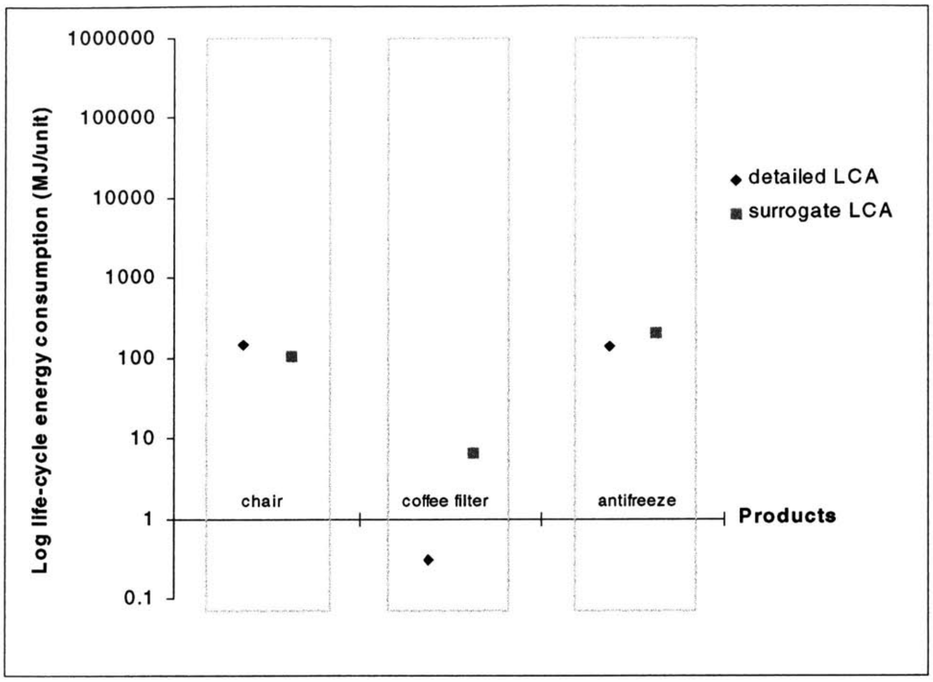


Figure 15: Comparison of life-cycle energy consumption for small-valued products predicted by the specialized surrogate LCA with those for detailed LCA results.

Thus, a data subset of 55 products with a reduced average level of life-cycle energy was used to train a specialized surrogate model. The improved accuracy for the chair, coffee filter, and antifreeze is shown in Figure 15. These results are improved, but not as good as for the larger-valued products. This may be due to the small size of the reduced training data set.

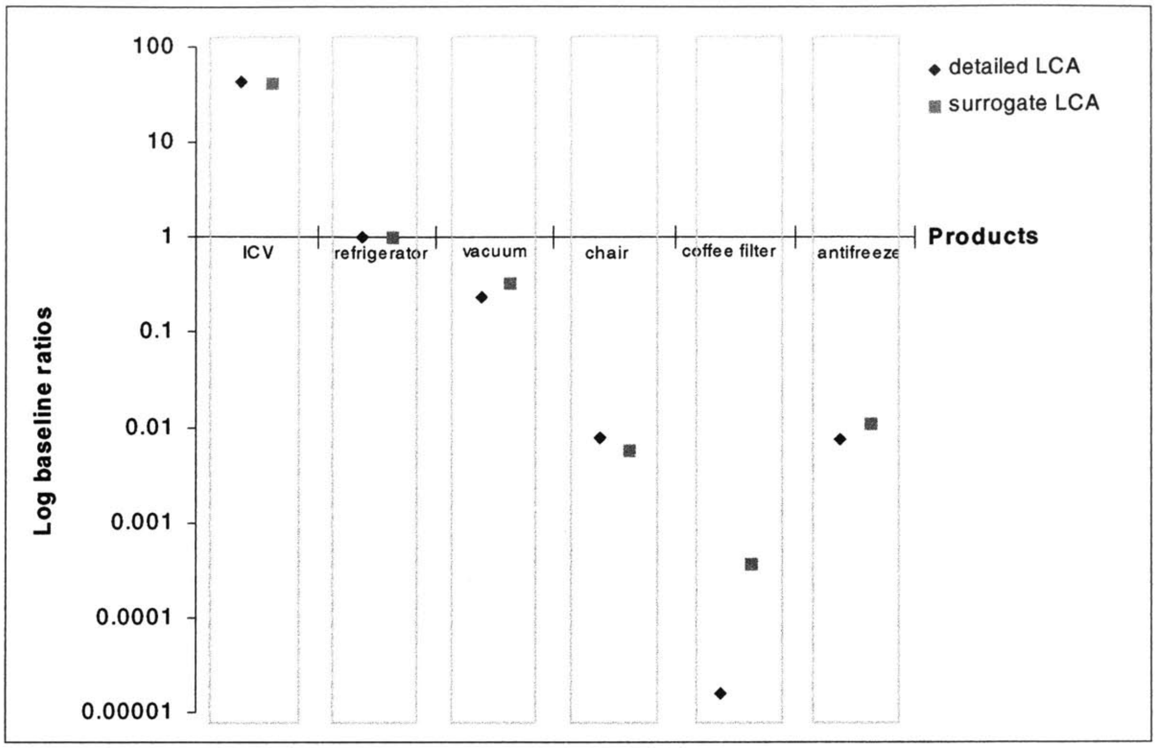


Figure 16: Relative comparisons of detailed and surrogate LCA results with the refrigerator as the baseline product.

The next test was to compare how the trained ANN would rank the different products in a relative sense. This is important if the ANN were used to compare very different design concepts. In Figure 16 the six different products are compared relative to the energy consumed by the refrigerator. Rank order remains the same for all products except the antifreeze, whose detailed LCA energy consumption value is almost identical to that of the chair.

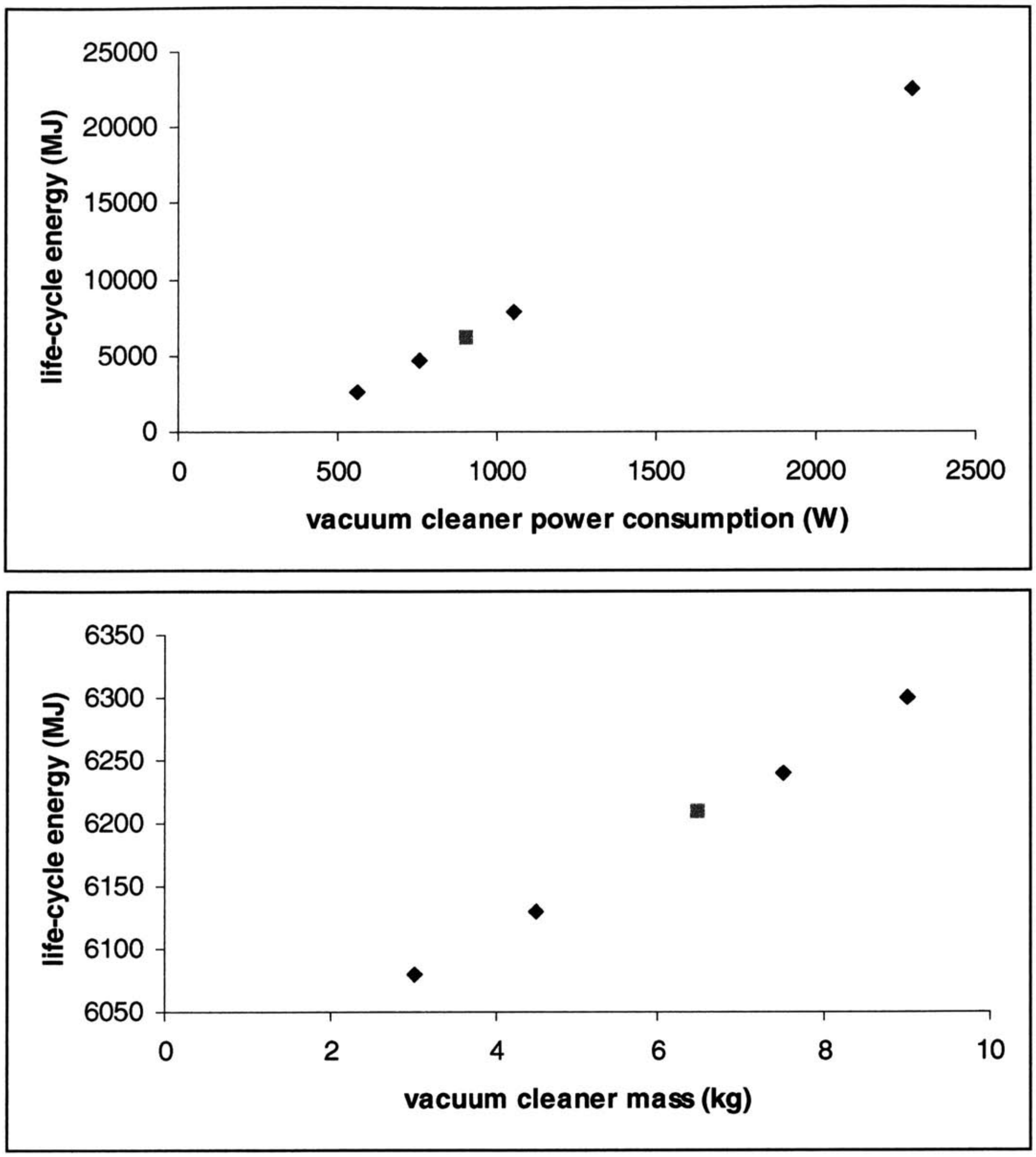


Figure 17: Results for power consumption and mass trends with respect to the vacuum cleaner are representative of those for all products tested.

