

Integrated Product Design and Life-Cycle Assessment

by

Inês Sousa

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Submitted to the Department of Civil and Environmental Engineering in Partial Fulfillment of the
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Signature of Author _____
Department of Civil and Environmental Engineering
May 8, 1998

Certified by _____
Ester and Harold Edgerton Assistant Professor of Mechanical Engineering
Thesis Supervisor

Certified by _____
David H. Marks
Professor of Civil and Environmental Engineering
Department Reader

Accepted by _____
Joseph M. Sussman
Chairman, Departmental Committee on Graduate Studies

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Abstract

Environmental responsibility is now recognized by major companies as an essential factor for their long-term success, as major market and regulation forces drive the incorporation of environmental considerations into the early stages of product development. Design for Environment (DFE) is a design strategy that allows the active practice of environmentally conscious product design while maintaining other cost and performance relationships.

The goal of this thesis was to develop a DFE analysis tool, asserting that environmental issues must be incorporated into product design in balance with existing traditional design considerations. For this purpose, a quantitative Life-Cycle Assessment (LCA) model of a new consumer electronics product (an LCD computer projector) was built using a commercial LCA software tool, and integrated with other design models using a collaborative design modeling framework called DOME (Distributed Object-based Modeling and Evaluation).

In doing so, the objective was to explore and discuss: (1) what is involved, methodologically and in terms of human interactions, in the process of developing such a collaborative modeling tool; (2) the behavior and value of the tool in understanding interactions between traditional and environmental design goals. Ultimately, an attempt was made to obtain insights, through a survey, into how the use of this DFE tool may be perceived by experts for assessing environmental performance against other design goals.

It was concluded that the LCA model integrated through the DOME framework formed a consistent methodological basis for evaluating trade-offs between environmental criteria and other design goals. It facilitated data exchange and interoperability between specialized models and tools, including the LCA model, and provided the ability to address uncertainty associated with controlling variables of the model using probability distributions.

Thesis supervisor: David Wallace

Title: Ester and Harold Edgerton Assistant Professor of Mechanical Engineering

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1. Introduction

1.1. Environmental quality and industrial development

A single industrial product has the potential to cause several adverse impacts on the environment throughout its entire life-cycle. The extraction and processing of raw materials, manufacturing, transportation and distribution, use and maintenance, recycling, and final disposal all produce environmental burdens, including generation of waste, and the depletion of natural resources.

Globally, it is recognized that current patterns of industrial development tend to exceed the limits of sustainability in terms of resource utilization and waste management. They also pose potential threats to crucial life support elements, such as global climate, biodiversity, vegetation, and agriculture (Fiksel, 1996).

In the last decade, however, the number of organizations addressing environmental issues in engineering and industry has increased significantly (Bras, 1997; Fiksel, 1996). To reduce the negative environmental impact of a product, three general approaches may be identified (Bras, 1997):

- Approaches applied within a single product life-cycle and focused on specific life-cycle stages. These include: (1) traditional environmental engineering, concerned with managing the fate, transport and control of contaminants, once they have been generated, or at the “end of pipe”; (2) pollution prevention, focusing on elimination of pollutants from existing products and processes technologies; (3) environmentally oriented Design for X approaches, such as Design for Recycling, focused on a specific aspect of a product’s life-cycle, which may negatively affect other aspects.
- Approaches focused on a complete product life-cycle and covering all life-cycle stages. It is generally agreed that this system-based view provides the largest capability for reducing environmental impact of both products and associated processes, extending beyond the scope of pollution prevention to include the negative impact resulting from the use and disposal of the product. However, it may not cover the broader needs of modern manufacturers often relied on multiple suppliers and having multiple product lines and multiple facilities, often in multiple countries.

- Approaches extending beyond a single life-cycle. These include: (1) Industrial Ecology, which considers the interactions of several product life-cycles over a larger time scale; it provides an integrated systems approach to managing the environmental effects of using energy, materials and capital in industrial ecosystems analogous to the metabolism of materials and energy in biological ecosystems; industries use each other's waste in an intelligent manner to create new products; (2) Sustainable development and technology, as the broadest approach, with the goal of meeting needs of the present generation without compromising needs of future generations.

The environmental impact reduction approaches extending beyond a single life-cycle - industrial ecology and sustainable development - have been implemented in a management level, with general strategies proposed but lacking of implementation details (Bras, 1997).

In this context, a new trend in which environmental quality is becoming compatible with industrial development is emerging in today's leading global companies (Fiksel, 1996). This compatibilization, referred by Fiksel (1996) as the basic premise, is possible if corporations can redesign their industrial systems to achieve both environmental quality and economic efficiency.

Acknowledging environmental responsibility is an important factor for the long-term success of companies (Fiksel, 1996). Some of the driving forces that are encouraging corporations to address environmental concerns during the design phase are consumer demand, environmental labeling initiatives, and increasingly stringent regulation (Hertwich et al., 1997; Sweatman and Simon, 1996). Particularly, industry is starting to recognize that incorporating environmental responsibility can increase profitability through higher productivity and reduced costs which are often achieved by designing products and processes in ways that enhance environmental quality (Bras, 1997; Fiksel, 1996).

1.2. Motivation

Design for Environment (DFE) is a practice that incorporates environmental issues into product design considering its entire life-cycle. It is becoming an essential strategy for long-term success in today's industrial environment. This emerging discipline is moving pollution prevention from the end-of-pipe to the design stage, where 80% of the cost of a new product is determined (Pelley, 1997).

To be effectively integrated into the product design process, DFE must be balanced against other design considerations, such as cost and performance (Fiksel, 1996). The number of DFE tools for assessing and improving product environmental performance has increased significantly in the last decade (Bras, 1997). Particularly, DFE assessment tools, such as Life-Cycle Assessment (LCA) methods, enable a systematic assessment and quantification of environmental performance across the life-cycle of a product. Tools for environmental decision support and trade-off analyses are less well established (Bras, 1997).

The need for integrated environmental assessment in product design is closely related with the need for designers to interact and collaborate efficiently by sharing common information, reaching agreements in an integrated, concurrent design environment. This is important since product design problems require specialized knowledge from many different fields, such as functional, aesthetic, and environmental, each of them characterized by different viewpoints, goals and constraints that have to be balanced with appropriate tradeoffs (Senin et al., 1997).

There are research projects devoted to provide designers with a formalized framework that manages conflicts between design constraints, assisting designers in making decisions (Senin et al., 1997). Borland et al. (1998) refer to existing concurrent and integrated design modeling approaches developed to address this issue.

In the CADlab at MIT, a collaborative design modeling framework called DOME (Distributed Object-based Modeling and Evaluation) has been proposed (Senin et al., 1997; Pahng et al., 1998a). DOME is a computer-aided design environment that allows models created by designers and environmental experts to communicate with each other to perform an integrated product design assessment.

The goal of this thesis is to develop a quantitative Life-Cycle Assessment (LCA) model of a new consumer electronics product, a LCD computer projector, and integrate it with other design models using DOME. The objectives underlying this model's development and integration in the early design phase are as follows:

- Define an appropriate methodology to approach purpose and scope of the design problem being addressed.

- Explore the behavior of the integrated LCA model and its potential value in understanding interactions between traditional and environmental design goals.
- Discuss on experience gained within the design team using the collaborative modeling approach.
- Gain insight, through a survey, into how the DOME integrated LCA model and existing qualitative DFE tools may be differently perceived by experts when applied to integrated product design, for assessing environmental performance against other design goals.

This work is motivated by the belief that environmental assessment in product design cannot be performed in isolation. Environmental issues can be successfully incorporated into product design only if balanced with the existing traditional design considerations.

1.3. Thesis outline

The thesis was structured considering that an overview on related topics was first required to provide a general background. Then, the principal contributions, as well as discussion and conclusions, are presented.

In Chapter 2, DFE related background is provided. Its highlights are: important driving forces that may influence the adoption of DFE by corporations, key methodological elements to integrate DFE into a new-product development process, required characteristics for DFE tools to provide efficient decision support in environmentally conscious design, and issues about integrating DFE tools into existing design practice and information management.

Chapter 3 is intended to provide background on the standard methodological framework for LCA, impact assessment methods currently proposed, and other approaches such as streamlined LCA and environmental weak-point analysis. Also, an overview on how LCA may be applied in product development and references on existing software LCA tools are provided. Advantages and shortcomings associated with this methodology are identified.

In Chapter 4, the basic concepts of DOME are provided. Two types of approaches using DOME to facilitate the incorporation of LCA into product design are presented.

Chapter 5 summarizes the process of creating the integrated LCA model, describing the methodology defined for this purpose, and also illustrative scenarios for the use of the tool in understanding interactions between traditional and environmental design goals. A discussion of experience gained through the development and integration of the LCA model is presented

Chapter 6 presents a comparison of the integrated LCA model with qualitative matrices, also considered to be a DFE analysis method, based on a discussion using data obtained from an informal survey performed by experts. Critical comments on the survey performed are also provided.

Finally, Chapter 7 concludes the thesis by summarizing the outcomes and experience obtained with this work.

2. Design for Environment

2.1. DFE as a design strategy

Design for Environment (DFE) may be defined as a process in which environmental attributes are treated as design objectives together with other conventional design goals rather than as constraints (Berkel et al., 1997). This design strategy presents the key feature of allowing the active practice of environmentally conscious and harmonious product development by incorporating life-cycle environmental objectives while maintaining or promoting quality and cost/performance relationships.

The practice of DFE is becoming an imperative strategy for long-term success in today's industrial environment (Fiksel, 1996). Environmental responsibility has been acknowledged in major companies as an essential factor, as competitive advantage is increasingly determined by reducing the costs of production and waste management, encouraging innovation in product simplification, and attracting new consumers concerned about the environmental performance of the products.

The growing trend for applying DFE in the design process should be considered together with the current view of product development. This view defines an effective product realization process as incorporating, among other things, a definition of customer needs and product performance requirements, a plan for product evolution beyond the current design, and design product/manufacturing processes considering the entire product life-cycle (Fiksel, 1996).

In this context, the practice of DFE fits naturally into the process of integrated product development, where all functional groups (engineering, manufacturing, marketing, etc.) involved in a product life-cycle participate concurrently as a team in the early identification and resolution of key product development issues, such as quality, manufacturability, reliability, maintainability, environment and safety (Fiksel, 1996). This process is strongly motivated by the economics of product development, which has shown that major life-cycle costs are determined in early design stages and that design changes increase the cost dramatically as the product development and prototyping process proceed into full-scale (Frei and Zuest, 1997; Fiksel, 1996).

DFE is therefore an application of the integrated product development approach to environmental performance (Fiksel, 1996). This design strategy offers the ability to anticipate environmental quality problems or opportunities during the design phase, avoiding costly changes and delays in the future.

Despite existing examples of successful DFE efforts in companies, there are significant challenges in implementing this practice systematically, as it requires a substantial organization commitment (Fiksel, 1996; Bras, 1997). Fiksel (1996) discusses key issues to consider in order to mature and integrate effectively DFE into company practices. Lenox et al. (1996) used surveys to reveal that very few DFE programs are fully integrated into product realization process, pointing out deficiencies in existing DFE tools and company management structures as possible causes.

This chapter provides DFE related background. It focuses on highlighting important driving forces that influence the adoption of DFE by corporations. Then, key methodological elements to integrate DFE into a new-product development process, as well as required characteristics for DFE tools to provide decision support will be addressed. Finally, this chapter discusses issues in integrating DFE tools into existing design practice and information management.

2.2. Motivating factors in adoption of DFE by corporations

There are several motivating factors encourage companies to adopt DFE practices. The following may be highlighted as relevant ones (Bras, 1997; Fiksel, 1996):

- Regulatory pressures. Both in the US and abroad, government regulations regarding the environmental impacts of products and processes are becoming more restrictive. For example, the US Clean Air Act has limited the use of a number of materials and take-back legislation in Europe concerning the disposal of products at the end of their useful life is starting to drive design for recycling efforts.
- Customer demand. Retail customers are becoming increasingly concerned about the environmental quality of the products that they purchase. Some customers are willing to pay more for a product if it is environmentally friendly. Also, industrial customers such as Original Equipment Manufacturers (OEM) are beginning to systematically review the

environmental performance of their suppliers, as they do not want future environmental liability for a supplier's product.

- **Product differentiation.** Product designs that incorporate environmental issues have a potential to be superior in terms of elegance, energy efficiency, and cost of ownership. Environmental concerns may also push for finding new creative solutions and products. Product differentiation can frequently influence a purchase decision if price and performance are comparable.
- **Profitability improvement.** Incorporation of environmental criteria into the product design can have a significant impact on product line profitability through savings in material diversity, manufacturing and other operating costs, as well as through increased market share.
- **Eco-labeling programs.** Both in the US and abroad, a number of eco-labeling initiatives, which measures the environmental sensitivity of products, have arisen. A product having an eco-label becomes a competitive advantage.
- **International standards.** Many leading companies are participating in a worldwide effort, coordinated by the International Organization for Standardization (ISO), to establish standards for environmental stewardship over the entire product life-cycle. The ISO 14000 (environmental management standards) certification may become a key element in achieving business success, like the ISO 9000 standards in the quality management field.

In general, the most important factor changing industry attitudes is that incorporating environmental responsibility can actually increase profitability, meaning DFE makes good business sense (Bras, 1997; Fiksel, 1996). Higher productivity, reduced costs and even increased market share generally are achieved by reducing pollution at the source and designing products and processes in ways that enhance environmental quality. For example, the reduction of material diversity leads to lower inventory, volume purchasing, and the opportunity to focus on a reduced number of manufacturing processes. Nevertheless, this does not imply that a financial reward, especially within a short term, can always occur from becoming environmentally responsible.

This trend was also revealed in a survey administered by Vanderbilt University's US - Japan Center for Technology Management to 175 US large corporations (Huang and Hunkeler, 1996). The participants were asked to list all the motivating factors that influence their efforts in environmental protection. The top ten driving forces were, in order of frequency reported, minimize costs, avoid future liability/remediation, be in compliance with current regulations, enhance image/marketing strategy, preempt regulatory changes, meet customer requests, identify improvement opportunities, capitalize on strategic opportunities, educate internally on environmental issues, and aid in the selection of process or material. Clearly, most companies selected as primary reason for corporate environmental efforts the desire to capitalize on strategic opportunities.

2.3. Methodological elements of DFE

DFE must be balanced against other design goals, such as cost and performance, to optimize a design. This section presents a systematization provided by Fiksel (1996) for key methodological elements to integrated effectively DFE into product development:

DFE metrics

DFE metrics support environmental performance measurement. They are driven by fundamental customer needs or corporate goals, reflecting industry-specific environmental issues.

There is a number of environmental quality metrics that can be used to establish design objectives. Examples of different types of metrics are toxic use measures (total kilograms of solvents purchased per unit of production), resource utilization measures (total energy consumed during the product life-cycle), environmental emission measures (greenhouse gases and ozone-depleting substances released per unit of production), and waste minimization measures (percent of product materials recovered at end of life).

The choice of high-level environmental metrics determines what types of signals are sent to engineering and manufacturing staff responsible for meeting operational goals, and also the available options for communicating company performance to outside audiences. Once DFE goals have been expressed in terms of specific metrics, these metrics are decomposed into quantitative parameters that can be estimated and tracked for a particular product design.

DFE practices

The availability of guidelines for practicing DFE was also identified as a key element needed to support the process of integrating DFE effectively into product development. These guidelines are based on in-depth understanding of relevant technologies and supported by engineering guidelines. The following are some of the more common DFE practices used in industry today:

- **Material substitution:** replacing product constituents with substitute materials that are superior in terms of increased recyclability, reduced energy content, etc.
- **Waste source reduction:** reducing the mass of the product or of its packaging, thus reducing the resulting quantity of waste matter per product unit.
- **Substance use reduction:** reducing or eliminating the types and amounts of undesirable substances, such as toxics and CFCs, that are either incorporated into the product or used in its manufacturing process.
- **Energy use reduction:** reducing the energy required to produce, transport, store, maintain, use, recycle, or dispose of the product and its packaging.
- **Life extension:** prolonging the useful life of a product or its components, thus reducing the associated waste stream.
- **Design for separability and disassembly:** simplifying product disassembly and material recovery using techniques such as snap fastening of components and color coding of plastics.
- **Design for recyclability:** ensuring both high recycled content in product materials and maximum recycling, i.e., minimum waste, at end of product life.
- **Design for disposability:** assuring that all non-recyclable materials and components can be safely and efficiently disposed.
- **Design of reusability:** enabling some components of a product to be recovered, refurbished, and reused.
- **Design for remanufacture:** enabling recovery of post industrial or post consumer waste for recycling as input to the manufacture of new products.

DFE analysis methods

The analysis methods enable a systematic assessment and quantification of environmental performance across the life-cycle of a product with respect to the DFE metrics and to analyze cost and quality tradeoffs. Design teams generally use analysis methods in four different ways:

- Screening methods to narrow design choices among a set of alternatives. Examples include threshold limits for chemical properties such as biodegradability, and material selection priority lists based on recyclability.
- Assessment methods to predict the expected performance of designs concerning particular objectives. Examples include calculation of expected materials recovery rates, or prediction of environmental consequences associated with specified emission levels.
- Trade-off methods to compare the expected cost and performance of several alternative design approaches with respect to one or more attributes of interest. Such methods may include “what-if” simulations, quality-function matrices, or parametric analyses that draw upon assessment methods.
- Decision making methods to assist design teams select from among alternatives when the trade-offs are complex or when large uncertainties are present. Examples include analytic hierarchy techniques, expert advisory systems, decision analysis, and other optimization methods.