Finally, the same six products were used to test the surrogate model's ability to generalize and predict trends correctly for a given product concept (Figure 17). The characteristics of each test-case product were held constant, with the exception of the attribute for which trends were being assessed—mass, power consumption, energy source, and use time. Mass and use time trends were assessed with all products, while power consumption and energy source were assessed only with the three products that transform energy. The results shown for the vacuum cleaner are representative in illustrating power consumption and mass trends as predicted by the surrogate LCA.

Energy Source trends also seemed appropriate for most products as illustrated by the vacuum cleaner in Figure 18. The energy source results are less certain because in some instances there were only a few products using a particular energy source in the training data set. Also, boundaries across energy sources may not have been consistent. For example: the human energy source products did not take into account the energy consumed and produced by humans; the solar energy source products regarded the solar cell as a black box—without consideration for the upstream effects of solar cell production. Additionally, it is not well understood how the ANN treats polytomous variables; correct predictions in trends for this variable were dependent on the ordering of the discrete choices as discussed in section 6.1.

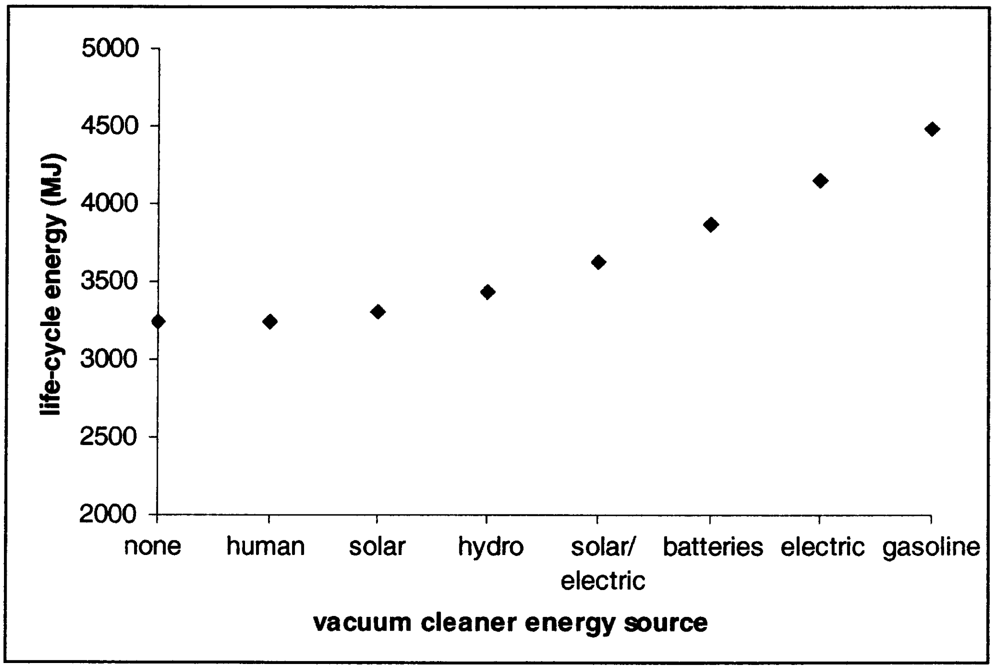


Figure 18: In use energy source trends for the vacuum cleaner.

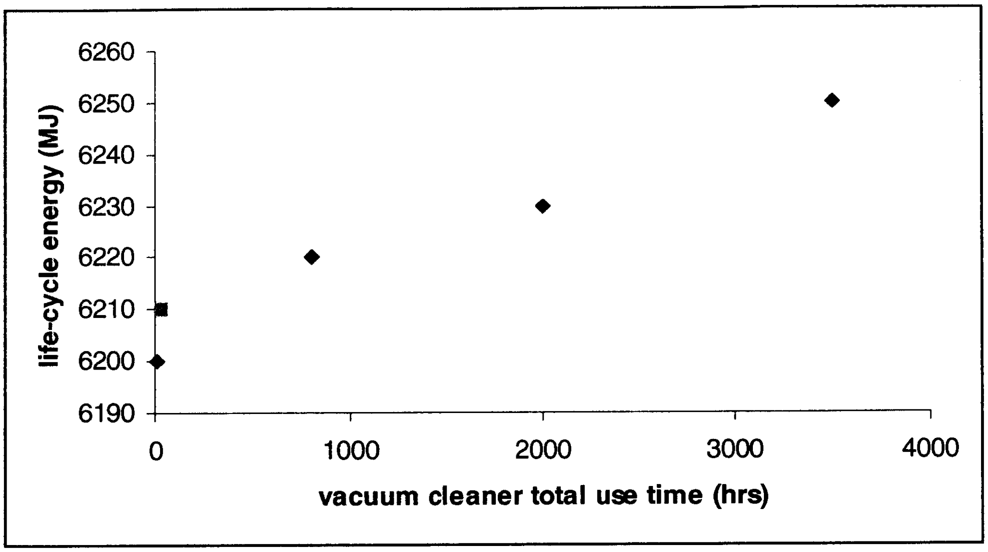


Figure 19: Small changes in life-cycle energy consumption resulted from drastic changes in use time.

Results produced in trying to assess trends with respect to use time were generally good; however, life-cycle energy changes were only seen through very large changes in use time (Figure 19). This may be due to the wide variety of use time values in the training data set across product groupings. For example, for products using an electric energy source, refrigerators are on all day, every day of their lives, while vacuum cleaners are used only every once in a while, i.e. for a smaller percentage of their lifetime. Classification could help in this situation as the neural net may not be able to directly link use time with life-cycle energy consumption as it should—there are products in the data set that have both lower and greater use times, with less energy consumption. Overall, the compilation of these tests confirmed the need to use a filtration process to group products with respect to dominant impacts.

7 Conclusions

The learning surrogate LCA model was developed with the idea of incorporating analytically based environmental assessment in early product design stages. The model's product descriptor input was developed through designer-known conceptual information that can be transformed to fully describe a product concept in an environmental sense. Development proceeded by gathering an extensive list of product descriptors from both environmental experts and designers. Then gradually, the list was narrowed motivated by ANN architecture complexity reduction measures. A series of tests ensured the final descriptor set was both known to concept designers and meaningful as fodder for the surrogate model.

Tests within the DOME integrated modeling environment have demonstrated it is possible to predict the life-cycle energy consumption of a product. A general surrogate model was able to rank products quite well with respect to life-cycle energy consumption and was numerically accurate to within 41% for products that transform energy. However, surrogate model tests and correlation tests both seemed to indicate the need for a product filtration technique to be incorporated in the learning surrogate model. Such a technique should improve accuracy. There is also a basis for the method to be used in predicting solid material, greenhouse effect, ozone layer depletion, acidification, eutrophication, winter smog, and summer smog.

The surrogate model provides a quick approach to evaluating the environmental performance of products with the guidance of an environmental expert. Use of the tool seems promising in allowing designers to learn about how the choices they make effect the Environment and in helping them to internalize these impacts. In this way, product descriptors provide a learning interface between environmental experts and designers—designers learn directly how minor or major design changes affect the Environment through models built on the knowledge of environmental experts.

8 Future Work

The future development of the surrogate model will focus mainly on the side of the environmental expert. This includes issues with pre-existing data, and use of the surrogate model. In terms of pre-existing data there are issues with in practice data availability and data management.

Pre-existing data is the core feature of the surrogate model—its availability is essential. Testing has been difficult due to lack of data, so it must be ensured that surrogate model developers have access to adequate data. Because it is proposed that environmental experts 'own' surrogate LCA models, data should not be a problem; however, they must be willing to provide this tool as a service. As the DOME system allows proprietary information to remain so, it would seem to suit an environmental expert's needs; nevertheless, contacts should be made throughout the environmental world to (1) study their reactions to the idea and (2) gain access to training data.