Assuming that DFE metrics have been defined and objectives have been set, analysis methods can be methodologically used to: (1) evaluate the degree to which a particular design meets cost or performance objectives; (2) compare alternative designs and evaluate their relative merits; (3) identify potential design improvements and evaluate their expected benefits. The following are examples of useful analysis methods that are commonly applied during product development.

- Qualitative methods. These methods assess the environmental performance of a product design throughout the life-cycle, and may include:
 - Checklists of criteria, stated in the form of questions or points to consider, such as material and supplier selection criteria, and product design criteria. The use of

checklists is one of the first DFE initiatives to be implemented, requiring modest resources and being effective for starting to encourage organizations to think about environmental issues and begin taking positive actions. There are also limitations: they provide only crude measures of performance improvement and no guidance regarding relative importance of different issues, and can reduce creativity by not covering key opportunities or problems that could have been considered otherwise.

- Matrices as a technique for performing trade-off analysis in design decisions. They involve creating a matrix diagram in which the rows represent competing options or objectives and the columns represent design attributes, providing a means for evaluating tradeoffs and interactions among design criteria.

- Quantitative life-cycle assessment methods. These methods, which will be addressed in more detail in Chapter 3, calculate the net energy or material flows associated with products and quantify potential environmental, health, safety, and economic impacts caused by environmental releases.

- Environmental accounting methods. These methods assess the costs incurred by the manufacturer, its customers, and other parties at various stages of the product life. They follow the principles of activity-based costing to capture the contribution of environmental improvements with regard to increased profitability.

There are advantages to qualitative assessment methods over quantitative methods: they are easier to apply, require minimal data, and can be useful even with large uncertainties. For many companies, qualitative methods are the logical first step in implementing DFE because they can provide benefits without requiring large resource expenditures. However, quantitative methods are potentially better for purposes of continuous improvement and competitive benchmarking.

2.4. Integrating DFE tools into design practice and information management

The number of tools for supporting DFE implementation have increased significantly in the last decade (Bras, 1997). Sweatman and Simon (1996) review a series of these tools currently available, ranging from tools for analysis such as life-cycle assessment to improvement tools, which facilitate and assist designers to improve product environmental performance. Particularly, the improvement tools include a variety of formats – workshops, checklists, handbooks, software

– to address key environmental issues such as design for eco-efficiency, design for remanufacture, design for energy efficiency, design for disassembly and recycling, hazardous material minimization, and compliance with regulations and standards.

The introduction of new DFE tools in a company or organization should consider that these tools must support efficient (speed) and effective (completeness/correctness) assessment and decision making in the integrated design process (Bras, 1997). In order to meet these requirements, Bras (1997) lists the following characteristics tools should ideally present:

- Simple: easy to use.
- Easily obtainable: at a reasonable cost.
- Precisely definable: it is clear how they can be evaluated.
- Objective: two or more qualified observers should arrive at the same result.
- Valid: they should measure, indicate, or predict correctly what they are intended to measure, indicate or predict.
- Robust: relatively insensitive to changes in the domain of application.
- Enhancement of understanding and prediction: good metrics, models and decision support tools should help insight and assist in predicting processes and product parameters.

DFE tools supporting integration of environmental issues into product design should also be selected according to the stage of the design process and specific constraints involved, such as ever shortening product development times (Sweatman and Simon, 1996). The type of product and business will also influence the need for tools. A carpet manufacturer, for example, will not need a disassemblability assessment tool like a consumer electronic manufacturer (Bras, 1997).

An important issue to consider is how can these tools be best integrated into existing and well-established design groups, tools and practices. Bras (1997) points out that one should always take into account the following:

- Users. It should be carefully planned by whom and where in the design process the tools are supposed to be used. Also, the simpler the assessment method is, the more easily it will be accepted by designers in their current day-to-day activities, being as useful as possible without being too time consuming.

- Incentives. Introducing new design guidelines and/or engineering standards dealing with environmental issues may not be enough unless a sign-off and/or check is required. For example, car manufacturers have introduced engineering guidelines for increasing vehicle recyclability, but require documentation from design engineers and suppliers. At the same time, these companies provide education and support services to designers and suppliers by specialized groups, and some companies reward suppliers financially for environmental excellence.

In the context of the DEEDS (Design for the Environment Decision Support) project, McAlloone and Evans (1996) addressed the issue of understanding the practice of design. The project stands on the belief that by first observing how designers do their job, interact with other designers and other organizational departments, it is possible to build a model of how design is performed for each company and where environmental considerations should be integrated into the design process. The in-depth survey of theoretical, practical and perceived design models carried out by the authors offered them insight into how formalized design theory is interpreted into everyday design. This is very important to acknowledge when considering how to update a company's design model to include environmental considerations.

In introducing new DFE tools into the design process, the question of how to minimize overlap and increase efficiency in information gathering and management is also a key concern to be considered (Bras, 1997). Fiksel (1996) points out the need for at least three types of capabilities for effective integration of DFE into product development:

- On-line design guidance. It consists on a body of knowledge accumulated by the design organization regarding its key technologies and design approaches and it should allow direct, real-time retrieval and maintenance of DFE knowledge by engineers and other professionals involved in the product development process. The form of on-line design guidance may range from a hypertext system containing cross-referenced rules of thumb to interactive "expert" systems that help to explore trade-offs among alternative designs.
- Predictive assessment tools. DFE requires automated tools for evaluating product performance to assure coverage of all product requirements and to identify design flaws or omissions. This is important particularly to handle the complexity of environmental issues associated even with simple products.

- Integration with CAE/CAD framework. To implement DFE tools in an integrated fashion that facilitates data exchange and interoperability with other CAE/CAD tools, it is necessary to adopt a framework architecture in which all tools shared common data models and interface specifications.

The implementation of such an information infrastructure in a company involves many technical and organizational efforts and challenges (Fiksel, 1996).

The objective of adopting a framework architecture should be to minimize the amount of information gathering and management in order to increase the efficiency of designers, while increasing their scope of concern and effectiveness and integrating new tools into existing and accepted design systems. This may lead to research and development of new systems, as conventional CAD systems may not be the most efficient support for a more integrated approach to life-cycle design due to their heavy focus on geometric information management (Bras, 1997).

3. Life-Cycle Assessment

3.1. Introduction to life-cycle concept

It is recognized that methods and techniques to better assess and reduce the negative impacts of human activities on the environment must encourage a comprehensive evaluation of all upstream and downstream effects of the activity or product under examination (SETAC, 1993). As a consequence, the life-cycle concept has influenced and shaped many approaches and techniques to assess and improve the environmental performance of products and production systems.

From an organizational standpoint, there is a goal to address pressures to integrate environmental considerations into the design, manufacture, distribution, use, and disposition of products, packages, and simultaneously achieve business benefits and environmental improvement (Fava, 1997). The traditional concerns of product functionality, quality and cost are further complicated by environmental considerations. Corporate environmental strategies are evolving toward a life-cycle approach as a tool for industry to identify and evaluate opportunities to minimize environmental burdens from “cradle-to-grave” (Huang and Hunkeler, 1996).

In this context, the principle of Life-Cycle Assessment (LCA) as a tool for product-oriented environmental management has become widely accepted as valuable both in Europe and in the United States (Guinée et al., 1993a; Hoffman III, 1997). Possible major applications of LCA are product improvement, design of new products, product information, ecolabeling and the exclusion or admission of products from or to the market (Guinée et al., 1993a). In the design process, LCA may be applied to the technical redesign of a product, providing the product designer with information on the environmental impacts of the system. It may also point the user to those parts of the operations where there is the greatest opportunity for improvement (SETAC, 1993).

In its most extensive form, LCA aims to quantify all environmental impacts of a product during its entire life-cycle, analyzing not the product itself but the product systems in the sense of production-consumption-waste treatment systems. The function of the product as it is used is the point of reference to which the environmental impacts are attributed. Besides this quantitative form of LCA, covering the entire life-cycle of a product, there are also streamlined approaches for the environmental assessment of products, using qualitative criteria and focusing on a limited

part of the life-cycle. They are relatively fast and simple because of the limited quality and quantity of the data that is needed (Guinée et al., 1993a).

It has been observed that current LCAs often yield mutually conflicting results. The discrepancies are related to both the research methods and the data used (Guinée et al., 1993a). Further, Huang and Hunkeler (1996) have showed through a survey sent to U.S. corporations that life-cycle thinking has not been adequately integrated throughout corporate organizations, mainly because industries are skeptical that a standardized method for impact assessments will be accepted in the next few years and they are concerned about the costs and inaccuracy associated with LCA.

In this chapter, the following sections are intended to provide background on the standard methodological framework for LCA, impact assessment methods currently proposed, and other approaches, such as streamlined LCA and environmental weak-point analysis. Also, an overview on how LCA may be applied in product development and references on existing software LCA tools will be provided. Advantages and shortcomings associated with these methodologies are identified.

3.2. Standardization in LCA

LCA began in the late 1960s as an exercise to obtain inventory data for a system-wide balance of energy and materials. The goal was to analyze the efficiency of resource use in products and materials and to use these inventories to make claims regarding environmental superiority. However, LCA did not provide clear differentiation between products and proved that most comparisons were inconclusive due to complex and disparate trade-offs. LCA practitioners also began to use the inventory data to characterize the overall environmental burden of a system with respect to specific environmental categories and a conceptual framework for impact assessment has been proposed (Owens, 1997).

At present, LCA is in a long-term process of standardization, both on national and international levels (Nissen et al., 1997). In an effort to develop broad consensus on harmonized methods for conducting LCA, the Society of Environmental Toxicology and Chemistry (SETAC) shaped the development of LCA in a series of workshops from 1990 to 1993 and produced documents reflecting consensus and current thinking on the practice of LCA (Klopffer, 1997; SETAC, 1993).

The methodological framework for LCA has been roughly agreed upon, following the SETAC guidelines (Nissen et al., 1997; Klopffer, 1997; Sweatman and Simon, 1996).

Definition of LCA methodological framework

In summary, LCA is a method for systematically assessing the environmental burdens associated with a product throughout its entire life-cycle encompassing the extraction and processing of raw materials; manufacturing; transportation and distribution; use, re-use, and maintenance; recycling; and final disposal (SETAC, 1993; Sweatman and Simon, 1996).

LCA is an analysis that implies a large and complex effort (Graedel and Allenby, 1995). It is a simplification of the physical system and, as all other scientific models, it cannot assert to provide an absolute and complete representation of every environmental interaction (SETAC, 1993). Rigid methodological rules are not defined for all aspects of LCA as the technique is still under development. Although many variations exist, there is preliminary agreement on the formal structure of LCA based on the SETAC guidelines, which includes four major stages (SETAC, 1993): goal definition and scoping, inventory analysis, impact assessment, and improvement assessment. Figure 1 presents the inter-relationship of these components in performing an LCA, representing the LCA methodological framework recommended by SETAC.

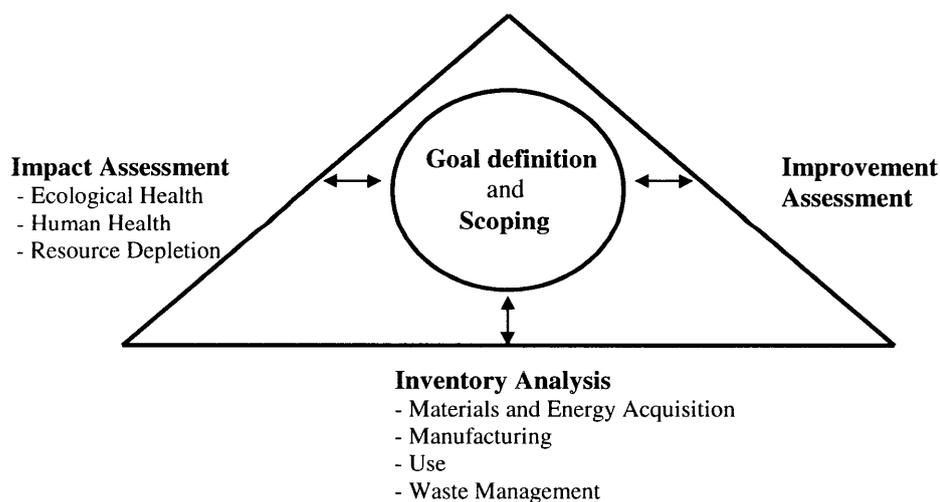


Figure 1. Technical framework for LCA. Source: SETAC (1993).

The methodological structure recently defined by the International Standards Organization (ISO) differs the SETAC structure in the last stage, which is called “interpretation” in the international

standard 14040. According to ISO, “Improvement Assessment” is only one of the many activities which may follow LCA but is not part of the true analysis (Klopffer, 1997).

Goal definition and scoping

Goal definition and scoping determine the direction and depth of the study. This stage consists of defining the study purpose and scope, and establishing the functional unit and a procedure for quality assurance of the results (SETAC, 1993).

The purpose should include a clear and unambiguous statement of the reason for carrying out the LCA, and the intended use of results. It should be defined in terms of what decision is to be used on the findings, what information is required, at what level of detail, for what purpose, and whether the results will be used for in-company applications to improve the environmental performance of the system, or externally, for example to influence public policy or consumer purchase choices (SETAC, 1993). The lack of a clear ambition and purpose for the LCA study in advance generates the risk of overdoing the inventory analysis and the impact assessment and of getting results that will not be properly used for practical decisions (Ryding et al., 1993).

The scope of a LCA defines the system, boundaries, data requirements, assumptions, and limitations. The scope should be well defined to ensure that the breath and depth of analysis are compatible with and sufficient to address the stated purpose, and all boundaries, methodology, data categories and variability, and assumptions should be clearly stated, comprehensible, and visible. Further modifications or refinements of the study scope may be required after the first evaluation of the different components during which key issues, such as most important processes, most relevant types of impacts, and most feasible options for improvement, additional information encountered, are identified (SETAC, 1993).

The functional unit, which is the measure of performance that the system delivers, must be clearly defined, measurable, and relevant to input and output data, avoiding ambiguity in the statement of purpose and clarifying the basis for the scope (SETAC, 1993). This unit of use is specified as a basis for comparison, as in all of the LCA applications some kind of comparison is made (i.e., a comparison of a product before and after improvement, a comparison of several design alternatives of a new product, or a comparison between different products with the same function) (Guinée et al., 1993a).

Specific data-quality goals should be clearly established, including the degree of confidence in individual input and output, in the data set as a whole, and ultimately in decisions that will be based upon the data (SETAC, 1993).

The spatial scale and the time horizon of the assessment must be articulated. This is important for the choice of representative processes and related data (Guinée et al., 1993a).

Inventory Analysis

Inventory analysis is an objective process that uses quantitative data to establish the levels and types of energy and materials inputs to a system and the environmental releases that result (see Figure 2). It is performed over the entire life-cycle of the product from materials extraction through manufacture, distribution, use and disposal (Graedel and Allenby, 1995).

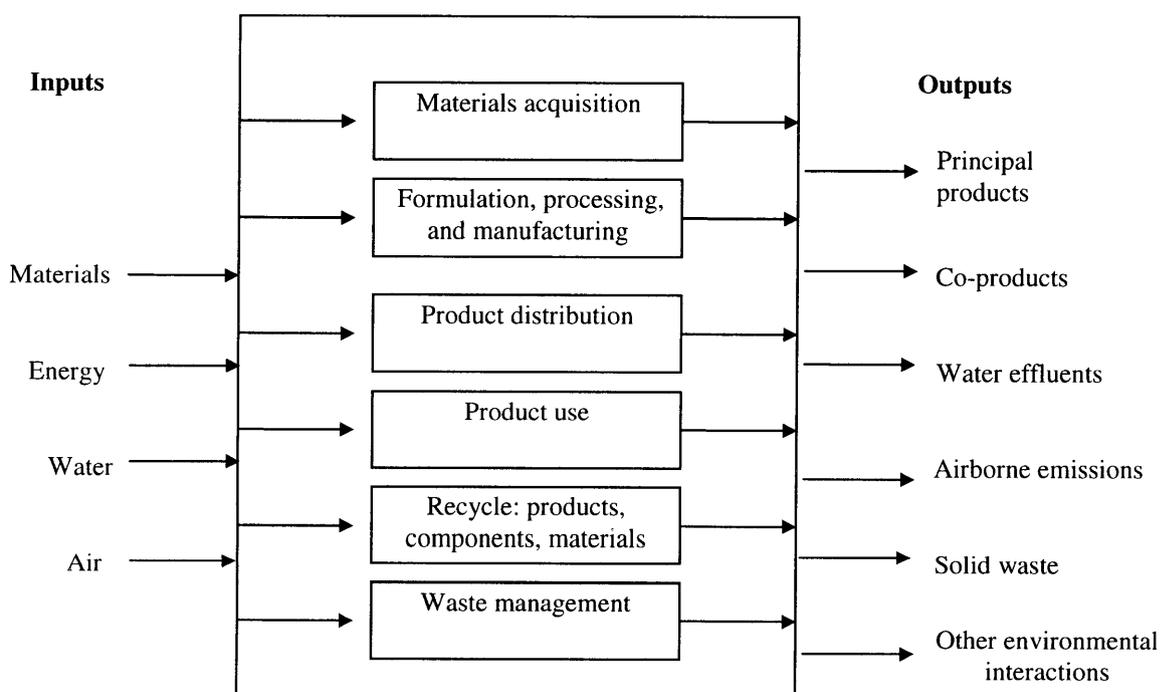


Figure 2. Elements of a life-cycle inventory analysis. Source: Graedel and Allenby (1995).

In Life-Cycle Inventory (LCI), detailed data are required and the quality of the data should be consistent with the purpose and scope of the study, including variability, uncertainties, and gaps. Sensitivity analysis should be carried out to test the effects on the results and limitations on the conclusions (SETAC, 1993).

LCI methodology is the best understood stage and practices are well developed. For over 20 years life-cycle related studies have focused on the quantification of energy and materials used and wastes released into the environment (SETAC, 1993; Klopffer, 1997; Graedel and Allenby, 1995). The inventory practice and methods are well defined by SETAC (1993) and EPA (1993).

In setting the product system as a collection of materially and energetically connected operations, the degree of sub-division of the total system into individual operations is frequently determined by the availability of data and the requirements set forth in the goal and scope of study. Therefore, it is important to identify key ancillary input data for the system under the study and decision rules should be clear and stated (SETAC, 1993).

In LCI, distinct elements may be identified: the definition of the processes of the product system, the specification of all processes and their data, and the compilation of the inventory tables per process or per functional unit of a product. These elements may be dealt with iteratively until the results are considered satisfactory (Guinée et al., 1993a).

The identification of the processes in the product system involves characterizing three aspects: (1) definition of the boundaries between product system and environment system; (2) definition of the boundaries between the product system under study and the other product systems; (3) the distinction between relevant and less relevant processes related to the product system under study. An advanced discussion of these individual aspects is provided by Guinée et al. (1993a). A highlight follows:

- (1) There is a double relation between the product system and the environment system: there are inputs from the environment through resource extraction and space requirements, and outputs to the environment through emissions of substances, noise, ionizing radiation, final waste. In this relation, there might be ambiguity, such as what is meant by resource extraction, where does the environment system end and where does the product system begin. Also, what is meant by waste? Is waste well kept waste dump to be considered as an output to the environment or is it to be considered as long-term waste processing, requiring space for the storage of the final solid waste, producing methane as a potential energy source and causing emissions to water, air and soil? Recently, several methods have been suggested for this purpose.

- (2) Usually there are several products produced or processed, and these products are often connected to other product systems. Parts of the environmental inputs and outputs must be allocated to one product system, another part to a second or third product system. The allocation can be done in proportion to a common physical unit of the products, in proportion to the economic value of the products or in proportion to the functions or services delivered by the products. Which approach may be used in relation to the allocation of environmental inputs and outputs of processes producing co-products, processing different waste flows or related to open-loop recycling, including reuse and recovery is a critical question. A possibility relies on the idea that it is not a choice between different approaches but that there is a need to develop a reasoned method for guiding the choice of allocation principles.
- (3) Due to the practical choice limiting the product system to those processes that have a relevant contribution to some environmental input or output, there is a trade off of completeness against practical feasibility. Current studies usually cut off the regression in the life-cycle by including the functioning of capital goods but excluding their production, and/or simplifying networks of processes. The scale of comparison determines the choice of representative processes, for example between firms and within countries.

Guinée et al. (1993a) present a case study, analyzing the causes of the different outcomes of a set of comparable studies. Different interpretations and choices related to the methodological elements can have a decisive effect on the final results. The specification of the basis of comparison, the system boundaries, and the classification involved with environmental problems varied considerably from study to study.

Impact Assessment

A stand-alone LCI can provide useful information for product improvements, benchmarking, energy savings, and emission reduction, but it does not place the inventory data and information into perspective for the comparative assessment of product systems. The impact assessment stage was added to the LCA technical framework to better understand the relative environmental significance of the system's inputs and outputs or the benefits from achieving improvements in the system (SETAC, 1993; Klopffer, 1997; Guinée et al., 1993b).

In the impact assessment stage, a technical, quantitative, and/or qualitative process is performed to characterize and assess the environmental impacts associated with the inventory. According to SETAC guidelines, three main steps may be considered (SETAC, 1993):

- (1) Classification. The data collected in the inventory stage are grouped together into a number of impact categories. The definition of the specific impact categories should be focused on the environmental processes involved, to enable the impact assessment to be as much as possible based on scientific knowledge about these processes.
- (2) Characterization. In this step, analysis/quantification and aggregation of the impacts within the given impact categories are performed. One approach is to develop and use equivalency factors for the different impact categories, such as the Global Warming Potential (GWP) and the Ozone Depletion Potential (ODP). A further development of the characterization step is to normalize the aggregated data per impact category in relation to the actual magnitude of the impacts within this category in some given area, to facilitate the comparison of the data from the different impact categories.
- (3) Valuation. The different specific impact categories are weighted so that they can be compared and trade-offs can be performed. In principle, this assessment reflects social values and preferences. A variety of tools, such as decision theory techniques, have the potential to make the valuation a more rational and explicit process, using both expert judgement and input from interested and/or affected parties. In a quantitative procedure (e.g., multi-criteria analysis), explicit factors may be used to aggregate the impacts, while in a qualitative procedure, the factors remain implicit. However, further research is needed for developing these methods.

Although the SETAC “Code of Practice” provides guidelines for carry out the impact assessment in the LCA framework, this stage is presently under development and there are no commonly agreed-to methodologies (SETAC, 1993; Owens, 1997; Hertwich et al., 1997). To better understand this lack of agreement and standard methods, further description of the currently available impact assessment tools in LCA will be provided in Section 2.3.

Improvement Assessment

Improvement assessment is the stage of an LCA in which needs and opportunities for reducing the environmental impacts or burdens of the systems under study are systematically identified and evaluated. It deals with the identification, evaluation, and selection of options for environmental improvements in products to minimize the associated environmental burden, given the fulfillment of intended function and performance characteristics (SETAC, 1993; Ryding et. al., 1993).

LCA data

In usual practice, data are collected from a wide range of sources: production sites, engineering texts, regulatory reports for industries, or industry literature. Frequently, data are not available directly from the most accurate source - production sites - and are considered proprietary. As a consequence, there is a considerable variation between individual data points regarding accuracy, consistency, uncertainty, and currency. Ranges, minima, maxima, or distributions have rarely been available in life-cycle studies, and data uncertainty analysis is not widely practiced (Owens, 1997).

A complete analysis of minor emissions is impractical for any individual operation and is not feasible for a complete cradle-to-grave system. Using assumptions or estimates is a common practice to address inventory data gaps (Owens, 1997).

SETAC (1993) recommends that key indicators of data quality should be provided, such as age, frequency and method of collection, geographic scope, time-period covered, completeness, representativeness, accuracy, precision, uncertainty, and estimates of variability. The selection and application of data quality indicators for specific data should be made by the LCA practitioner based on the nature of the data and on the uses to which they will be put.

3.3. Impact assessment methods in LCA

In LCA, a number of impact assessment methods for the evaluation and comparison of an inventory's pollution loads and resource demands have been developed but no solution has yet been accepted broadly (Hertwich et al., 1997). In this section, an overview on different methods,

representative of quantitative impact assessment methods used for LCA currently available, is provided in order to understand their similarities and differences.

Health Hazard Scoring

Health Hazard Scoring (HHS) system focuses on occupational health and risks of accidents that might lead to injury or pollution releases. It uses the analytical hierarchy process (AHP), based on pair-wise comparison, to compare and rank alternatives and is based on a toxicity scoring method developed for the Environmental Protection Agency (Hertwich et al., 1997).

Equation 1 defines the HHS score as the product of two vectors, the health hazard vector HP and the site-specific vector F. Each vector consists of seven elements, representing oral and inhalation toxicity, eye irritation, dermal irritation, carcinogenicity, reactivity, and flammability. Equation 2 shows that HP is itself the product of the chemical hazard H and the phase matrix P. For the site-specific F vector, an expert is asked to score the importance of specific endpoints at a given site in a pair-wise comparison of endpoints and the relative scores are converted to a vector using the AHP matrix (Hertwich et al., 1997).

$$\text{HHS} = \overline{\text{HP}} \times \overline{\text{F}} \quad (1)$$

$$\overline{\text{HP}} = \overline{\text{H}} \times (\text{P}) \quad (2)$$

Material Intensity Per Service-Unit

Material Intensity Per Service-Unit (MIPS) is a measure of the total mass flow caused by the consumption of a service-unit. The material input includes any material that is moved by the production process and carries with it an “ecological rucksack”, the amount of material that had to be used for its production. The total mass is aggregated in kilograms over the life-cycle of a product and related to the service provided by the product (Hertwich et al., 1997).

Swiss Eco-Points

Swiss Eco-Points (SEP) method is based on the concept of critical pollution loads. The method considers the scarcity of environmental absorption capacity by relating a production process load to the actual load of a particular pollutant as well as the critical load that can be absorbed by the

receiving environment (see Equation 3). The sum of “points” from all pollutants gives a measure of the total environmental impact (Hertwich et al., 1997).

$$\begin{aligned} \text{SEP score} &= (\text{relative emissions}) \times (\text{scarcity factor}) \\ &= \left(\frac{E}{E_{\text{acceptable}}} \right) \times \left(\frac{E_{\text{total}}}{E_{\text{acceptable}}} \right) \times 10^{16} \end{aligned} \quad (3)$$

The critical flow or maximum acceptable pollution load ($E_{\text{acceptable}}$) represents the absorption capacity of an environmental compartment for a particular pollutant. Critical loads can be defined either as ecological critical loads or as politically maximum acceptable limits (Baumann and Rydberg, 1994). The first ratio in Equation 3 measures how important an emission (E) is by comparing it to the acceptable level, and the second ratio is a measure of scarcity, where the current pollution load (E_{total}) is independent of the investigated process or product in the environmental compartment (Hertwich et al., 1997). The factor 10^{16} is included to express the score in eco-points g^{-1} if the emissions are given in tonnes. A schematic representation of the Eco-points method is represented in Figure 3.

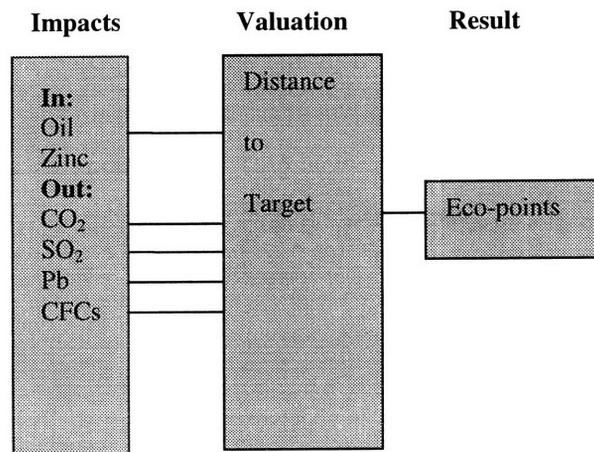


Figure 3. Schematic representation of the Swiss Eco-Points method. Source: Goedkoop (1995).

Sustainable Process Index

Sustainable Process Index (SPI) determines the area required to sustain a process based on harvest rates for inputs, and the area necessary for the degradation of effluents without violating environmental standards. This method is based on an operational definition of sustainability, in the sense that a sustainable economy utilizes resources at or below the rate at which they are

created and it produces only waste streams that can be dissipated in the environment without threatening the life-support system or human health, and without accumulating in the environment (Hertwich et al., 1997).

A particular activity or product is related to an area, using dilution volumes and resource generation rates, where the surface area of the planet is seen as the ultimate constraint for human activity. The area required for a particular production process is the area required for raw materials and energy production, the area of the installation, the living area of the process staff, and the dilution area for waste dissipation. This area is divided by the per capita area of the region in which the production occurs, so that the index measures how many persons' life-support capacity the process of interest demands (Hertwich et al., 1997).

Environmental Theme

In Environmental Theme (ET) method, the total impact is calculated in several steps (Baumann and Rydberg, 1994). First, the environmental loads of the product are aggregated into selected environmental themes, and the impacts caused by the product are calculated by theme, using a measure of the relative equivalence of the pollutants. Then, the sum of equivalent loads of a theme is normalized by dividing by the corresponding total pollution of the same theme within the geographical area relevant to the study, resulting in an impact fraction IF_i (see Equation 4).

$$IF_i = \frac{\sum_{j=1}^p \text{Load}_j \times Eqv_{ij}}{\sum_{k=1}^p \text{Load}_{k,tot} \times Eqv_{i,k}} \quad (4)$$

The impact fractions are summarized to a total impact after being multiplied by weight factors to take into account the relative severity of the different environmental themes. The ET method gives some freedom in the choice of themes and in the way the weight factors are determined steps (Baumann and Rydberg, 1994).

Environmental Priority System

Environmental Priority System (EPS) is a valuation method that builds on the SETAC guidelines for LCA. EPS requires the actual determination of damage in the characterization step and

assigns a monetary value to that damage, based on methods of environmental economics. This method defines “safeguard subjects”, human health, biological diversity, production, resources and aesthetic values. In the characterization step of LCA the impact on each of these “safeguard subjects” is determined and quantified. Based on actual expenditures taken by society to avoid damage or on “willingness to pay” to avoid negative effects, the monetary value of the safeguard subjects has been calculated in Environmental Load Units (1 ELU = 1 ECU) (Hertwich et al., 1997). The emission index for each material is calculated by Equation 5:

$$\text{Emission index} = F1 \times F2 \times F3 \times F4 \times F5 \times F6 \quad (5)$$

where F1 is an evaluation factor which represents existing environmental and health costs; F2 is the intensity and frequency of the occurrence of the problem; F3 describes the geographical distribution; F4 represents the durability of the problem; F5 shows how much 1 kg of substance contributes to the problem; F6 is the average cost of reduction per kg of pollutant by means of end of pipe as a measure of the possibility of immediate action against the problem (Baumann and Rydberg, 1994). A schematic representation of the EPS system is represented in Figure 4.

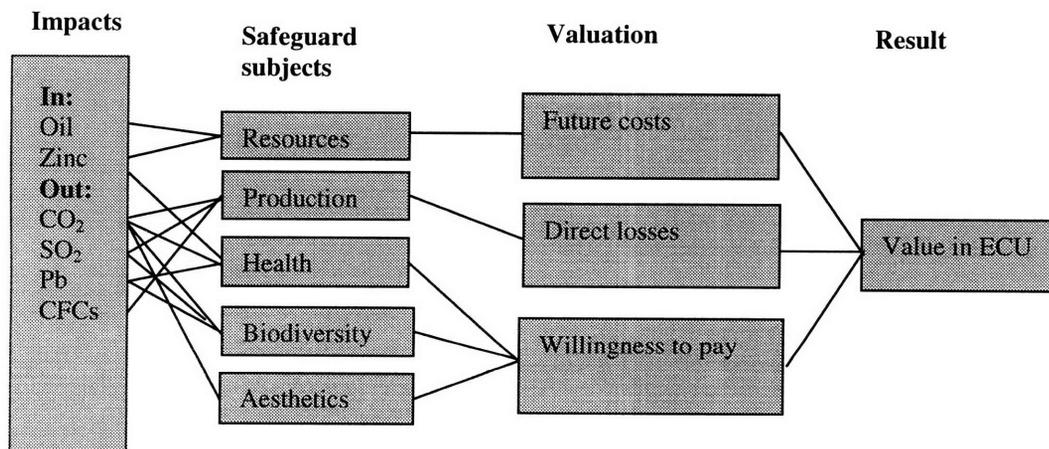


Figure 4. Schematic representation of the EPS method. Source: Goedkoop (1995).

Eco-Indicator

The Eco-indicator method is an extension of the current LCA method according to the SETAC guidelines. The weighting is based on the distance-to-target principle, i.e., the distance between the current and target values for a certain effect, and the greater the distance, the more serious the

effect. The effects of raw materials depletion, space requirements for waste and local effects are not evaluated (Goedkoop, 1995).

The target value is based on an analysis of the damage caused by an effect on a European scale. A simplified model for establishing a direct correlation between effect and damage is considered. The Eco-indicator method regards the damage levels (one extra death per million inhabitants per year, health complaints as a result of smog periods, 5% long-term ecosystem impairment) to be equal. Equation 6 is used for calculating the impact (Goedkoop, 1995) A schematic representation of the Eco-indicator method is represented in Figure 5.

$$\text{Impact} = D_k \times \sum_i \frac{E_i}{T_i} \quad (6)$$

where E_i = effect and T_i = target level at the critical damage value D_k .

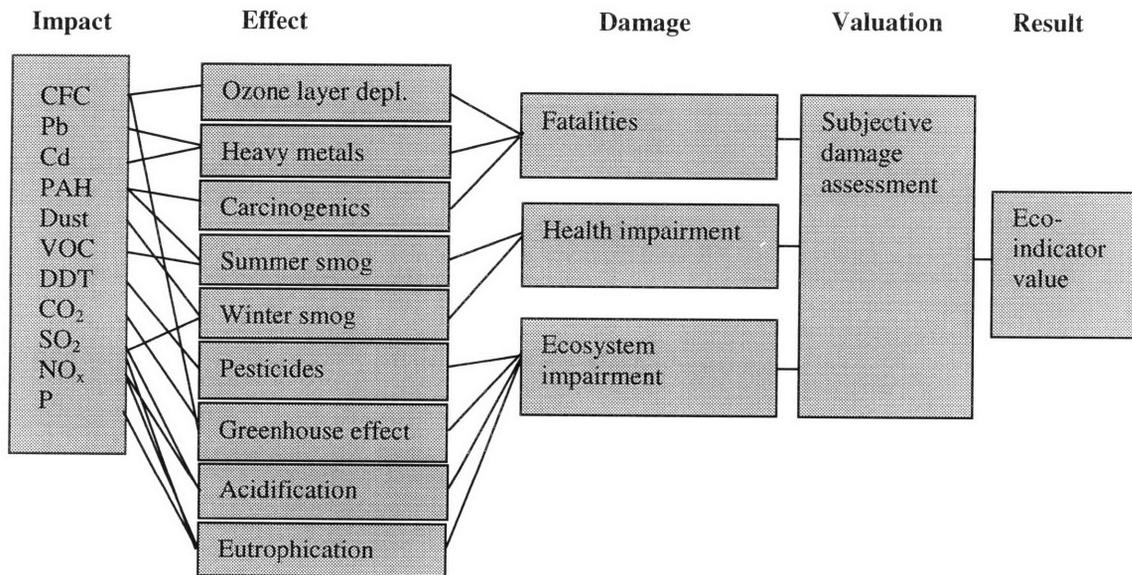


Figure 5. Schematic representation of the Eco-Indicator method. Source: Goedkoop (1995).