Due to lack of data mostly related to proprietary issues, some types of products may not have been sufficiently well represented to provide an optimal learning process during testing. Therefore, appropriate tests to check the ability of the neural network in adapting to new product concepts were difficult to design. However, it is hypothesized that a neural net given appropriate training data would be better at predicting impacts when queried with information on incremental products rather than innovative ones. Further tests could be conducted to determine to what extent a neural net could provide reasonable predictions for innovative products.

Management of pre-existing data will be a key issue for surrogate model users. In order to achieve a quick turn-around time, an appropriate LCA database must be kept at all times. This means descriptor and LCI information must be extracted from pre-existing LCA studies and stored for training. In terms of the surrogate model training process it is essential that this information is complete and as accurate as possible. This is perhaps one reason to revisit the abbreviated LCI list, as it was sometimes difficult to find data for all the elements. As well, it is essential that descriptors are defined properly—including appropriate ordering of categories for qualitative variables.

In this sense, the qualitative variables may require more research, as well as their relationships with the quantitative descriptors. The following data manipulation techniques may prove helpful: stepwise variable selection for regression, cross-classification of data for converting from quantitative to categorical and removing sparseness, collapsing across and within categorical variables, causal ordering, identifying fixed and sampling zeros, and methods for handling incomplete information (Bishop 1975; Fienberg 1980).

As research continues in product classification, the model's range of applicability should be broadened. Traditional product design is not the only area where this type of method would be helpful in the early stages of development to quickly assess and discard the most detrimental of concepts. Use of the model is aimed beyond traditional consumer product design, at being able to handle construction projects, policy issues, and other developmental ventures. As new product classifications are built, the product descriptor set should be revisited to ensure they fully describe the new class of products.

References

Abrahamson S, DR Wallace, N Senin, and P Sferro, "Integrated Design in a Service Marketplace," *Computer-Aided Design*, 32(2), 2000, pp.97-107.

Allenby, BR, *Design for Environment: Implementing Industrial Ecology*, Doctorate of Philosophy Dissertation, Rutgers University. NJ: Rutgers, 1992.

Alting, L and J Legarth, "Life-Cycle Engineering and Design," *Annals of the CIRP*, 44(2). 1995, pp.569-580.

Barnthouse L, J Fava, K Humphreys, R Hunt, L Laibson, S Noesen, JW Owens, JA Todd, B Vigon, K Weitz, and J Young, editors, *Life-Cycle Impact Assessment: The State-of-the-Art*. Pensacola, FL: Society of Environmental Toxicology and Chemistry (SETAC), 1997.

Baumann, Henrikke. Assistant Professor in the Environmental Systems Analysis Group, Chalmers University of Technology, Sweden. Personal communication, March 2000.

Bhamra, TA, S Evans, TC McAloone, M Simon, S Poole, and A Sweatman, "Integrating Environmental Decisions into the Product Development Process: Part 1 The Early Stages," *First International Symposium on Environmentally Conscious Design and Inverse Manufacturing*. IEEE, 1999, pp.329-333.

Bishop, YMM, SE Fienberg, and PW Holland, *Discrete Multivariate Analysis: Theory and Practice*. Cambridge, MA: The MIT Press, 1975.

Borland, N and DR Wallace, "Environmentally Conscious Product Design: A Collaborative Internet-based Modeling Approach," to appear in the *Journal of Industrial Ecology*, 1999.

Borland, N, DR Wallace, and HP Kaufmann, "Integrating Environmental Impact Assessment Into Product Design," *Proceedings of 1998 ASME Design Engineering Technical Conference*, DETC98/DFM-5730. Atlanta, GA: Georgia Institute of Technology, 1998.

Bose, NK and P Liang, *Neural Network Fundamentals with Graphs, Algorithms, and Applications*. New York, NY: McGraw-Hill, Inc., 1996.

Brezet, H, A Stevels, and JP Rombouts, "LCA for EcoDesign: The Dutch Experience," *First International Symposium on Environmentally Conscious Design and Inverse Manufacturing*. IEEE, 1999, pp.36-40.

Brezet H and C van Hemel, *Ecodesign: A Promising Approach to Sustainable Production and Consumption.* Paris, France: United Nations Environmental Program (UNEP) Industry and Environment, 1997.

Clark, T and M Charter, *Eco-design Checklists for Electronic Manufacturers, Systems Integrators, and Suppliers of Components and Sub-assemblies,* 1999. http://www.cfsd.org.uk.

Consoli F, D Allen, I Boustead, J Fava, W Franklin, AA Jensen, N deOude, R Parrish, R Perriman, D Postlethwaite, B Quay, J Séguin, and B Vigon, editors, *Guidelines for Life-Cycle Assessment: A "Code of Practice".* Pensacola, FL: Society of Environmental Toxicology and Chemistry (SETAC), 1993.

De Schepper, M, *An LCA-datamodel for Use in Conceptual Integrated Product Design,* Research Project conducted at MIT. Delft, The Netherlands: Industrial Design Engineering, Delft University of Technology, 1999.

Deniz, JC, *Learning Theory Applications to Product Design Modeling,* Master of Science in Mechanical Engineering. Cambridge, MA: Massachusetts Institute of Technology, 2000.

Design for Sustainability (DfS) Group, TU Delft. Various student LCA research reports on consumer products conducted from 1994-1997.

Devore, JL, "Chapter 13 Nonlinear and Multiple Regression," *Probability and Statistics for Engineering and the Sciences,* 4th edition. Belmont, CA: Wadsworth, Inc., 1995.

EcoBilan. TEAM® 2.0 Users Manual. 1996.

Ehrenfeld, JR, "Colorless Green Ideas Sleep Furiously: Is the Emergence of 'Sustainable' Practices Meaningful?," *Greening of Industry Conference.* Rome, 1998.

Environmental Defense, *Product Take-Back,* 1999. http://www.environmentaldefense.org/programs/PPA/vlc/take_back.html

Fienberg, SE, *The Analysis of Cross-Classified Categorical Data,* 2nd edition. Cambridge, MA: The MIT Press, 1980.

Fiksel, J, *Design for Environment: Creating Eco-efficient Products and Processes.* New York: McGraw-Hill, 1996.

Franklin Associates, Ltd., *Energy and Environmental Profile Analysis of Children's Disposable and Cloth Diapers.* Prairie Village, KS: FAL, 1990.

Franklin Associates, Ltd., *Life Cycle Assessment of Ethylene Glycol and Propylene Glycol Based Antifreeze.* Prairie Village, KS: FAL, 1994.

Graedel, T, B Allenby, and P Combrie, "Matrix Approaches to Abridged Life-Cycle Assessment," *Environmental Science and Technology.* 29(3), 1995, pp.134-139.

Hanssen, OJ, *Sustainable Industrial Product Systems: Integration of Life Cycle Assessment in Product Development and Optimization of Product Systems,* Doctor Techn. Thesis. Trondheim: Norwegian University of Science and Technology, 1996.

Hanssen, OJ, "Sustainable product systems – experiences based on case projects in sustainable product development," *Journal of Cleaner Production,* vol. 7, 1999, pp.27-41.

Hubka, V, translated and edited by WE Eder, *Principles of Engineering Design.* London: Butterworth & Co Ltd., 1982.

Hubka, V and WE Eder, *Engineering Design: General Procedural Model of Engineering Design.* Zürich, Switzerland: Heurista, 1992. ISBN 3-85693-026-4.

Keoleian, G, K Kar, M Manion, and J Bulkley, *Industrial Ecology of the Automobile; A Life Cycle Perspective.* Society of Automotive Engineers, Inc. 1997.

Keoleian, G, "Is environmental improvement in automotive component design highly constrained? – an instrument panel case study," *Journal of Industrial Ecology,* 2(2). 1998, pp.103-117.

Kitzmiller, C and Jagannathan, V, "Design in a Distributed Blackboard Framework, Intelligent CAD," *Proceedings of IFIP TC/WG 5.2 Workshop on Intelligent CAD.* North-Holland, Amsterdam, 1989, pp.223-233.

Lindahl, M, "A New Promising Tool for Efficient Design for Environment," *Proceedings of the First International Symposium on Environmentally Conscious Design and Inverse Manufacturing.* IEEE, 1999, pp.734-739.

Linton, JD, "An Investigation of the Feasibility of Using a Standardized Impact Database for Conducting Life Cycle Assessment of Products and Design Options," *Proceedings of the 6th International Seminar on Life Cycle Engineering.* Kingston, Ontario, Canada: Queen's University, 1999, pp.432-442.

Masters, T, *Practical Neural Network Recipes in C++.* San Diego, CA: Academic Press, 1993.

McAloone, TC, TA Bhamra, and S Evans, "Success in Environmentally Conscious Design: How is it Achieved and Maintained?," *Proceedgins of the 1998 IEEE International Symposium on Electronics and the Environment.* IEEE, 1998, pp.171-175.