Although these impact assessment methods are used for the same purpose, they differ in the effects they consider, the depth of analysis, the way values influence the final score, and use of ordinal or cardinal measures of impact (Hertwich et al., 1997).

In performing index comparisons, the relative importance of CO₂, SO₂ and NO_x in SEP, ET and EPS methods, expressed as index ratios CO₂:SO₂:NO_x, was observed to be 1:200:250 1:220:350

and 1:150:6100, respectively. These differences in results are highly influenced by the distinct effects considered by each method, structural differences in the algorithms, and choice of background data (Baumann and Rydberg, 1994).

The purpose of all these evaluation methods is to rationalize decision-making in a company or authority concerning the environment. Differences resulting from distinct approaches may be considered useful as decision-makers may be referenced to different conceptions and criteria for environmental evaluation: the carrying capacity of the natural environment, politically established critical loads, society's willingness to pay, or others (Baumann and Rydberg, 1994).

Hertwich et al. (1997) and Baumann and Rydberg (1994) provide comparisons focused on similarities and differences between environmental assessment methods. Advantages and disadvantages these methods incorporate are also discussed.

Newell (1998) argues the deficiencies of currently available impact assessment methodologies and highlights that existing methods are not transparent enough. They do not expose the subjective elements inherent to LCA, which makes it impossible to explore the implications of different assumptions on the results. The methodology called "Explicit LCA" is proposed as an alternative approach, claiming innovations such as exposing the subjective elements and making a model that explicitly contains all steps in the causal chain from emissions to impacts to value.

3.4. Streamlined LCA and environmental weak-point analysis

In industry, experience has shown that it is rarely feasible to perform traditional LCA involving quantitative analysis throughout the entire life-cycle for all products and processes. Several reasons may contribute for this fact (Graedel and Allenby, 1995; O'Connor and Blythe, 1997):

- High completion costs, time required, labor intensive: the staff time and expense needed to complete a comprehensive assessment is often prohibitive.
- Unavailability of the required assessment data: much of the data are difficult or impossible to acquire, e.g., factory energy use may not have been allocated to specific products, and residue streams may have been merged.
- An assessment taking several months to perform makes no sense, with product life-cycles and design-to-market intervals of several months to 2 or 3 years.

Thus, simpler approaches for assisting the designer in incorporating LCA in product design have been suggested. The following approaches are forms of LCA simplification.

Streamlined LCA

Most corporations and many other organizations have adopted the LCA philosophy but have implemented it in a practical form suited to their own needs and constraints (Graedel and Allenby, 1995; O'Connor and Blythe, 1997; Eagan and Weinberg, 1997). Alternative streamlining approaches have been proposed, including a qualitative approach, which maintains the essence of LCA (considering the entire life-cycle of a product) but not requiring the collection of huge quantities of data (O'Connor and Blythe, 1997).

In streamlined LCA, modifications range from methods to shrink the boundaries and minimize the amount of data to be collected, to methods that combine qualitative and quantitative data. A number of companies have developed matrix approaches making LCA accessible through a series of questions for each section of the matrix, thus helping the designer to focus on key issues (O'Connor and Blythe, 1997).

Graedel and Allenby (1995) define the various forms of simplified matrix approaches as abridged LCA (ALCA). This approach considers only those elements deemed most important, and then only the constituents of those elements thought to be most significant. As examples, noise can be disregarded for many stages of many products, potential water contamination may only occur at certain life stages, if 80% of a product represents a single raw material, all others might be ignored unless toxic. The use of ALCA is demonstrated in Graedel et al. (1995) through a comparison of consumer products.

Environmental weak-point analysis

Simplified environmental assessments have been proposed for use by designers in an average company and in the time frame for new product design, where speed and cost make compromises in scope and accuracy. The purpose is to supplement LCA for a first indication "in the field" use of environmental weak points, which could then be possibly be further examined by LCA methods (Nissen et al., 1997).

As an example, the model for electronics design presented by Nissen et al. (1997) is briefly explained here. The proposed evaluation model is not life-cycle oriented (i.e., it evaluates the contents of a product and not the processes, and is based mainly on existing environmental ratings embedded in the German legislation). The data needed for the environmental score of a material can be obtained from original sources or from the materials safety data sheets: Hazardous Substances Declarations (R-values), Allowable Workplace Concentration (MAK), Water Pollution Classification (WGK).

The concept is to combine these values by projecting them onto a common normalization scale, and the result is a worst-case indicator of the environmental performance of a material. With these material ratings, a materials database specifically for electronics has been build and is used as the basis for a component pre-evaluation. Each material is attributed one number which describes the relative ecological impact of the material, and the material weights in the product are multiplied with this evaluation to achieve the component assessment. This approach neglects the impact of non-separable material connections but may identify the major areas of concern.

Nissen et al. (1997) assert that, for the fast and practical identification of ecologically relevant components during the electronics design, a rough assessment method is sufficient. Since it does not assess the real life-cycle of a product, this method needs less specific data from the manufacturers of sub-components - which means faster turnaround, a pre-requisite for applying a tool during the design phase.

Although these simplified methods are important for raising designer awareness and estimating first-order environmental effects, it has been argued that these tools still require extensive training and practice before they can be used properly, and product designers generally lack the environmental training necessary for carry on these analysis (Borland et al., 1998).

3.5. LCA as DFE tool in product design

LCA is the basis for most DFE analysis tools (Sweetman and Simon, 1996). This section provides an overview on how LCA may be applied in product design and main references on existing software LCA tools are provided.

3.5.1. LCA in product design phases

Several authors, including Ulrich and Eppinger (1995), have discussed the distinct phases involved in product design and development processes. Although design teams often iterate back and forth between design stages as needed, the following categorizes the design phases, based on existing standard and accepted systematic approaches (Pahl and Beitz, 1988; Hoffman III, 1997):

- (1) Conceptual design. In this phase, the product is conceived in conceptual terms emphasizing the purpose that the product will fulfill. It involves the identification of the essential problems through abstraction, the establishment of function structures and the search for the appropriate solution principles and their combination. The design tools used at this phase in product design must be general in nature, questioning past design approaches and directing the design team to new, improved design options.
- (2) Embodiment design. During this phase the designer, starting from the concept, defines the layout and forms, and develops a technical product or system according with technical and economic considerations.
- (3) Detail design. In this phase, the concept and the part structure have been well defined and attention shifts to the design of individual parts. The arrangement, form, dimensions, and surface properties of all the individual parts are finally laid down, the materials specified, the technical and economic feasibility re-checked and all drawings and other production documents produced.
- (4) Prototype manufacture. In this phase, the full product is developed. This is when process and product come together: the product has been manufactured once, and the information about manufacturing process, total assembly time, supplier specifications, part sizes, and material composition are all potentially known. Few changes may be made at this stage that will significantly alter the character of the product.

In order to perform a true green design all environmental implications of a product should be weighed against alternatives as early in the design process as possible. In a new product, details will not be fixed in the conceptual phase and therefore the first decisions must be based on

general approximations. Re-valuations should follow at all stages of the design process (Nissen et al., 1997).

LCA has been difficult to apply in the context of new product design, especially for complex products that employ multiple parts or materials (Hoffman III, 1997). During the conceptual phase, a full quantitative analysis such as the traditional LCA is not feasible because exact information about size, material composition, and construction is not available. Both the traditional and environmental tradeoffs are not known. Hoffman III (1997) considers this fact a paradox since an LCA requires detailed knowledge of a product but the product has little detail.

Newell (1998) presents a different point of view. It is argued that the non-site-specific nature of life-cycle inventory generation and impact analysis are appropriate during the conceptual phase, where it may not yet be determined which components of a product will be made in house, which will be outsourced, and which suppliers will be used.

During the progression from concept to final product, more design details become available. Hoffman III (1997) refers to existing LCA tools that are useful in the conceptual phase (abridged LCA) and in prototype manufacture (traditional LCA), and proposes a tool to address the detailed design stage as a scoring system based on multi-attribute value theory.

Alting and Legarth (1995) present a different approach in defining the principal steps in the application of LCA in product development. As shown in Figure 6, a successful environmentally conscious product development process is divided into seven distinct phases, each with special tool requirements and five major fields of activities.

LCA is used throughout the development procedure, initially on a reference product, which is a product that has the same basic functionality and/or technology as the product target being developed (B). This initial full-blown LCA applied in the analysis and goal definition phases reveals the good and bad environmental features of the reference product, in order to identify improvement potentials, focus points and subsequently design strategies (C, D), and perform an environmental product specification (E).

Phases Activities	Idea phase	Analysis phase	Goal definition phase	Develop. phase	Detail design phase	Establish. phase	Production phase
Synthesize product	. Environ. A Policies . Ideas . Market asp.		Environ. D design strategies	Environ. design rules F Life-cycle information			
Model life- cycle		Life-cycle modeling B1 - reference product Life-cycle inventory B2 - reference product		Life-cycle modeling F - concepts/components Life-cycle inventory F - concepts/components			
Identify focus		Life-cycle assessment B3 - reference product Life-cycle diagnosis C - reference product		Life-cycle assessment G - concepts/components			
Specify goals			Environ. E specification				
Verify results				Life-cycle modeling – inventory and assessment H - new product			

Figure 6. Environmentally conscious product development. Source: Alting and Legarth (1995).

LCA is used throughout the development procedure, initially on a reference product, which is an own or competing product that has the same basic functionality and/or technology as the product target being developed (B). This initial full-blown LCA applied in the analysis and goal definition phases reveals the good and bad environmental features of the reference product, in order to identify improvement potentials, focus points and subsequently design strategies (C, D), and perform an environmental product specification (E).

In the actual development and detailed design phases LCA may be used to model and identify the environmental performance of various concepts for the product itself or subassemblies (G), also using sets of environmental guidelines (F). This is where the actual choices about construction materials and manufacturing processes are made, taking into account the total life-cycle performance of the relevant options.

Modeling the environmental consequences of the relevant design options leads to the conceptual and structural detailed design of the product, after which it is possible to establish production, and perform another full-blown (H) to see if initial goals for environmental performance are met, and which may serve as a basis for the work with the next product generation.

3.5.2. Existing LCA tools for DFE

LCA tools are often judged upon their strength at both inventory and assessment stages. A tool with a strong inventory includes a broad range of materials and process, and the better assessment tools enable the data to be assessed in a variety of fashions (Sweatman and Simon, 1996).

A large number of software tools have been developed to implement LCA methodologies. These tools differ significantly in terms of: the scope of problems they can address, the quantity and quality of data provided, ease of use and the method of environmental impact assessment and visualization (Jackson and Wallace, 1997). Alting and Legarth (1995) and Sweatman and Simon (1996) review a wide range of these tools. Also, a study commissioned by Environment Canada evaluated 37 software tools currently available for LCA (Menke et al., 1996).

Borland et al. (1998) discuss the use of these LCA tools by product designers. Although these methods support environmentally conscious design, product designers tend to lack expertise in making decisions on environmental assessment issues, as environmental experts do not have the necessary expertise for product design. Borland et al. (1998) propose the incorporation of environmental experts using these LCA tools in the design process through a specialist-based collaborative structure based on network communication.

3.6. Benefits and shortcomings of LCA

LCA provides a broad screening approach using mass loadings to identify possible issues in the environmental, resource and human health areas. There are several demonstrated benefits that this methodology may offer, such as (Owens, 1997):

- Evaluation of the overall material and energy efficiency of a system.
- Identification of pollution shifts between operations or media.
- Identification of trade-offs in materials, energy, and releases.

- Benchmarking of system efficiency improvements and reductions in releases.

LCA may be most useful specifically during the design phase of the products. In this phase, screening information for issue identification is needed to identify and to avoid significant environmental problems that were previously hidden (Owens, 1997).

Beyond product design, LCA encounters increasing analytical limitations and consequently it must be used with caution (Ehrenfeld, 1997; Owens, 1997). Among others, LCA methodology has been criticized for the following limitations (Fiksel, 1996; Hendrickson et al., 1997):

- Defining system boundaries for LCA is arbitrary and controversial.
- LCA is data-intensive and expensive to conduct.
- Impact assessment in LCA is fraught with scientific difficulties.
- Equally credible analyses can produce qualitatively different results.
- LCA does not account for non-environmental aspects of production quality and cost.
- LCA cannot capture the dynamics of changing markets and technologies.
- LCA results may be inappropriate for use in eco-labeling.

Owens (1997) provides an in-depth discussion about the constraints on moving from inventory to impact assessment and technical shortcomings in the state-of-the-art for impact assessment. The constraints imposed by inventory are loss of spatial, temporal, dose-response, and threshold information, varying widely according to the environmental issue in question and models used to extrapolate the inventory data. As a result, LCA may have limited values in local and/or transient biophysical processes, and issues involving biological parameters, such as biodiversity, habitat alteration, and toxicity.

In examining the appropriate uses of LCA, one issue has been the distinction between two views of this methodology (Fava, 1997; Owens, 1997): (1) conceptually as a thought process that guides the selection of options for design and improvement, providing a spectrum of useful insights on a system; (2) methodologically as a sound, complete characterization useful for all types of comparisons and judgments of environmental performance.

The difference between these points-of-view may also be interpreted as whether LCA is a stand-alone tool, sufficient for making definitive comparisons, or must be integrated with non-LCA

complementary tools, such as risk assessment and environmental impact assessment, to provide meaningful and relevant answers. Given the scientific and technical limitations inherent to LCA, this approach has limited stand-alone capability for making comparisons, and therefore its broad screening capabilities need to be integrated with other environmental tools in an overall environmental management framework (Owens, 1997; Fava, 1997; Ehrenfeld, 1997).

The goal is to have each tool performing the task and providing the information to which it is best suited, while other complementary tools address its weakness and limitations (Fava, 1997). For example, if one were trying to assess the efficient use of resources in a product system, LCA could provide information internally to a company to identify opportunities to improve the efficiency. But, if the goal were to address customer concerns on health and toxic effects, the problem could be addressed by conducting a human health and ecological risk assessment. Finally, if one were trying to address “overall environmental preference” of one product system over another, a variety of tools, including site-based assessments and LCA could be suitable.

Newell (1998) presents a different point of view in proposing a decision-oriented LCA tool called “Explicit LCA” (XLCA), as a quantitative LCA methodology suitable to environmentally rank alternative technologies. He supports the idea that in the early design phase, a low precision assessment tool is appropriate and sufficient for ranking technologies, as long as it addresses the objective and subjective elements of LCA explicitly in order to explore their effects on the outcome. It is required that the LCA tool must be used by environmental experts who are members of product development teams, not designers, to devote time and apply expertise in addressing environmental problems.

In any case, comparisons and choices have to be made in product design and LCA, if used appropriately and consciously regarding methodological limitations, adds important environmental content and context to other factors, such as performance and price (Ehrenfeld, 1997).

Designers have often missed important sets of problems and opportunities by focusing on only a part of the life-cycle (Ehrenfeld, 1997). Although LCA does not provide the right answer, this methodology has the potential for identifying environmental issues from a systemwide perspective, being helpful to understand the problems better.

4. Distributed Object-based Modeling and Evaluation Framework

4.1. A framework for integration of LCA in product design

The integration of LCA in product design is directly related with the need for using methods capable of integrating environmental criteria with traditional design considerations. The goal is to share specialized knowledge characterized by different view points, goals and constraints in order to balance complex sets of design objectives, also considering the environment (Jackson and Wallace, 1997a; Senin et al., 1997a; Borland et al., 1998).

In this context, a method for rapidly building integrated analytical models or design tools is needed so that designers can have a comprehensive outlook and evaluate the current state of the development process, each according to their own expert viewpoint. DOME (Distributed Object-based Modeling and Evaluation), a design modeling framework created in the Computer Aided Design laboratory (CADlab) at MIT, was developed to facilitate integrated product life-cycle design.

This chapter provides a background for DOME, the modeling framework with which the LCA model developed in the present work is integrated into the design process. The basic concepts of DOME are provided to give a general overview of the framework. Two types of approaches provided by DOME to facilitate the incorporation of LCA into product design are presented.

4.2. The DOME framework

The DOME framework uses distributed computer-based models for the modeling and evaluation of product design problems and collaborative design, in a network-oriented design environment. The goal is to enable rapid integrated product development using a flexible modeling tool to reduce the time for a concurrent design iteration and facilitate an understanding of tradeoffs and decision making. In assisting integrated product life-cycle design, the framework provides designers, manufacturers and customers with the ability to rapidly construct integrated design problem models accounting for interactions between different viewpoints and to incorporate distinct existing analysis applications under a common design environment (Senin et al., 1997a).

A general overview of the DOME framework is provided here below. The framework issues addressed are presented based upon descriptions published in Borland (1996), Senin et al. (1997a, 1997b), Jackson and Wallace (1997a, 1997b), Borland et al. (1998), Pahng et al. (1998a, 1998b), Kaufmann (1998).

4.2.1. Modular modeling

Decomposition of a problem into manageable sub-problems can be used to manage complexity by distributing modeling tasks. The DOME framework asserts that modular modeling is key approach to multidisciplinary problem model decomposition as modularity breaks down the overall complexity, distributes knowledge and responsibility among designers, and facilitates reusability of modeling elements.

In DOME framework, the design problem is divided into a set of modules which each describe a conceptually separate part of the decomposed problem in the form of variables and relations. This decomposition allows for specific sections of the problem to be modeled by people with the relevant expertise, with the possibility of each module being regarded as a “black box” representing a specific aspect of a design.

Modules have embedded models, which may include data, mathematical models and complete software programs, and may also contain design requirements which characterize its own design viewpoint. Modules are visible to other modules through a standardized interface. As an illustration, Figure 7 presents a simplified module representing a motor.

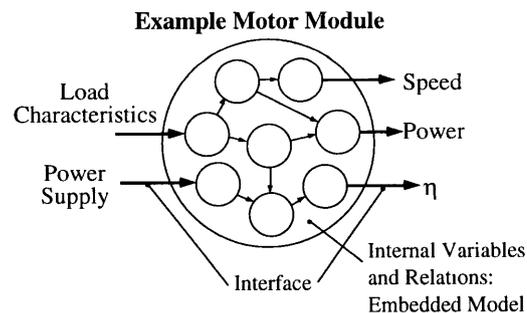


Figure 7. A simplified module representing a motor: interface and embedded model. The variables contained in the module are represented as interconnected circles and the directed arcs imply dependency. Source: Senin et al. (1997a).

A collection of completed modules is linked together to create the integrated design tool. This is accomplished using input and output interfaces which allow modules to provide services to other modules through their interfaces and the completed model to behave as an integrated system.

Once defined, modules can be reused to accelerate and standardize the development of models for new design problems, analogous to the concept of creating “objects” in an object-oriented programming language and then storing them in libraries for reuse. The reuse of modules is provided by storing them in a hierarchical catalog structure, where catalogs can be used to help the designer explore alternatives by selecting different modules. As an example, a pre-defined LCA module could be connected into a new design problem to provide environmental assessment capabilities to a new model being constructed.

A wrapper is a module that has an external application as its embedded model. The wrapper mediates interactions between the module interface and the external application, allowing preexisting software programs to communicate with other modules in the framework. Therefore, custom created computer programs and third party external applications, like domain specific analysis tools (such as LCA software, a spreadsheet, a database manager) and CAD systems, can be embedded into a module so that they become part of an integrated design model.

A Model Definition Language (MoDeL) has been developed for defining the problem models in the framework. Both deterministic (exact) and probabilistic (uncertain) variables may be defined in a given problem. Currently, relations involving probabilistic variables are solved using algorithms based on Monte-Carlo simulation and Bootstrap techniques.

The consistency of a set of related variables within or between modules is maintained by a solver so that changes in independent variables are reflected in the design model scope according to the defined relations. If a design variable changes (e.g. due to a designer choice) the solver propagates the change through all the variables related directly or indirectly to the design variable. The solver, which invokes this update mechanism and accounts for uncertainty, is a major part of the design modeling framework and guarantees an efficient spreadsheet-like behavior.

4.2.2. Distributed modeling

In DOME framework, the computer-based model representing the current state of the design process is distributed among the designers in a service network, taking advantage of the modular approach, as opposed to other approaches currently used, where the model is maintained in a central database accessed remotely by the designers or exchanged "over-the-wall" in a one to one relation. The framework also presents the flexibility of integrating a mixed approach. Figure 8 illustrates the architectural differences between these approaches.

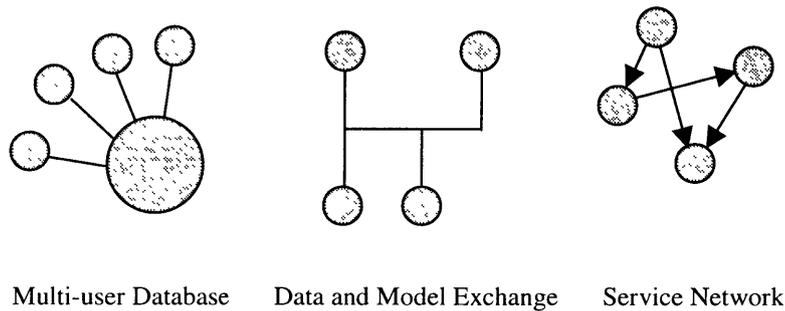


Figure 8. Three different approaches in concurrent engineering. Source: Pahng et al. (1998b).

In the distributed model paradigm, DOME framework allows designers to define mathematical models in a collaborative design environment using sets of interconnected modules distributed over the network, therefore collectively constituting a distributed model for a collaborative, multidisciplinary design problem. The modules interact with each other through standard Internet communication protocols compliant with the Common Object Request Broker Architecture (CORBA) standard, exchanging information and services, and reacting to each other's changes.

In the distributed environment, each group of designers can define their own part of the model and load it in their local work area, eventually connecting it to the other parts of the design problem through the appropriate networked interfaces (Intranet, Internet, WWW). The following example illustrates a simple design scenario.

Figure 9 shows a DOME model involving two product designers and three modules. Designer 1 defines modules A and B while designer 2 defines module C, and the two domains communicate through an Internet connection. Each group of designers typically has write access to the local parts of the model and read access to relevant aspects of the remote parts of the model, which allows them to see the remote effects of their local decisions.

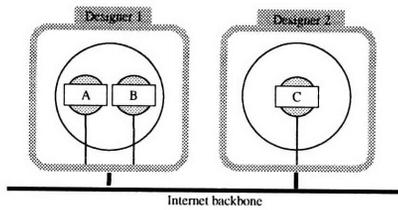


Figure 9. DOME distributed model as it is physically modeled.

Source: Senin et al. (1997a).

Figure 10 shows that both of the designers would see the complete model of the problem, but each with different access privileges. Designer 1 would see modules A and B as local (usually write access) and module C as remote (usually read-only access). Conversely, designer 2 would see module C as local. Depending on access privileges, however, the remote part of the model could be viewed either as a single distributed object (AB), or as several individual remote modules.

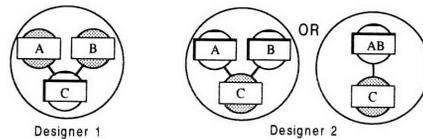


Figure 10. DOME distributed model as it is seen by the designers involved.

Source: Senin et al. (1997a).

4.2.3. Evaluation modeling

The framework presents evaluation modeling capabilities based on a goal-based approach. Other evaluation methods could also be used, such as Utility Theory or AHP. An evaluation model includes both the definition of the designer's preference structure and the comparison of design performance variables to this preference structure, with the possibility of associating uncertainty and evolving as the understanding of a design problem changes over time.

According to the goal-based approach, design solutions are evaluated against a set of designer's goals stated as requirements or specifications. These goals are defined in terms of acceptability functions which indicate the subjective probability that the designer will judge values of a quantity as "acceptable", to indicate desired performance levels.

A specification-like acceptability function is represented as a piecewise linear function of its associated attribute, ranging from 0 (reject the performance variable value with certainty) to 1 (accept the performance variable values with certainty). A design criterion evaluates a performance variable against a specification to determine its acceptability, meaning to compute the probability that the current value of the quantity will be deemed acceptable. This goal-based acceptability design evaluation is illustrated in Figure 11. The overall probability of acceptance for a design is assessed by aggregating the probabilities of acceptance for all the individual requirements.

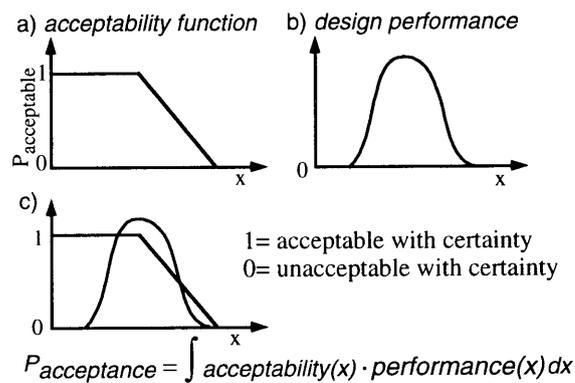


Figure 11. Goal-based acceptability design evaluation. Source: Jackson and Wallace (1997a).

In order to group design criteria according to particular design viewpoints, evaluation lens has been developed. A lens, a special type of module, provides the service of evaluating multiple criteria corresponding to a particular aspect of a design problem.

4.2.4. Optimization

In addition to the ability to create and explore changes in design models involving both continuous parameters and catalog selections (mixed variable problems), and to evaluate design solutions against design preferences, the framework is linked to an automated search engine which interacts with the problem model, generating candidate solutions and evaluating them using lenses. The optimization engine is based on Genetic Algorithms (GA). This optimization technique was selected because it does not require the specification of a feasible starting point or any assumptions about the characteristics of the search space, and has the potential to locate several locally optimal design alternatives, in addition to the global solution, in a single

optimization, which provides designers with insight into the design space and freedom to select from a number of possibilities.

The search engine generates new solutions by sending a set of values to the design variables/replaceable modules in the problem model. The search algorithms then evaluate the quality of the design by invoking the design lenses representing different viewpoints and their corresponding evaluation services, and these evaluation results are used as inputs to an objective function. Figure 12 illustrates the integrated design problem modeling and optimization architecture.

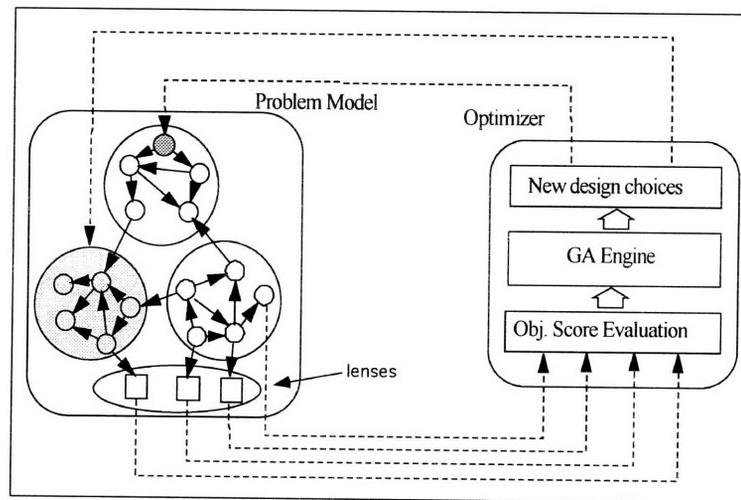


Figure 12. Integrated design problem modeling and optimization architecture.

Source: Senin et al. (1997b).

4.2.5. Implementation

The DOME framework has been implemented in C++ on Silicon Graphics®, Inc. (SGI) platforms. The modeling core is based on an Object-oriented Modeling and Evaluation (OME) library and the CORBA standard is used for the distributed computing environment. The CORBA implementation is ORBIX® from IONA Technologies. CORBA serves as an information and service exchange infrastructure above the computer network layer and provides the capability to interact with existing CAD applications and Database Management Systems (DBMS) through other Object Request Brokers based on the CORBA standard.

4.2.5. Key qualifying factors for application

There are key qualifying factors which play an important role for this framework to be applied:

- integrated model (service exchange network) is not hard coded for a specific problem
- facilitates the construction of integrated tools for new problems
- models grow and evolve as projects grow and evolve
- operates in a distributed heterogeneous environment
- protects proprietary models and data
- captures uncertainty in data, model, or in expert's service quality.

The DOME framework has been applied to a variety of design problems, such as electromagnetic shielding enclosure design (UTRC), co-generative electricity plant design (Swiss Federal Institute of Technology), and Watson product development project (Polaroid).

4.2.6. DOME development vision

At the present time, organizations and experts publish information on web pages and individual web pages are connected together to form topical databases and catalogs. The development vision for DOME is seen as an evolution of this framework towards a web-based collaborative design environment, predicting that in the future organizations and experts will publish services that operate through the World Wide Web (WWW) and services will be connected together to form concurrent product development systems.

4.3. Integrating LCA in DOME framework

The DOME framework provides two types of approaches to facilitate the incorporation of LCA into product design: (1) modular method; (2) collaborative method. These approaches are not necessary mutually exclusive so that a design problem modeling may involve both methods combined in a flexible way that fulfill the goals and scope of the study.

In the modular method, generalized modules may be used to represent the product life-cycle using DOME environment. Jackson and Wallace (1997b) describe an approach for modeling product life-cycles in order to create time-dependent inventories for use in environmental impact assessment. The approach illustrates a modular method in order to simulate the time-based

fluctuations of resource flows related to complete product life-cycles. This relevant time-related issue is not addressed in most impact assessment tools, which are based upon static inventory data and do not take into account that in many instances environmental impact is dependent upon emission rates and accumulation of materials (Jackson and Wallace, 1997b).

Although it is only focused on the LCI stage, the approach also illustrates that DOME framework may be used to facilitate the incorporation of LCA into product design through the creation and combination of modules for modeling the product life-cycle stages. A general process module is defined relating resource inputs and outflows, based upon an embedded mathematical model. The generality of the process module defined allows sections of a network to be embedded within larger modules, thus facilitating the re-use of network sections in different product life-cycles.

A specific model used within modules represents average process behavior as a function of a set of empirical process parameters for simulating a variety of life-cycle processes, such as material processing, transportation, and assembly. By linking process modules together, the designer can represent complete manufacturing networks for product life-cycles, and specify the required system output or product demand as a function of time. The integrated network calculates the necessary time-dependent resource flows throughout the network, and this time-based inventory information can be used in conjunction with existing LCA tools to perform an environmental impact assessment which accounts for time-related effects.

The collaborative method uses existing LCA software tools to be incorporated into modules so that they become part of an integrated design model, based on the collaborative modeling concept proposed by Borland et al (1998). In this method, a specialist-based collaborative structure allows environmental experts to rapidly provide an impact assessment to product designers, based on a given set of inputs. The collaborative approach assumes that product designers and environmental experts are specialists in their own fields, each may have some knowledge of and training in the other's field, but neither is capable of doing the other's job in a thorough way.

The environmental experts build life-cycle models, and designers separately build appropriate engineering models. Through an internet-based communication using an interface negotiated between the environmental experts and the designers, the two groups exchange relevant information, allowing for concurrent modeling even though their proprietary data, specialized

models and tools are separate. This method has the advantage of distributing expertise and keeping models proprietary, yet integrated (Borland et al., 1998).

The integrated LCA model created in the present study was built based on the collaborative approach. A more detailed description about the collaborative concept applied to this model will be provided in Chapter 5.

5. The integrated LCA model

5.1. Introduction

The integration of LCA with traditional design considerations in product design should be performed in a way that facilitates making appropriate tradeoffs between design objectives. The environmental criteria should be part of the concurrent design environment so that they can be balanced with traditionally design criteria, such as product cost, functionality and user quality.

The process of creating an integrated LCA model of a new LCD computer projector in a joint MIT/Polaroid project is the main topic of this chapter. The goal was to build an LCA model for integration into the product design tool, allowing the resulting tool to predict the performance and environmental effects of design changes.

In an integrated product design process, the creation of the integrated LCA model included two main tasks:

1. Development of a flexible parametric LCA model for assessing the environmental performance of a computer projector using commercial life-cycle software.
2. Use of the DOME collaborative modeling framework to interface the LCA model with other design models developed by other team members.

The extent to which the integrated LCA model was developed is directly linked to the project purpose and circumstances. The company was a design integrator while the major components were outsourced. This project was in the early design phase where product details were not fixed.

In this context, the integrated LCA model was developed based on a quantitative streamlined LCA, intended to be used for assessing trends in environmental performance relative to a benchmark design. Similarly, the whole integrated design tool was used to address early design decisions based on approximations.

The following sections summarize the process of creating the integrated LCA model and provide illustrative scenarios for the use of the tool in understanding interactions between traditional and environmental design goals.

5.2. The LCA model

In the process of creating the integrated LCA model, the first task was to build a flexible parametric LCA model. The LCI modeler TEAM[®] (Ecobilan, 1996; Menke, 1996) and a DOME/TEAM[®] wrapper (Borland et al., 1998) were used for this environmental modeling purpose.

The intended use of the LCA model in the product design tool was to identify trends in environmental performance relative to a benchmark design. Thus, a quantitative streamlined approach was taken in developing the model. The design uncertainties influenced the methodology used in the model development. In the inventory stage, this approximate perception of the product and the product system led to simplifications in the model structure and difficulties in defining and obtaining the required data.

The methodology for developing the quantitative streamlined LCA model was based on parameterizing the benchmark projector, including its main components, and for each component estimating the approximate material composition by weight. Worhach and Sheng (1997) and Worhach and Sheng (1997) developed modeling methodologies based on a similar type of concept for a printed circuit board (PCB) assembly and a six-layer PCB fabrication process, respectively. However their methodologies are much more process driven and achieve a significantly higher resolution in modeling, supported by site production databases of representative products.

The methodology involved the following steps:

1. Tear down of the benchmark projector.
2. Identification of major projector components.
3. Estimation of materials and material composition by weight for each component
4. Conceptualization of the LCI model
5. Implementation of the LCI model, including data collection, uncertainty representation
6. Implementation of a more detailed version of the LCI model

5.2.1. Tear down of the benchmark projector

In the early stage of the process, there was a need to understand the product architecture being designed. A tear down of the benchmark projector, a projector currently available in the market, was performed to understand of and visualize the major components of the product (see Figure 13). This was also important for deciding which elements to include in the LCI model.