Meuller, KG and CB Besant, "Streamlining life cycle analysis: a method," *EcoDesign '99: First International Symposium on Environmentally Conscious Design and Inverse Manufacturing*. IEEE, 1999, pp.114-119.

Pahng, KF, N Senin, and DR Wallace, "Distributed Modeling and Evaluation of Product Design Problems," *Computer-Aided Design*. 30(6), 1998, pp.411-423.

Peters, A, A Sharma, K Weitz, and J Baskir, *Streamlining LCA Case Study Report: Liquid and Powder Coatings*, draft report. Research Triangle Park, NC: RTI, 1996.

Potts, Amy. Principal Designer, Potts Design, Stoneham, MA. Personal communication, February 2000.

PRé Consultants, *PRé Consultants BV and SimaPro LCA Software*, http://www.pre.nl/, 1999.

Reuleaux, F, translated by HH Suplee, *The Constructor: A Hand-book of Machine Design*. New York: The Engineering Magazine, 1904.

Rombouts, JP, "LEADS-II: A knowledge-based system for ranking DfE-Options," *Proceedings of the 1998 IEEE International Symposium on Electronics and the Environment*. IEEE, 1999, pp.287-291.

Schuckert, K, K Saur, H Florin, P Eyerer, H Beddies, J Sullivan, J Hu, "Life cycle analysis: getting the total picture on vehicle engineering alternatives," *Automotive Engineering*. 1996, pp.49-52.

SETAC (1999), *Streamlined Life-Cycle Assessment: A Final Report from the SETAC North America Streamlined LCA Workgroup*, eds. Todd, J. A. and M. A. Curran. Pensacola, FL: Society of Environmental Toxicology and Chemistry and SETAC Foundation for Environmental Education, 1999. http://www.setac.org/.

Sfantsikopoulos, M and D Pantelis, "Concurrent product design and environmentally conscious manufacturing". Edited by Samir Bilatos and Hong Zhang. *1997 ASME International Mechanical Engineering Congress and Exposition*. DE-Vol.94, MED-Vol.5. Dallas, Texas: 1997, pp 207-213.

Sharma, A, K Weitz, A Peters, and J Baskir, *Streamlining LCA Case Study Report: Disposable Versus Reusable Shop Towels*, draft report. Research Triangle Park, NC: RTI, 1996a.

Sharma, A, K Weitz, A Peters, and J Baskir, *Streamlining LCA Case Study Report: Recycled and Virgin Newsprint*, draft report. Research Triangle Park, NC: RTI, 1996b.

SimaPro 4 User's Manual. The Netherlands: PRé Consultants BV, 1999. http://www.pre.nl last updated 1/14/00.

Sousa, I., Wallace, D. R., Borland, N. and J. Deniz, "A Learning Surrogate LCA Model for Integrated Product Design," *Proceedings of the 6th International Seminar on Life Cycle Engineering*. Kingston, Ontario, Canada: Queen's University, 1999, pp.209-219.

SPSS Inc., *SPSS® Base 10.0 Applications Guide*. Chicago, SPSS Inc., 1999.

Susskind, L, MIT Lecture on Environmental Impact Assessment, January 2000.

UK Ecolabeling Board, *Ecolabeling criteria for washing machines*. PA Consulting Group,1992.

Ulrich, KT and SD Eppinger, *Product Design and Development*, New York, NY: McGraw-Hill, Inc., 1995.

US Congress, Office of Technology Assessment, *Green Products by Design: Choices for a Cleaner Environment*, OTA-E-541. Washington, DC: US Government Printing Office, 1992.

Appendices

Appendix A: Product Descriptor Definitions

Attribute name	**definition (example of value, ranking, and binary levels of information) (short example)**
manufacturing cost	unit manufacturing cost (e.g., $65, high-mid-low cost, n/a)
product price	unit selling price of product (e.g., $65, high-mid-low price, n/a)
lifetime	life period of product once it is produced until it is disposed of (e.g., 5 years, long-mid-short lifetime, n/a)
in use energy source	type of energy source when in use (e.g., batteries vs. solar vs. wall outlet, n/a, does [not] need an energy source during use)
manufacturing process	main process used in manufacturing (e.g., anodizing vs. casting vs. welding, n/a, [no] associated manufacturing process)
in use power consumed	power consumption when in use (e.g., 60 W, high-mid-low wattage, [no] power consumed while in use)
in use operation	main mode of operation (e.g., manual on/off vs. standby vs. sensor control, n/a, does [not] require power)
in use hours of operation	number of daily hours in use (e.g., 24 hr, continuous-some-limited usage, does [not] require power)
durability	endurance for wear or decay (e.g., time to failure, tougher-same-more fragile, n/a)
modularity	product integrates a combination of distinct building blocks or modules (e.g., # of modular components, more-average-less components, is [not] modular) (e.g., electric motor systems)
serviceability	ease of maintenance when needed (e.g., time required by technician, high-mid-low level of servicability, does [not] require service)
upgradability	product accommodates evolutionary technological or user needs through upgrades (e.g., n/a, high-mid-low level of upgradability, can[not] accommodate upgrades)
assemblability	ease of assembly (e.g., # of parts or fasteners, high-mid-low level of assemblability, assembly [not] applicable) (e.g., product parts are assembled in a single, linear motion)
disassemblability	ease of disassembly to recover/separate parts and materials (e.g., # of parts or fasteners, high-mid-low level of disassemblability, disassembly [not] applicable)

in use flexibility	product can be configured by the user to exhibit different capabilities (e.g., # of configurations, high-mid-low level of in use flexibility, single or multi-functional) (e.g., 35mm cameras can be used with different lenses and flash options)
recyclability	product is easily recycled after use (e.g., % product that can be recycled, high-mid-low level of recyclability, can[not] be recycled)
reusability	able to be reused (e.g., # of times reused, more-same-less reuse, can[not] be reused)
strength	product exhibits strength properties (e.g., 80kPa, higher-mid-lower strength, n/a) (e.g., oxygen bottle made of aluminum liner, reinforced epoxy and glass fiber to provide high strength and hardness so that bottle does not explode under high pressure or when knocked)
mass	total product mass (e.g., 8 kg, more-same-less mass, [no] mass) (e.g., a service or data file has no mass)
product volume	product volume (e.g., 42 m^3, more-same-less volume, [no] volume)
conductivity	product contains conductive materials (e.g., %, more-same-less amount used, [no] conductive materials used) (e.g., gold plating enables good contacts and thus reduction of information loss in printed circuit board)
biodegradability	product contains biodegradable materials (e.g., %, more-same-less amount used, [no] biodegradable materials used) (e.g., pen made of biodegradable material that degrades when disposed in a composting site)
polymers	product contains polymers (e.g., %, more-same-less amount used, [no] polymers used) (e.g., PET, PC, PVC, ABS)
paper	product contains of paper (e.g., %, more-same-less amount used, [no] paper used) (e.g. a label)
wood	product contains wood (e.g., %, more-same-less amount used, [no] wood used) (e.g., pine, linden, chestnut)
ferrous metals	product contains ferrous metals (e.g., %, more-same-less amount used, [no] ferrous metals used) (e.g., steel, cast iron)
nonferrous metals	product contains nonferrous metals (e.g., %, more-same-less amount used, [no] nonferrous metals used) (e.g., aluminum, copper, zinc)
ceramics	product contains ceramics (e.g., %, more-same-less amount used, [no] ceramics used) (e.g., oxides, porcelain, stoneware)
glass	product contains glass (e.g., %, more-same-less amount used, [no] glass used) (e.g., decor glass, toughened glass)
fibers	product contains fibers (e.g., %, more-same-less amount used, [no] fibers used) (e.g., cotton, nylon, cloth, wool, polyester)
fluids/lubricants	product contains fluids/lubricants (e.g., %, more-same-less amount used, [no] fluids used)

concrete	product contains concrete (e.g., %, more-same-less amount used, [no] concrete used)
post-consumer material	product contains post-consumer material (e.g., %, more-same-less amount used, [no] post-consumer material used) (e.g., recycled paperboard)
other materials	product contains other materials (e.g., %, more-same-less amount used, [no] other materials used)
distribution volume	total product volume including packaging (e.g., 60 m^3, more-same-less volume, [no] volume)
transport distance	total transport distance in product's life-cycle (e.g., 5000 km, farther-same-shorter, transport [un]necessary)
means of transportation	means of transportation (e.g., train vs. vehicle vs. airplane, n/a, transport [un]necessary)

Appendix B: The On-line Survey

(http://attributes.n3.net)

This survey was organized in an effort to identify what designers know about their products during the *conceptual phase* of design. Your responses will help advance our research at MIT in the Center for Innovation in Product Development (CIPD). Thank you in advance! - Ines Sousa (iss@mit.edu) and Julie Eisenhard (liberty@mit.edu)

Please enter your name and company information.