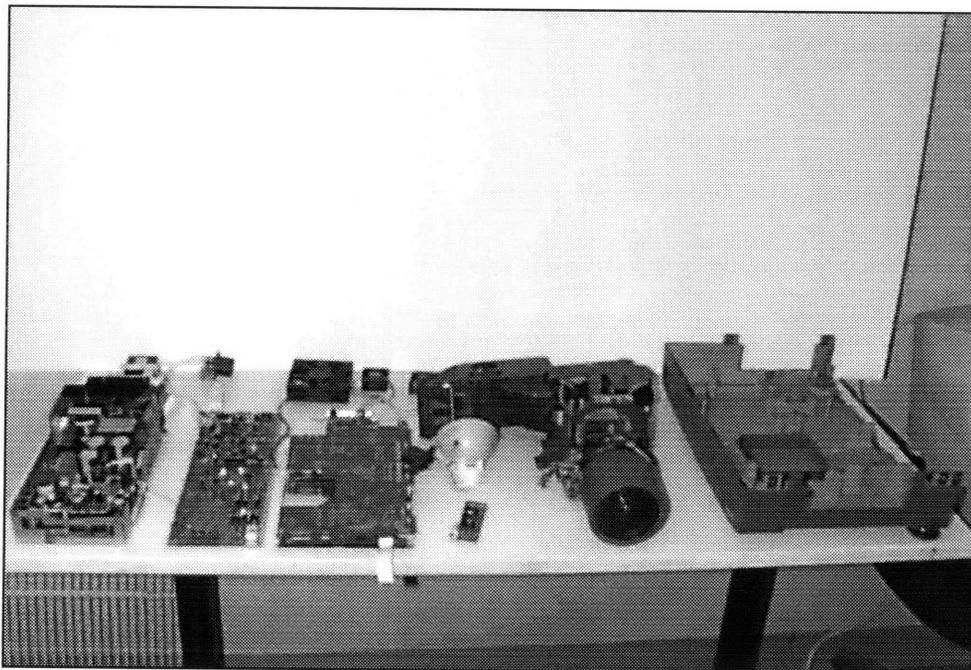


Figure 13. Tear down of the benchmark projector.

5.2.2. Identification of major projector components

Identification of major projector components was required to create a component-based model. Table 1 presents the major components that were identified based on the tear down and explanations provided by engineers from the company.

At the company, other projectors currently available in the market were also torn down. It was observed that the components vary in number and in functional combinations, with some of the components being optional. This fact influenced the modeling approach, which had to be flexible enough to account for such design differences.

Table 1. Major components of the benchmark projector.

PROJECTOR MAJOR COMPONENTS
-- Light engine
- prisms
- liquid crystal panels (LCD)
- printed circuit board (PCB)
- lamp
- intake fan
- optics fan
- electric magnetic shielding
- housing for optics and lamp
-- Power supplies
- general and optics power supplies
- fan
- electric magnetic shielding
- power supply PCB
-- PCBs
- main PCB with computer input/output
- video PCB
- infra-red (IR) receiver PCB
- user PCB
-- Housing
- top enclosure
- bottom enclosure
- rear panel
- lamp door
- intake filter door
-- Others
- remote control
- interconnection cables
- flex interconnects
- exhaust fan
- general fasteners
- carrying handle
- lens, lens-ring focus, lens-ring zoom, lens cap
- adjustable feet, rear feet
- speaker with wires and plug
- security lock

5.2.3. Estimation of materials and material composition by weight for each component

The estimation of major materials and approximate material composition by weight for each component was necessary to provide a flexible quantitative structure in the component-based model. The projector decomposition was restructured and quantified as shown in Table 2, to

address the issues of lack of information/understanding and component variability. Design uncertainties in the early design phase, as well as difficulties in obtaining the required data, led to the adoption of this type of approach.

Table 2. Major materials in the benchmark projector.

COMPONENTS/MATERIALS	WEIGHTS (%)
Light engine	100
glass	40
steel	6
aluminum	39
ceramic	1
epoxy	1
plastic PC	13
Fan (intake, optics, power supply, exhaust)	100
plastic ABS	80
copper	3
steel	15
board substrate (FR4)	2
PCB (main, video, power supply, IR receiver, user, I/O)	100
board substrate (FR4)	83
integrated circuits (IC)	5
resistors	0.3
capacitors	3
connectors	0.6
coils	8
gallium arsenide (AsGa)	0.1
Lens	100
aluminum	3
plastic ABS (ring-zoom, ring-focus, cap)	16
glass	81
Shielding	100
plastic PC	25
aluminum	75
Power supply (general, optics)	100
steel	38
copper (transformers)	52
plastic PC	6
aluminum (heatsinks)	4
Housing	100
plastic ABS	88
steel	11
synthetic rubber (PU)	1
Cables	100
copper	70
plastic PVC	30
Flex Interconnects	100
polyimides (PI)	100
Remote control	100
plastic ABS	57
board substrate (FR4)	20
batteries	23
Speakers	100

5.2.4. Conceptualization of the LCI model

In the conceptualization of the LCI model, it was necessary to define the boundaries of the product system and the assumptions involved, given the goals and scope of the project. The following assumptions for the LCI model should be noticed:

- The product system involves the production, use and end-of-life phases, not including material transport and product distribution. For the purpose of assessing trends in environmental performance relative to a benchmarking design and considering a minor contribution to the life-cycle impacts comparing with the use phase (Alting and Legarth, 1995), it was believed that the transport issue could be excluded from the analysis without influencing significantly the ranking of design alternatives.
- The use phase was considered to contribute with a major part the life-cycle impacts. Products that consume electricity during operation, such as a computer projector, have shown that large parts of the contributions to the total overall environmental impact come from the consumption of energy in the use phase (Alting and Legarth, 1995).
- In the production phase, energy and materials used and wastes released to the environment are mainly quantified based on materials' production activities. It was assumed that materials' production activities were sufficient to produce significant results for ranking design alternatives according to the purpose and scope of the project. Again, this is related to the purpose of assessing trends in environmental performance relative to a benchmarking design, and also to the difficulties encountered in obtaining data relative to component production (due greatly to the uncertainty about the suppliers' chain).
- For PCBs in the production phase the LCI inputs and outputs are accounted for considering the sub-components production processes. Although it was possible to implement this particular approach because data could be found for these components the option for considering these data is not simply based on availability. In fact, while PCBs do not represent a very high percentage of electronic products in either weight or volume, their components production processes use a wide range of materials – many of which are considered toxic, generate large volumes of hazardous waste, or have a high amount of energy invested (Nissen et al. 1997; EPA-DFE, 1998)

- In the end-of-life phase, it was assumed that projectors are disposed of via landfill. The LCI inputs and outputs are quantified only for the plastics constituting the projector housing, with three possible end-of-life strategies: landfill, recycling/landfill, and incineration/landfill. These scenarios were defined in the model to explore additional general trends in the environmental performance of the projector, given the initial broad purpose and scope of the project.

In the LCI model, the degree of sub-division of the total product system into individual operations is determined by a component/material-based approach, with the functional unit defined as one computer projector over its lifetime. To address issues of lacking information/understanding, component variability, types of components, and material composition, each type of component was considered in the component/material-based model by mass. The following expressions (Equations 7 and 8) represent this approach:

$$\begin{aligned} \text{Mass}_{\text{projector}} = & \text{Mass}_{\text{light engine}} + \text{Mass}_{\text{fans}} + \text{Mass}_{\text{PCB}} + \text{Mass}_{\text{lens}} + \text{Mass}_{\text{shielding}} + \text{Mass}_{\text{power supplies}} + \\ & + \text{Mass}_{\text{speakers}} + \text{Mass}_{\text{housing}} + \text{Mass}_{\text{cables}} + \text{Mass}_{\text{flex interconnects}} + \text{Mass}_{\text{remote control}} \end{aligned} \quad (7)$$

$$\text{Mass}_{\text{component } x} = \sum_i \text{Mass}_{\text{material}_i} (\%) \quad (8)$$

In Equation 7, masses of components are defined in the model as controlling variables. Different design options include components with different masses. For each component (Equation 8), an estimation of approximate material composition by mass is considered in the model. For example, for the housing and PCBs components, the percentages by mass are as follows:

$$\text{Mass}_{\text{housing}} = 88\%(\text{ABS}) + 11\%(\text{steel}) + 1\%(\text{PU}) \quad (9)$$

$$\begin{aligned} \text{Mass}_{\text{PCB}} = & 83\%(\text{FR4}) + 8\%(\text{coils}) + 5\%(\text{ic}) + 3\%(\text{capacitors}) + \\ & + 0.6\%(\text{connectors}) + 0.3\%(\text{resistors}) + 0.1\%(\text{AsGa}) \end{aligned} \quad (10)$$

Figure 14 shows a schematic representation of the conceptualization of the LCI model.

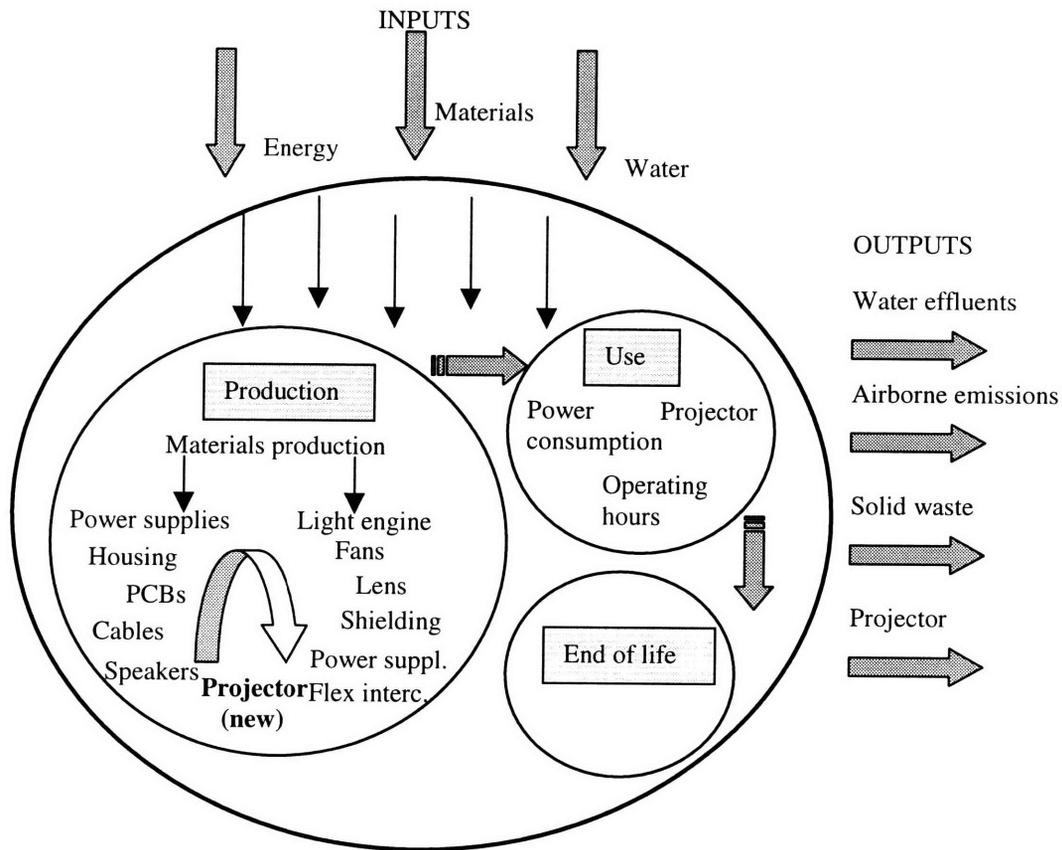


Figure 14. Schematic representation of the conceptualization of the LCI model.

5.2.5. Implementation of the LCI model

The LCI model was implemented using Ecobilan's life-cycle inventory modeler TEAM[®] (Tools for Environmental Analysis and Management). This software package provides (Ecobilan, 1996):

- Database blocks of life-cycle inventories for various processes. Each database contains quantified input and output data values collected from common industry sectors or activities. During the course of the model implementation, Ecobilan provided MIT CADlab with new databases, specialized in the electronics industry.
- Framework for modeling the flows between processes, where the total mass of each input and output of the system can be calculated for each unit of system output.
- Means for defining external variables to allow for simulations driven from control panels that are external to TEAM[®]. These variables can be exported to a spreadsheet, their

values linked to control panels and imported back for running a simulation, through an intermediary text file.

Figure 15 shows a snapshot of part of the implemented model.

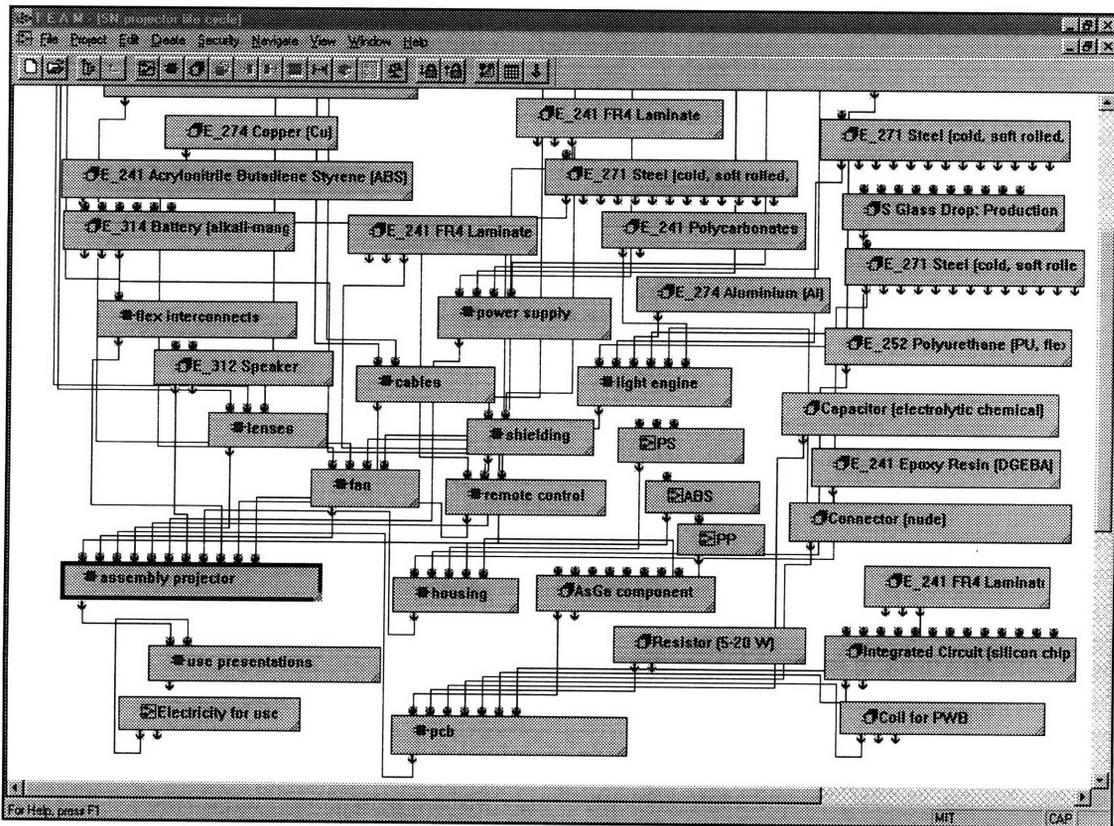


Figure 15. A screen image of the LCI model in TEAM®.

In the projector life-cycle system model, the basic building blocks are the projector components linked to the projector assembly node as inflows. The projector use node is the destination node for the projector assembly node outflow. Figure 16 exhibits the projector assembly node, which has eleven inflows (projector components) and one outflow (new projector).

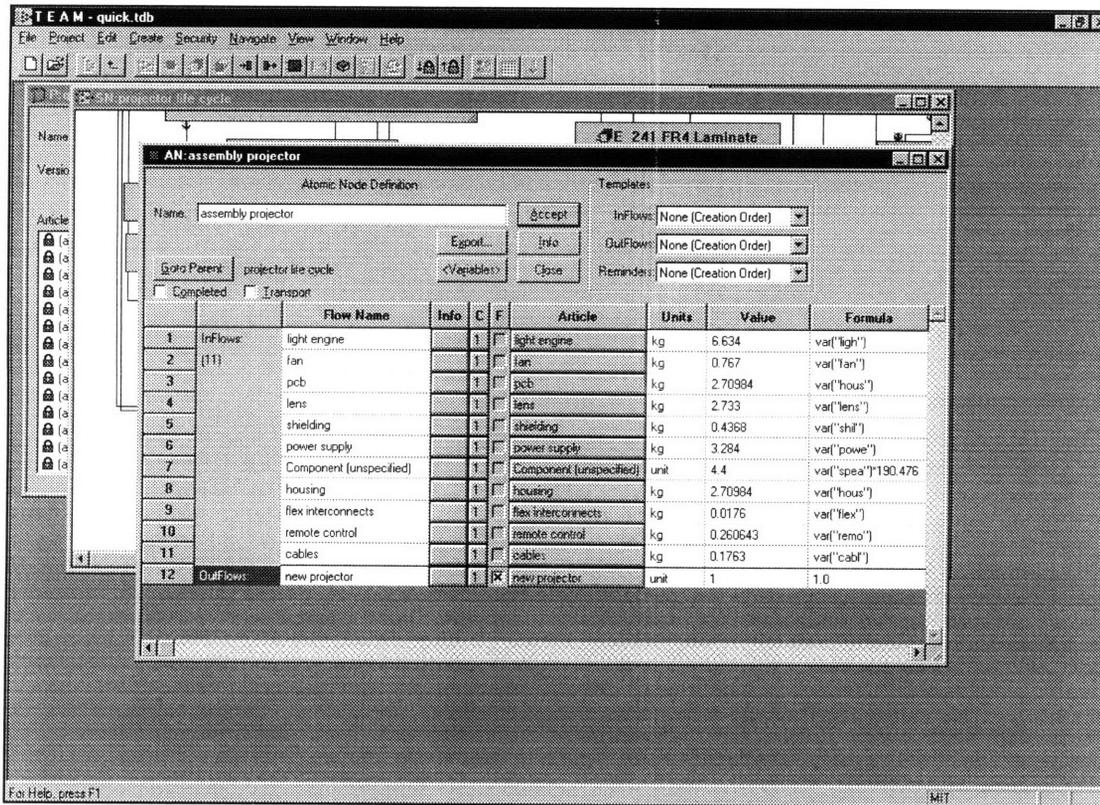


Figure 16. Inflows and outflows of the projector assembly node.