Last name: ☐ First name: ☐

Company: ☐

---

1 Please mark the type of information you know (or can easily find out) about the following product attributes while in the *conceptual phase* of design. Attribute definitions can be found by clicking on their appropriate names (a second browser window will pop up). Use the following examples as 'definitions' for the levels of information:

- if you are able to specify or estimate an attribute in a qualitative or quantitative sense, select ***value***.
- if you cannot specify the attribute, but would be able to rank concepts with respect to the attribute, select ***ranking***.
- if you know whether or not your product will contain (e.g.) polymers, but cannot estimate the percentage or rank a concept among others with respect to polymers, select ***binary***.
- if the attribute is not able to be known in conceptual design, select ***unknown***.
- if the attribute does not at all apply to the types of products you design, select ***N/A***.

Product Attribute Name	known: at what level?			unknown	N/A
	value	ranking	binary		
manufacturing cost	☐	☐	☐	☐	☐
product price	☐	☐	☐	☐	☐
lifetime	☐	☐	☐	☐	☐
in use energy source	☐	☐	☐	☐	☐
manufacturing process	☐	☐	☐	☐	☐

in use power consumed	☐	☐	☐	☐	☐
in use operation	☐	☐	☐	☐	☐
in use hours of operation	☐	☐	☐	☐	☐
durability	☐	☐	☐	☐	☐
modularity	☐	☐	☐	☐	☐
serviceability	☐	☐	☐	☐	☐
upgradability	☐	☐	☐	☐	☐
assemblability	☐	☐	☐	☐	☐
disassemblability	☐	☐	☐	☐	☐
in use flexibility	☐	☐	☐	☐	☐
recyclability	☐	☐	☐	☐	☐
reusability	☐	☐	☐	☐	☐
strength	☐	☐	☐	☐	☐
mass	☐	☐	☐	☐	☐
product volume	☐	☐	☐	☐	☐
conductivity	☐	☐	☐	☐	☐
biodegradability	☐	☐	☐	☐	☐
polymers	☐	☐	☐	☐	☐
paper	☐	☐	☐	☐	☐
wood	☐	☐	☐	☐	☐
ferrous metals	☐	☐	☐	☐	☐
nonferrous metals	☐	☐	☐	☐	☐
ceramics	☐	☐	☐	☐	☐
glass	☐	☐	☐	☐	☐
fibers	☐	☐	☐	☐	☐
fluids/lubricants	☐	☐	☐	☐	☐
concrete	☐	☐	☐	☐	☐
post-consumer material	☐	☐	☐	☐	☐

other materials	☐	☐	☐	☐	☐
distribution volume	☐	☐	☐	☐	☐
transport distance	☐	☐	☐	☐	☐
means of transportation	☐	☐	☐	☐	☐
Other (please indicate):					
☐	☐	☐	☐	☐	☐
☐	☐	☐	☐	☐	☐
☐	☐	☐	☐	☐	☐
☐	☐	☐	☐	☐	☐
☐	☐	☐	☐	☐	☐

---

2 How you would characterize the products you design? (Check all that apply.)

☐ aerospace/defense	☐ housewares	☐ toys
☐ automotive	☐ industrial equipment	Other (please indicate)
☐ buildings/building materials	☐ medical	☐
☐ chemical	☐ packaging	☐
☐ consumer electronics	☐ shoes	☐
☐ exhibits	☐ soft goods (textiles)	☐
☐ furniture	☐ sporting goods	☐

---

3 If you feel you have absolutely no experience in environmentally conscious design, you may skip to section 4 now.

> **A** Which do you think are the most important attributes from an environmental standpoint from the attributes listed below? (Check all that apply.)

☐ manufacturing cost	☐ serviceability	☐ conductivity	☐ fluids/lubricants
☐ product price	☐ upgradability	☐ biodegradability	☐ concrete

☐ lifetime	☐ assemblability	☐ polymers	☐ post-consumer material
☐ in use energy source	☐ disassemblability	☐ paper	☐ other materials
☐ manufacturing process	☐ in use flexibility	☐ wood	☐ distribution volume
☐ in use power consumed	☐ recyclability	☐ ferrous metals	☐ transport distance
☐ in use operation	☐ reusability	☐ nonferrous metals	☐ means of transportation
☐ in use hours of operation	☐ strength	☐ ceramics	☐
☐ durability	☐ mass	☐ glass	☐
☐ modularity	☐ product volume	☐ fibers	☐

B Background: You are designing a product. Suppose all else remains equal; the following 5 decisions will affect *only* the environmental performance of the product. The boxes below represent stages of the thought process, or a chain of logic, you would go through when making a decision in each of the 5 presented cases with respect to the product you are designing. Please let us know the product you are designing: .

Instructions: In each case:

1. make a realistic decision;
2. then select the impact category for which you feel your decision will have the most impact (positive or negative). Try to select a different impact category to think about for each decision.
3. Fill in as many or as few of the boxes in between to try to help us understand how you link these two selections. If you run out of boxes, simply insert a comma between your thoughts within a box.

Example (see below): If I am making a decision with regard to the attribute means of transport, perhaps I would select [cargo truck] from the drop menu as the means for transporting my product. Then, I might choose [particulates] as my impact category from that drop menu. I chose this category because I associate cargo trucks with [low fuel economy], therefore [more diesel fuel consumption], therefore a [greater amount of particulate emissions], where the brackets represent the boxes below. Feel free to edit the example if you don't agree with our decision or our logic!

Decision Example: Means of Transport

airplane
ship
[✓ cargo truck]
train

↓

low fuel economy

↓

more diesel

↓

more particulate

↓

______

↓

Decision 1: Material choice

plastic
paper
glass
aluminum

↓

______

↓

______

↓

______

↓

______

↓

Decision 2: Reusability

disposable
reusable once
reusable multiple times

↓

______

↓

______

↓

______

↓

______

↓

Choose the category below, on which your decision above will have the most impact.

[✓ CO2]
life-cycle energy
CFC
solid material
particulates
NOx
SO2

CO2
life-cycle energy
CFC
solid material
particulates
NOx
SO2

CO2
life-cycle energy
CFC
solid material
particulates
NOx
SO2

Decision 3: In use energy source

[✓ batteries]
public electricity
gasoline
diesel

↓

______

Decision 4: Manufacturing process

[✓ rapid prototyping]
casting metals
plastic molding
shaping powder

↓

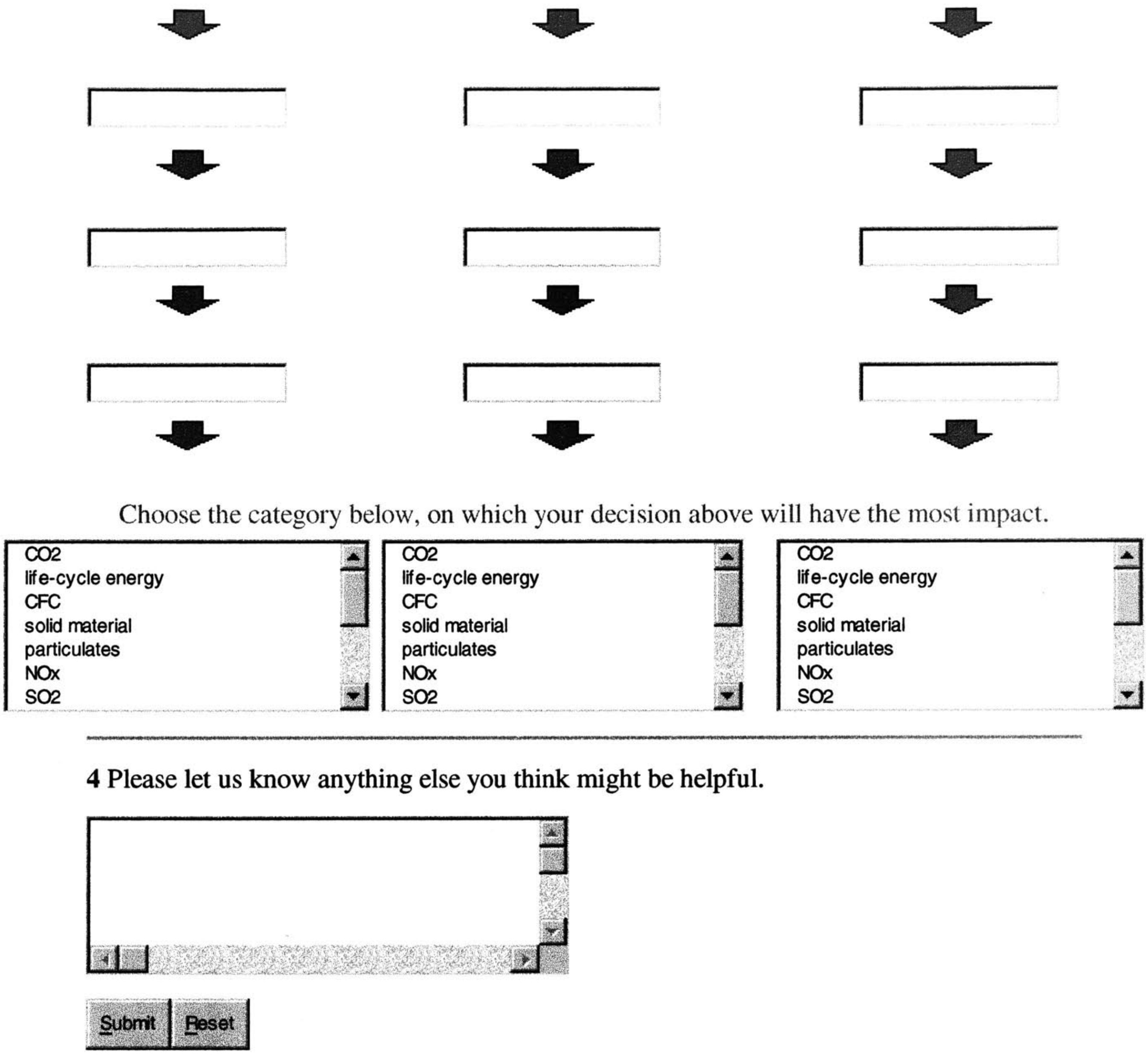
______

Decision 5: In use operation

[✓ constant use]
manual on/off
stand-by mode
sensor (e.g. thermostat, motion)

↓

______

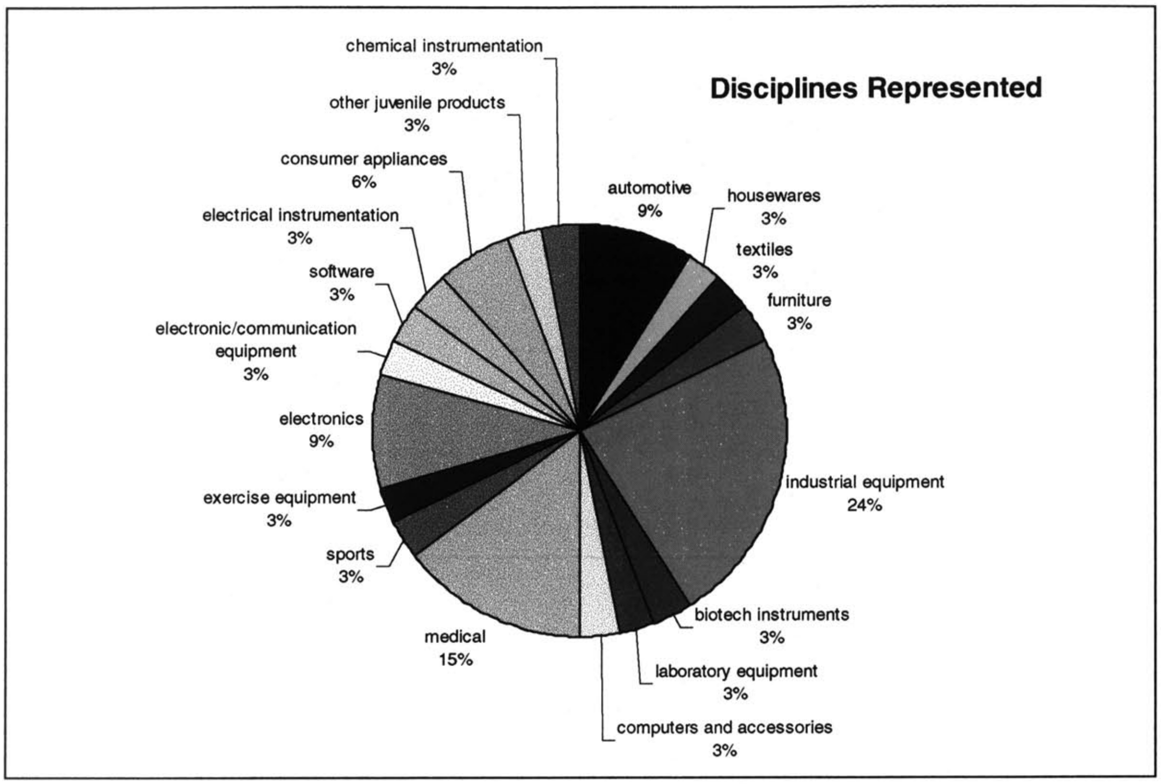


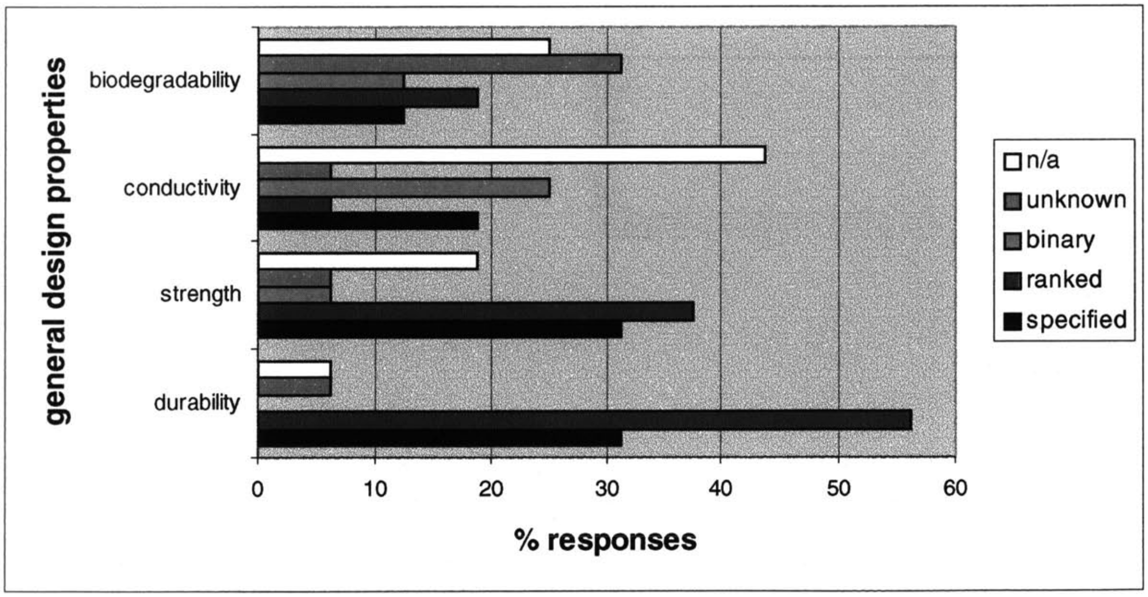
Choose the category below, on which your decision above will have the most impact.

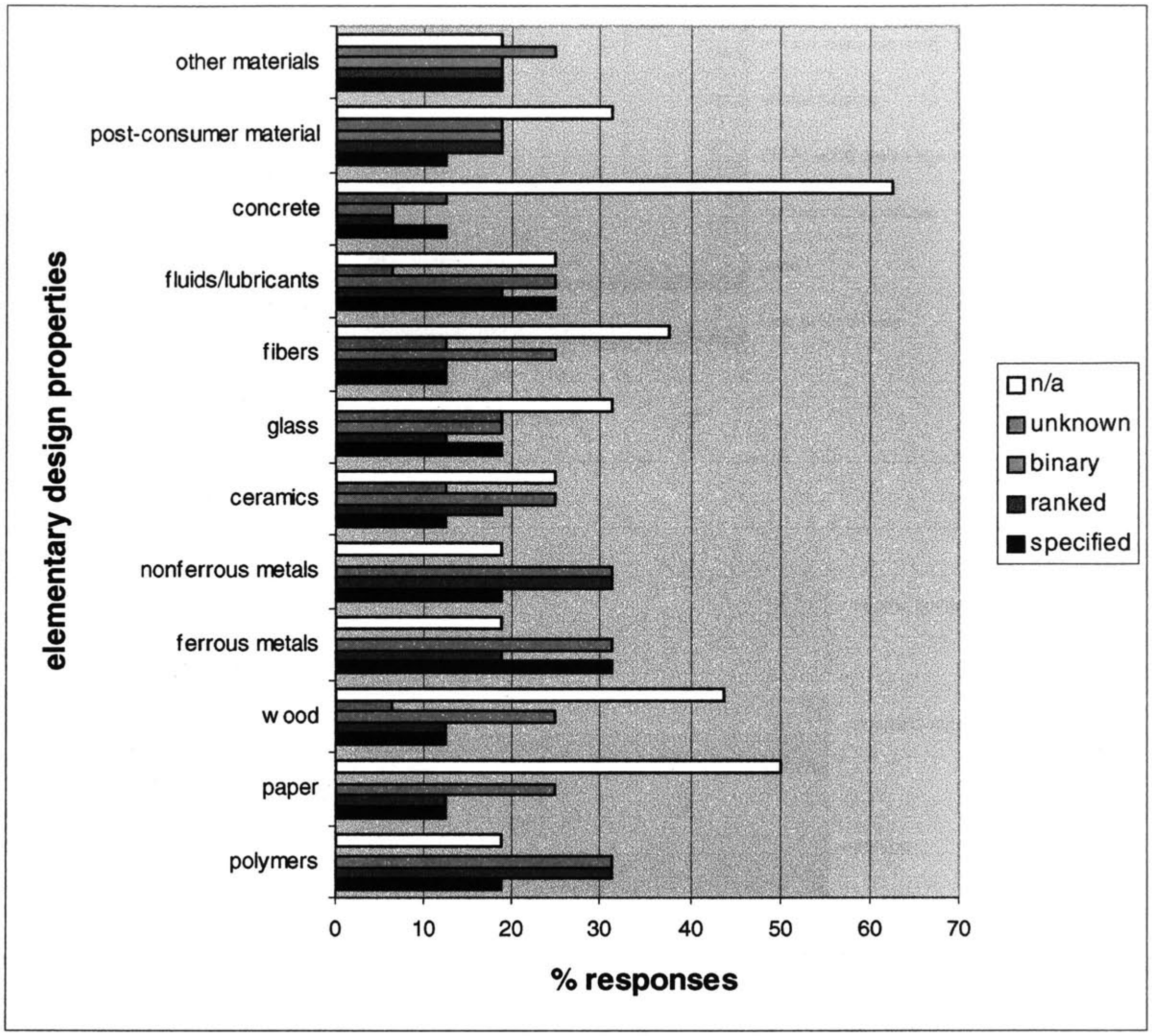
4 Please let us know anything else you think might be helpful.