Materials and electricity production models feed the projector components, assembly and use nodes. Figure 17 shows a snapshot of one of the production models used in the LCI model, where a table of inflows and outflows lists the production process data.

The production processes for electricity consumed in the use phase and for the plastics used in the projector housing were defined as subsystems. The electricity subsystem (see Figure 18) models different electricity mix possibilities as different locations are considered for using the projector (Canada, US, Japan, OECD Europe). The models for production of different sorts of fossil fuels (coal, fuel oil, natural gas, and lignite) and electricity (coal, fuel oil, natural gas, lignite, hydro and nuclear) feed the electricity distribution nodes specific for each location.

TEAM - [ANE 241 Polystyrene (PS, High Im)]

File Project Edit Create Security Navigate View Window Help

Atomic Node Definition

Name: E_241 Polystyrene (PS, High Impact) Accept

Global Node: E_241 Polystyrene (PS, High) Export (NFD)

Global Parent: PS Variables Qtn

Compliant

Template:

InFlow: None (Creation Order)

OutFlow: None (Creation Order)

Reminders: None (Creation Order)

		Flow Name	Info	C	F	Article	Units	Value	Formula
1	InFlow:	(f) Coal (in ground)				(f) Coal (in ground)	kg	0.224	0.224
2	(f)	(f) Oil (in ground)				(f) Oil (in ground)	kg	1.77	1.77
3		(f) Lignite (in ground)				(f) Lignite (in ground)	kg	5.0227	0.0177
4		(f) Natural Gas (in ground)				(f) Natural Gas (in ground)	kg	0.9054	0.9054
5		Wood (used as: fuel)				Wood (used as: fuel)	MJ	0.01	0.01
6		Water (Used) (Local)				Water (Used) (Local)	gme	5.4	540000e-6
7		Water: Unspecified Origin				Water: Unspecified Origin	gme	5.4	5.4
8		(f) Braukite (CaCO3, ore)				(f) Braukite (CaCO3, ore)	kg	0.001	1000/1e6
9		(f) Sulphur (S, in ground)				(f) Sulphur (S, in ground)	kg	5.9e-005	155.2632/5471e6
10		(f) Sodium Chloride (NaCl, in ground or in sea)				(f) Sodium Chloride (NaCl, in ground or in sea)	kg	0.0021	2159/1e6
11		(f) Sand (in ground)				(f) Sand (in ground)	kg	0.00015	154/1e6
12		(f) Iron (Fe, ore)				(f) Iron (Fe, ore)	kg	0.00004	0.04/1e6
13		(f) Limestone (CaCO3, in ground)				(f) Limestone (CaCO3, in ground)	kg	0.025	25000/1e6
14	OutFlow:	Polystyrene (PS, high impact)				Polystyrene (PS, high impact)	kg	1	1
15	(g)	(g) Plasticizer: unspecified				(g) Plasticizer: unspecified	g	2	2000/1000
16		(g) Carbon Monoxide (CO)				(g) Carbon Monoxide (CO)	g	1.2	1200/1000
17		(g) Carbon Dioxide (CO2, fossil)				(g) Carbon Dioxide (CO2, fossil)	g	2800	2800000/1000
18		(g) Sulphur Dioxide (SO2 as SO2)				(g) Sulphur Dioxide (SO2 as SO2)	g	12	12000/1000
19		(g) Nitrogen Dioxide (NOx as NO2)				(g) Nitrogen Dioxide (NOx as NO2)	g	12	12000/1000
20		(g) Hydrogen Chloride (HCl)				(g) Hydrogen Chloride (HCl)	g	0.035	35/1000
21		(g) Methane (CH4)				(g) Methane (CH4)	g	11	11000/1000
22		(g) Hydrocarbons (unspecified)				(g) Hydrocarbons (unspecified)	g	3.0	3000/1000
23		(g) Aromatic Hydrocarbons (unspecified)				(g) Aromatic Hydrocarbons (unspecified)	g	0.2	200/1000
24		(g) Polycyclic aromatic Hydrocarbons (PAH, unspecified)				(g) Polycyclic aromatic Hydrocarbons (PAH, unspecified)	g	0.003	3/1000

For Help, press F1

MIT

Figure 17. A screen image of the Polystyrene (PS, high impact) TEAM® model.

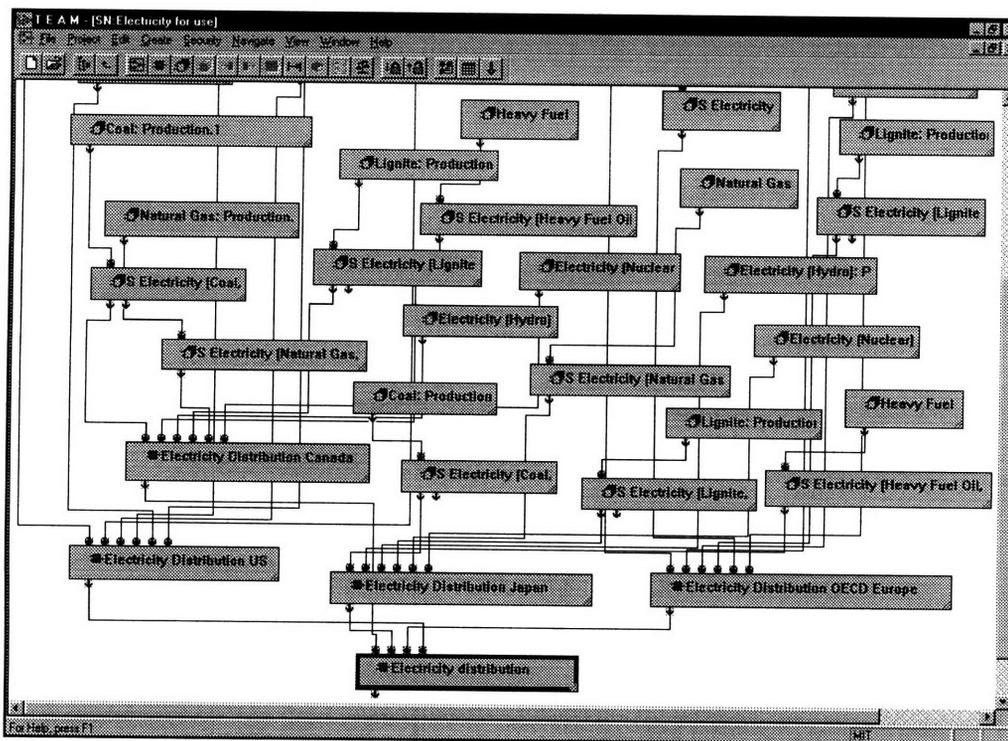


Figure 18. A screen image of part of the electricity distribution subsystem.

The subsystems for the housing plastics model the production and end-of-life phases of these materials. Figure 19 shows the subsystem defined for the polystyrene, where end-of-life models were incorporated to account for material and energy flows due to landfill, recycling and incineration activities.

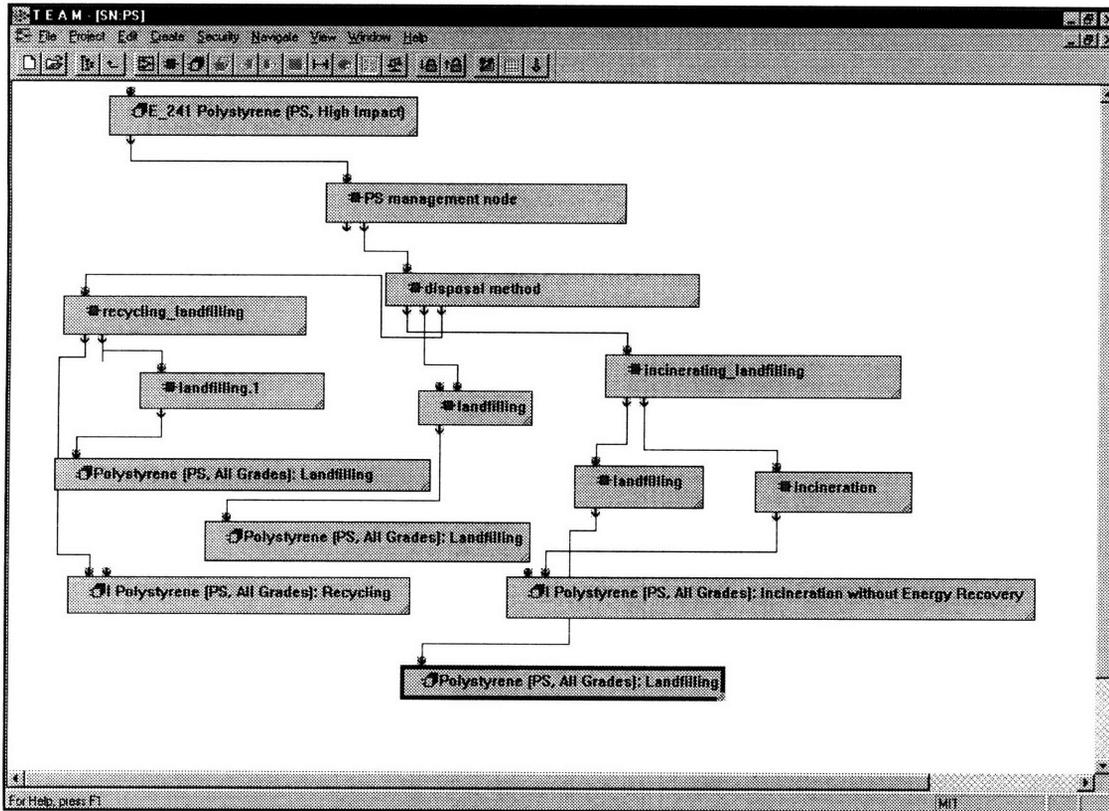


Figure 19. The polystyrene (PS) subsystem.

The LCI model is controlled by external variables, which were exported into an external variable file to allow later communication with DOME framework. These variables were defined to control the model, taking into account:

- The designers' needs. There was a negotiation in which type of information was relevant to exchange, allowing for concurrent modeling.
- The possibility of defining mixed variable problems in the DOME framework. Discrete choices among a list or catalog of distinct elements may be performed along with variations of independent design parameters defined over continuous intervals.

- The uncertainty associated with lack of information/understanding of the processes in the system, data collected from different sources, component variability, and weight measurements. The DOME framework provides means for defining probability distributions to be associated with external variables defined in the LCI model.

The external variables defined in the LCI model are listed in Appendix A. They may be grouped according to the following categories:

- Catalog selections of projector use location. The model allows choosing the location where the projector is used among USA, Canada, Japan and OECD Europe, which present different combinations in energy mix.
- Catalog selections of plastics included in the projector housing. The distinct types of plastics considered in the model are ABS (acrylonitrile butadiene styrene), PS (polystyrene), and PP (polypropylene).
- Catalog selections of end-of-life strategies for the plastics included in the projector housing. The distinct end-of-life scenarios considered for these selections are landfill, recycling/landfill, and incineration/landfill.
- Variation of projector power consumption and minimum time before failure defined as independent variables over continuous intervals.
- Variation of masses of the projector components defined as independent variables over continuous intervals.
- Account for uncertainty in the model. The variables with uncertainty associated are percentages in mass of materials in each component, and percentages of housing plastic recycled and incinerated in the end-of-life scenarios.

Figure 20 shows the selection node named electricity distribution, which is included in the electricity subsystem. This node is connected to all the different electricity mixes defined in the model and selects the electricity mix to use depending on the value of the external variable “use”.

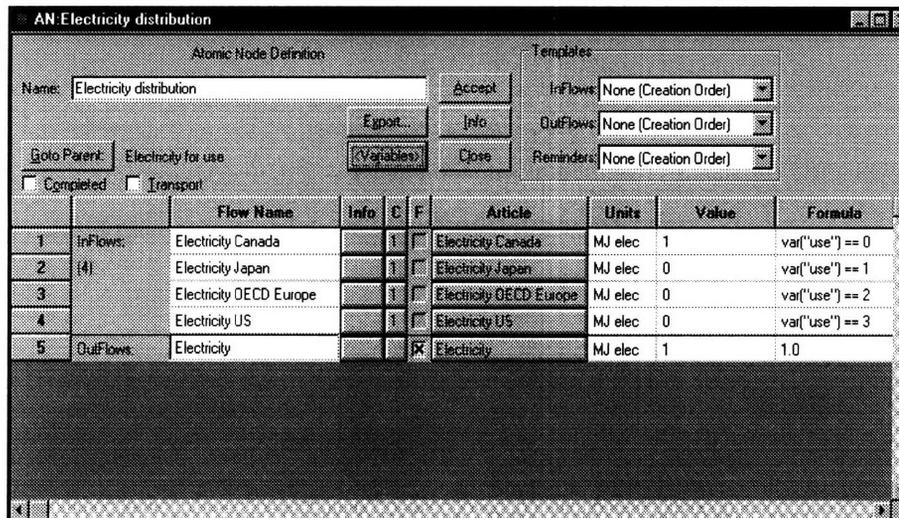


Figure 20. The electricity distribution node as a selection node.

The sources of data used in the LCI model were mainly provided by Ecobilan. New databases specialized for the electronics industry allowed the inclusion of sub-component production process data for PCBs and production processes for speakers.

The data sets available for production of different fossil fuels (coal, fuel oil, natural gas, and lignite) and electricity (coal, fuel oil, natural gas, lignite, hydro and nuclear) were specific for the US production conditions. They were also used to model the processes in the other countries, assuming that existing differences are not relevant for the purpose of comparing different electricity mixes. For the plastic ABS, no end-of-life specific data were available in the databases and so they were approximated with PE (polyethylene), for which there were existing end-of-life databases.

OECD statistical data on electricity compiled by the International Energy Agency (IEA, 1997) were used for quantifying electricity generation by source. The electricity mix in the use phase for each location was estimated, based on country-specific data available in the compilation. The distribution losses were assumed to be in average 7% of the electricity produced in all locations.

The inventory data generated by the LCI model is fed into the TEAM[®] wrapper implemented by Nick Borland at the MIT CADlab (Borland et al., 1998), to allow communication with the DOME

framework. In the wrapper, environmental impact assessment methods assign weightings to each of the effluents and calculate a total impact for each category of interest.

The implementation of the environmental impact assessment methods used the weighting factors considered in TEAMPlus[®], a separate analysis program provided by Ecobilan for driving TEAM[®] simulations and presenting environmental impact assessment results. The methods applied for this assessment purpose are as follows:

- Indices proposed by the Center of Environmental Science (CML), Netherlands:
 - air acidification
 - depletion of non renewable resources
 - depletion of the ozone layer (high)
 - depletion of the ozone layer (low)
 - eutrophication
 - eutrophication (water)
- Swiss critical volume method proposed by the Swiss Federal Office of Environment, Forests and Landscape (BUWAL) for calculating the indices:
 - CVCH - water
 - CVCH – air
- Natural resource depletion indices:
 - EC (R - fraction of reserve)
 - EC (Y - inverse of remaining years of use)
 - EC (R*Y - inverse of remaining years of use and the reserve size)
- Swiss ecopoints method proposed by the Swiss Federal Office of Environment, Forests and Landscape (BUWAL) for calculating the indices:
 - Ecopoints - air
 - Ecopoints - water
 - Ecopoints - energy and waste
 - Ecopoints – total
- Environmental Priority Strategies Method (EPS) proposed by the Swedish Environmental Research Institute (IVL) for calculating the indices:
 - EPS - air
 - EPS - water
 - EPS - land use
 - EPS - metal resources
 - EPS - non renewable energy
 - EPS - total

- Atmospheric acidification index:
 - ETH - air acidification
- Greenhouse effect indices proposed by the International Panel on Climate Change (IPCC)
 - IPCC - greenhouse effect (20 years)
 - IPCC - greenhouse effect (50 years)
 - IPCC - greenhouse effect (100 years)

TEAMPlus[®] provides brief descriptions, including identification of main limitations, and an assessment database for each of the assessment methods used in the program. Appendix B lists the weighting factors assigned to the effluents for calculating environmental impacts in each category of interest.

5.2.6. Implementation of a more detailed version of the LCI model

A more detailed version of the LCI model was also implemented using TEAM[®]. The objective was to explore the degree of influence in the analysis through a higher modeling resolution, although the computational times were approximately increased by a factor of 10.

The external variables defined in this version of the LCI model are listed in Appendix A. In addition to what was included in the initial version, the more detailed version accounted for:

- PCB assembly processes, considered environmentally relevant by EPA-DFE (1998). The sources of data were the recent databases specialized in electronics industry provided by Ecobilan.
- PCB as a component of the remote control, as opposed to considering only the FR4 board substrate as the electronics feature in the remote control.
- Additional use locations: OECD North America, OECD Pacific, and 24 countries OECD countries.
- Recycling activities for the remote control batteries.