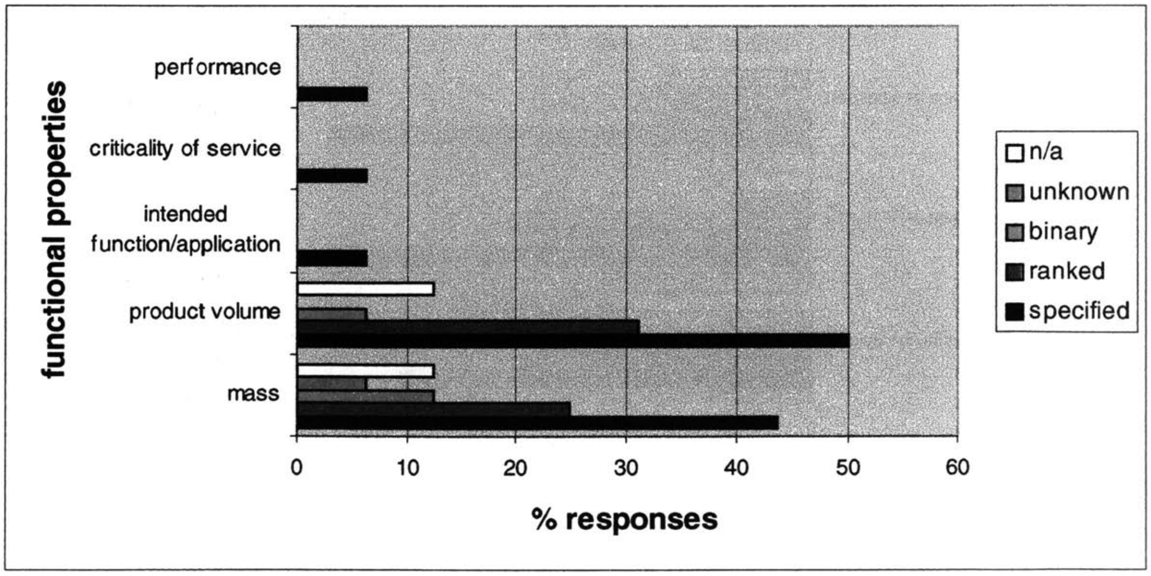
THANK YOU!

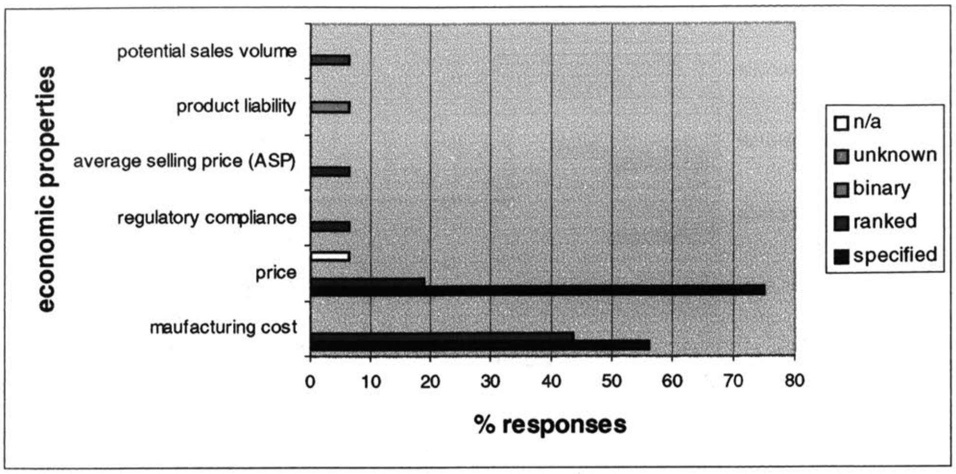
Appendix C: Complete Survey Results

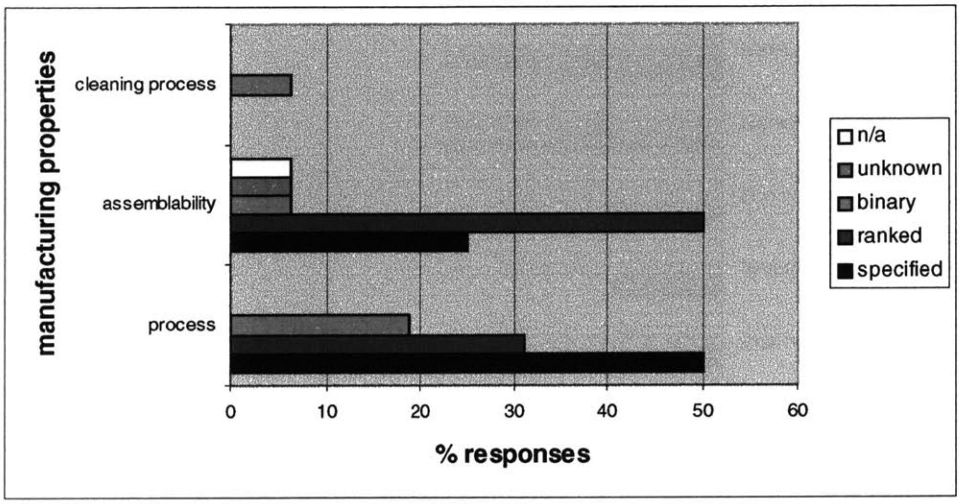


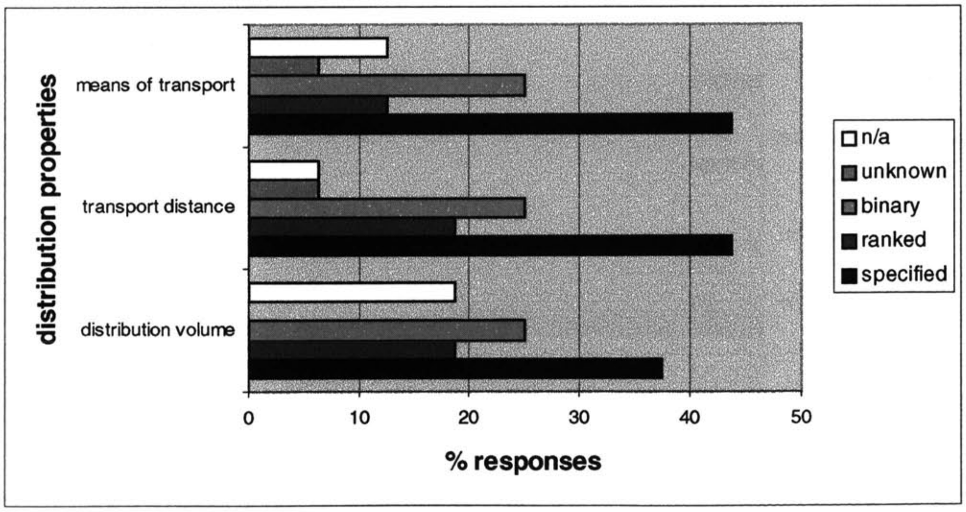


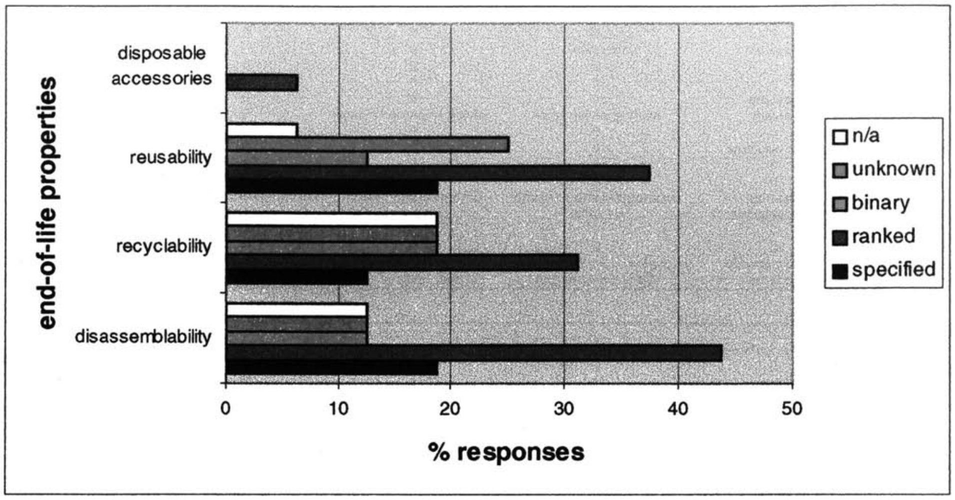

elementary design properties
other materials
post-consumer material
concrete
fluids/lubricants
fibers
glass
ceramics
nonferrous metals
ferrous metals
wood
paper
polymers
0
10
20
30
40
50
60
70
% responses
n/a
unknown
binary
ranked
specified


functional properties
performance
criticality of service
intended function/application
product volume
mass
0
10
20
30
40
50
60
% responses
n/a
unknown
binary
ranked
specified


economic properties
potential sales volume
product liability
average selling price (ASP)
regulatory compliance
price
maufacturing cost
0
10
20
30
40
50
60
70
80
% responses
n/a
unknown
binary
ranked
specified


manufacturing properties
cleaning process
assemblability
process
0
10
20
30
40
50
60
% responses
n/a
unknown
binary
ranked
specified


distribution properties
means of transport
transport distance
distribution volume
0
10
20
30
40
50
% responses
n/a
unknown
binary
ranked
specified



	Example Case:					
	Means of Transport					
0	cargo truck	low fuel economy	more diesel consumption	more particulate emissions	0	particulates
Metal analyzer	cargo truck	low fuel economy	more diesel consumption	more particulate emissions	0	particulates
0	cargo truck	low fuel economy	more diesel consumption	more particulate emissions	0	particulates
0	cargo truck	low fuel economy	more diesel consumption	more particulate emissions	0	particulates
personal transportation	cargo truck	low fuel economy	more diesel consumption	more particulate emissions	0	particulates
automobile	cargo truck	low fuel economy	more diesel consumption	more particulate emissions	0	particulates
brain monitor	cargo truck	low fuel economy	more diesel consumption	more particulate emissions	0	particulates
Industrial Pump	cargo truck	low fuel economy	more diesel consumption	more particulate emissions	0	particulates
0	cargo truck	low fuel economy	more diesel consumption	more particulate emissions	0	particulates
0	cargo truck	low fuel economy	more diesel consumption	more particulate emissions	0	particulates
defibrillator	cargo truck	low fuel economy	more diesel consumption	more particulate emissions	0	particulates
gas chromatograph instrument	airplane	low fuel economy	more diesel consumption	more particulate emissions	0	particulates
0	cargo truck	low fuel economy	more diesel consumption	more particulate emissions	0	particulates
0	cargo truck	low fuel economy	more diesel consumption	more particulate emissions	0	particulates
Thin Film Deposition System	cargo truck	low fuel economy	more diesel consumption	more particulate emissions	0	particulates
Car window system	cargo truck	low fuel economy	more diesel consumption	more particulate emissions	0	particulates

	Case 1:					
	Material selection					
0	plastic	0	0	0	0	life-cycle energy
Metal analyzer	aluminum	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
personal transportation	steel	low cost material	easy to recycle	0	0	solid material
automobile	aluminum	mass reduction	increased fuel economy	recycled content	recyclability	CO2
brain monitor	0	0	0	0	0	0
Industrial Pump	steel	Strength	Less material req'd.	Safer	0	life-cycle energy
0	0	0	0	0	0	0
0	0	0	0	0	0	0
defibrillator	plastic	low resin available	different resin choosen	not biodegradable	0	solid material
gas chromatograph instrument	plastic	complex shapes	eliminates multiple parts	uses less material	could be recycyled	life-cycle energy
0	0	0	0	0	0	0
0	0	0	0	0	0	0
Thin Film Deposition System	steel	lowest cost/strength	0	0	0	solid material
Car window system	glass	black out paint	lead based paint	land fill scrap	0	solid material

	Case 2:					
	Reusability					
0	reusable multiple times	0	0	0	0	0
Metal analyzer	reusable multiple times	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
personal transportation	reusable once	0	0	0	0	hydrocarbons
automobile	0	0	0	0	0	0
brain monitor	reusable multiple times	0	0	0	0	0
Industrial Pump	reusable multiple times	No solid waste	Will not deplete Resource	0	0	solid material
0	0	0	0	0	0	0
0	0	0	0	0	0	0
defibrillator	reusable multiple times	contaminatation	spread of disease	lawsuits	0	0
gas chromatograph instrument	reusable multiple times	long lifetime	0	0	0	solid material
0	0	0	0	0	0	0
0	0	0	0	0	0	0
Thin Film Deposition System	reusable multiple times	lower cost of ownership	0	0	0	solid material
Car window system	reusable once	window lift motor	replace worn parts	remanufacture motor	use as service part	life-cycle energy

	Case 3: In use energy source					
0	0	0	0	0	0	0
Metal analyzer	batteries	recyclable	0	0	0	life-cycle energy
0	0	0	0	0	0	0
0	0	0	0	0	0	0
personal transportation	gasoline	0	0	0	0	hydrocarbons
automobile	gasoline	existing infrastructure	existing engine technology	0	0	CO2
brain monitor	0	0	0	0	0	0
Industrial Pump	public electricity	0	0	0	0	life-cycle energy
0	0	0	0	0	0	0
0	0	0	0	0	0	0
defibrillator	batteries	not enough delivered energy	different energy source	other issues-environmental	0	0
gas chromatograph instrument	public electricity	available	conventional	appropriate	0	SO2
0	0	0	0	0	0	0
0	0	0	0	0	0	0
Thin Film Deposition System	public electricity	No other choice practical (75kW)	high energy use	0	0	life-cycle energy
Car window system	batteries	Motor draws current	Current creates torque	Torque moves window	0	life-cycle energy

	Case 4: Manufacturing Process					
0	0	0	0	0	0	0
Metal analyzer	other	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
personal transportation	welding & soldering	ɔt welding delivers other product rɛ	0	0	0	life-cycle energy
automobile	casting metals	meet tech specs	recycled content	recyclability	meet mass target	life-cycle energy
brain monitor	rapid prototyping	0	0	0	0	0
Industrial Pump	rapid prototyping	0	0	0	0	life-cycle energy
0	0	0	0	0	0	0
0	0	0	0	0	0	0
defibrillator	plastic injection molding	resins	biodegradable	safety	not as effective	0
gas chromatograph instrument	plastic injection molding	complex geometry	simplified assembly	simplified inventory	0	life-cycle energy
0	0	0	0	0	0	0
0	0	0	0	0	0	0
Thin Film Deposition System	other	assembly/test of parts	waste packaging materials	more in landfill	0	solid material
Car window system	other	elastomer extrusion	trim bead scrap	0	0	life-cycle energy

	Case 5: In use Operation					
0	0	0	0	0	0	0
Metal analyzer	manual on/off	0	0	0	0	life-cycle energy
0	0	0	0	0	0	0
0	0	0	0	0	0	0
personal transportation	manual on/off	no emssions when vehicle is off	0	0	0	hydrocarbons
automobile	manual on/off	0	0	0	0	0
brain monitor	constant use	0	0	0	0	0
Industrial Pump	constant use	0	0	0	0	life-cycle energy
0	0	0	0	0	0	0
0	0	0	0	0	0	0
defibrillator	manual on/off	battery left on	needs further recharging	etc.	0	particulates
gas chromatograph instrument	constant use	must withstand worst case	0	0	0	life-cycle energy
0	0	0	0	0	0	0
0	0	0	0	0	0	0
Thin Film Deposition System	constant use	high productivity	sted energy use (low standt	0	0	life-cycle energy
Car window system	manual on/off	0	0	0	0	life-cycle energy