- Landfilling activities inputs and outputs, other than the ones related with the housing plastics. For some components' materials, data were unavailable in the databases and difficult to obtain.
- Uncertainty associated with electricity mix for the production phase and components/mass ratios obtained for the PCB sub-components in weighting measurements.

5.3. The process of establishing communication with DOME system model

In the first task, the LCA model was built, supported by traditional methods of communication with designers such as actual meetings and e-mail. The subsequent task of integrating the LCA model into the DOME system model followed the collaborative modeling approach proposed by Borland et al. (1998). The main steps involved in the process of establishing communication with DOME design tool are described below and schematically represented in Figure 21. Borland et al. (1998) and Kaufmann (1998) describe in detail the collaborative modeling communications architecture and the associated data structure that was implemented.

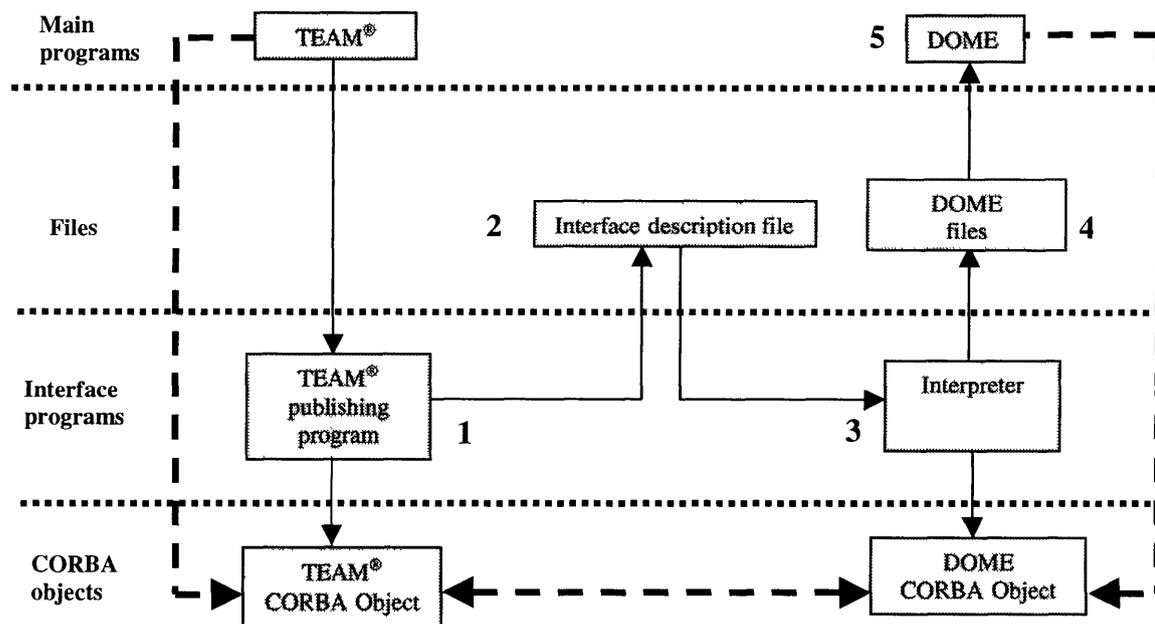


Figure 21. The process of establishing communication with DOME. Solid lines show the initial connection procedure. Dashed lines represent automated network communication, once communication is initially established. Adapted from Borland et al. (1998).

In order to integrate the LCA model with other projector design models, the distributed communication with the DOME global model must be established. For this purpose, the LCA model was first published (1), using TEAM[®] publisher program written in MS Visual C++[®] by Nick Borland and Heiner Kaufmann at the MIT CADlab (Borland et al., 1998).

In TEAM[®] publisher, the publishing process is done graphically. First, to define the interface with DOME global model, the external variables that control the LCA model, discrete choices and continuous parameters, were identified and described. Then, to allow the LCA model to be published, TEAM[®] model file, publication name and publication directory were properly defined.

Figure 22 shows a screen image of the TEAM[®] publisher program. It illustrates the information required to publish the LCA model, when defining the discrete variable “type plastic” with catalog choices for plastic types alternatives for the projector housing.

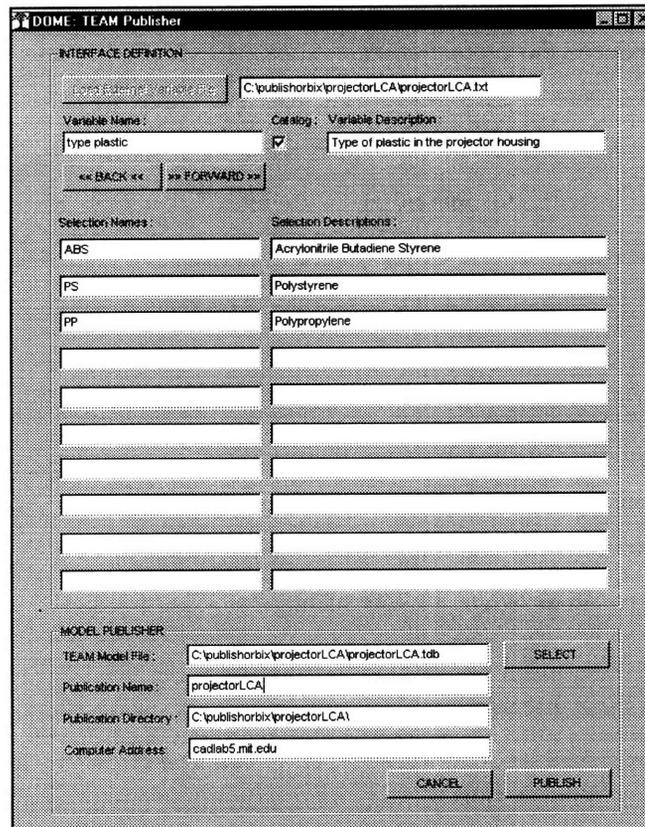


Figure 22. A screen image of the TEAM[®] publisher program.

The data entered in TEAM[®] publisher program are automatically written to a generic interface description file (IDF) that defines the LCA model interface with DOME model (2). The file lists the variables and their associated descriptions.

Once complete, the interface description file was sent by FTP to the designer's work environment. An interpreter program (3) then read the file and converted it into DOME modeling language files and catalog files (4). After loading the DOME model files into the DOME framework, environmental assessment capability was finally added to the DOME system model (5). The background communication between the models, represented in Figure 5 with dashed lines is automated, based on the CORBA communication architecture briefly described below (Borland et al., 1998).

The publishing program, when publishing the LCA model, launches a CORBA server with a unique name, which acts as a wrapper for TEAM[®], and awaits service requests from authorized clients. The server expects a stream of real numbers as inputs, defined and ordered by the interface definition produced during the publication process.

On the designer side, the interface file interpreter builds a CORBA client object, automatically created to be compatible with the server, and integrates it into the system model. When the DOME system model requests an environmental assessment, the CORBA client object gathers input information and contacts the CORBA server. The data it sends to the server over the network is a stream of real numbers, in the order predetermined by the interface definition file. When the CORBA server receives the service request, it launches TEAM[®] using those inputs. The final environmental assessment values are then returned to the DOME client via CORBA in the same manner. From that point on, because of the DOME structure, each time a change is made in the DOME system model that might affect the environmental assessment, the new values are used to automatically calculate a new assessment.

5.4. The integrated LCA model

The LCA model, integrated in the DOME framework using the communication process described previously, provides the DOME system model with the ability to evaluate and compare projector environmental performance with other performance metrics. It is important to know the system

model in which the LCA model was included to better understand the relevance of this integration process in performing tradeoffs between different design goals.

Therefore, before describing the LCA model as part of the DOME framework, an overview of the DOME model system will be provided.

5.4.1. Description of the DOME model

The DOME model was structured for the early design phase of a new projector where the company integrates the product design and all major components are outsourced. The model was decomposed into five areas of expertise, as shown in Figure 23, distributed across several computers using different programs, and integrated via the DOME framework.

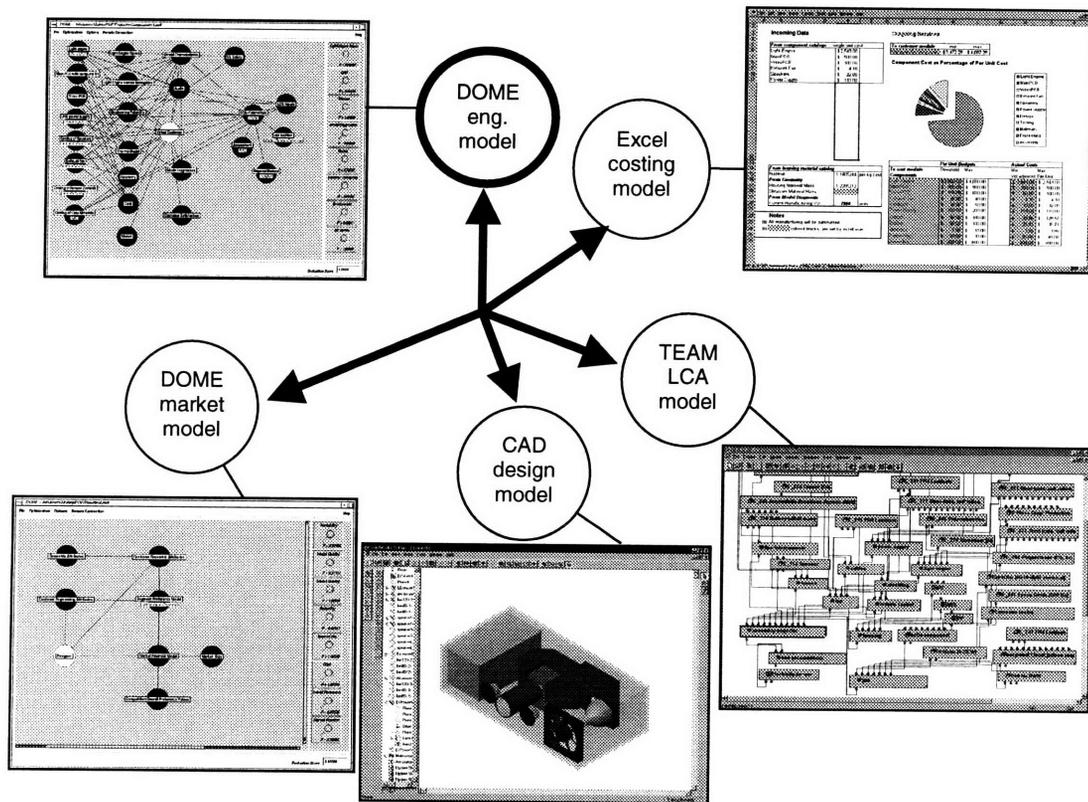


Figure 23. Schematic representation of the projector system model.

The mechanical engineer, representing the company's integrating role, is working on the overall model shown in Figure 24, using DOME to obtain decision support and optimization capabilities in approaching the whole system.

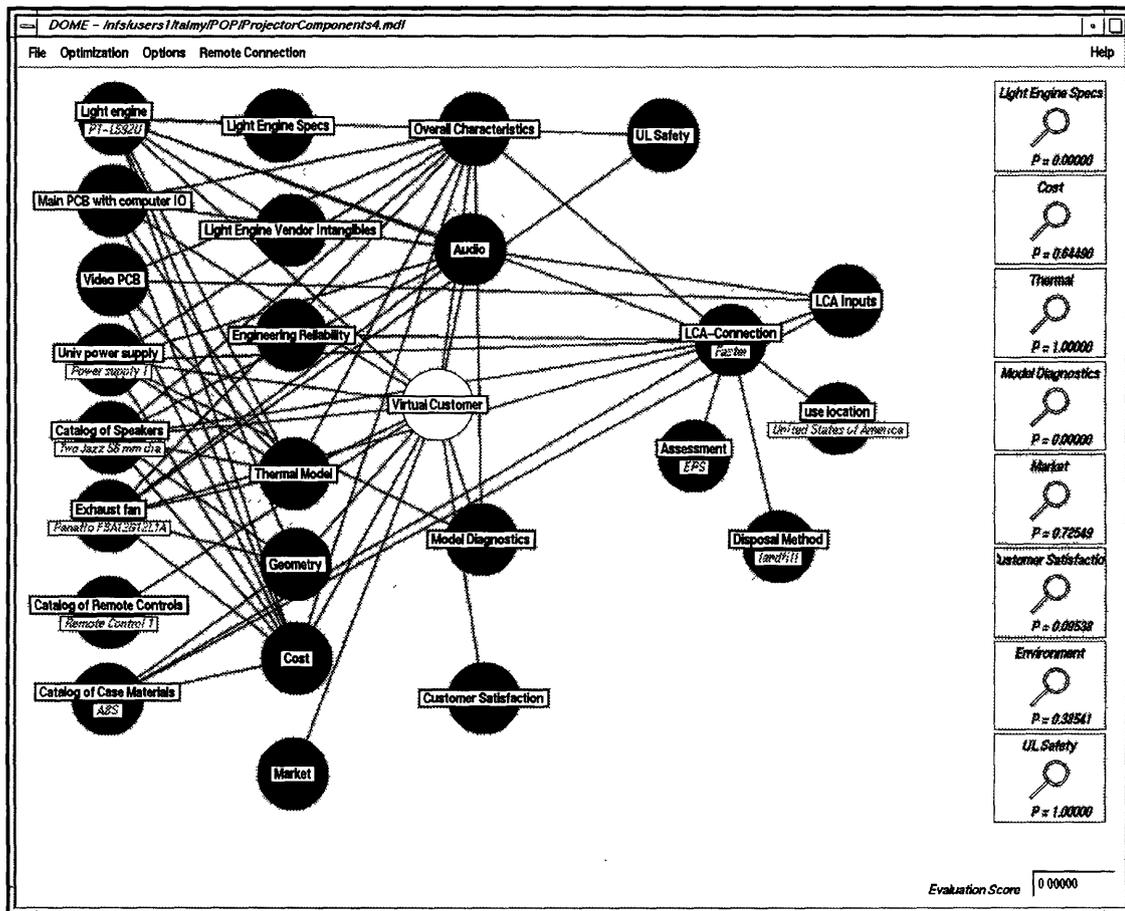


Figure 24. The overall projector DOME model.

The engineer is interested in exploring the several projector design configurations, taking into account the following design issues related with company's design goals:

- Supplier and technology benchmarking. The DOME engineering model includes, apart from the modules representing the other areas of expertise, key aspects of functional performance, with mathematical models embedded, such as the thermal model, and intangibles issues the company defined to be important to consider in product development process (for example, ease dealing with vendor). The engineer has the possibility to perform strategic assessment of changes in core technology, which is

mainly driven by the light engine, through catalog selections among distinct suppliers for several projector components.

- Manufacturing cost benchmarking. The cost module has embedded a cost model, which is an Excel[®] model built by the financial expert in another computer, using his program of choice and exerting decisions in his individual model, as his local range of influence. The engineer has the possibility of assessing manufacturing cost implications with this cost module.
- Product design details. The geometry module has an embedded CAD model, which is a SolidWorks[®] model built by the CAD designer, also using his program of choice for building geometric models and exerting decisions in his individual model.
- Market and customer impacts. The market module is linked to the customer module, which has embedded a customer model. This model was built by the marketing expert using DOME to pattern customer preferences given cost and several projector characteristics. The engineer has the possibility to predict projector characteristics that will map to customer attributes.
- Environmental impacts. The LCA-Connection module contains the connection node to the TEAM[®] software. It embeds the LCA model already described, which is a TEAM[®] model. The engineer may predict projector environmental performance associated with design options and balance them with the other performances traditionally considered in product design.

The projector DOME model is therefore a global model distributed over the network, using DOME's distributed modeling capabilities to link other analysis programs. These modeling programs communicate with DOME framework using the same type of CORBA-based communication as the one already described for TEAM[®].

In exploring the numerous possible design alternatives using this combination of programs and individual models, the engineer uses evaluation lenses. These lenses evaluate design performances against specification criteria to support the engineer in exploring tradeoffs between different design goals. The lens defined for the projector model are the light engine specs, cost,

thermal, model diagnostics, market, customer satisfaction, environment, and UL safety. The optimization capabilities of DOME framework can be used to find the most appropriate design solutions given the company's design criteria.

In the DOME framework, changes corresponding to design decisions are automatically propagated through the design providing interactive feedback on the effect of those changes relative to design goals.

5.4.2. Description of the integrated LCA model

The LCA model is integrated in the projector DOME model as shown previously in Figure 24. The lines indicate data flow between the LCA-connection module and other modules in DOME global model. The modules involved in this integration, which in turn are linked to other modules in the system, can be grouped as follows:

- Projector components catalog modules. Components chosen from different suppliers are modeled in the system to assess their influence in the environmental performance of the projector.
- Projector case materials catalog modules. Projector housings made of different type of plastics are modeled in the system to assess their influence in the environmental performance of the projector.
- Engineering reliability, overall characteristics and LCA inputs modules. These modules incorporate the variables that are inputs for the LCA model, such as the variable “minimum time before failure”, in the engineering reliability module, and the variable “total power consumption”, in the overall characteristics module.
- Use location catalog module. Different locations for using the projector are defined in the system to assess possible differences in the environmental performance of the projector.
- Disposal methods catalog module. Different end-of-life strategies for the plastics incorporated in the projector housing are considered to assess possible differences in the environmental performance of the projector.

- Assessment catalog module. This module incorporates the environmental assessment data flow coming from the LCA-connection module and provides the criteria to evaluate the incorporated values.

The LCA-connection module is itself a catalog module for choosing between the two different versions of the LCA model. Figure 25 shows the contents of the LCA-connection module.

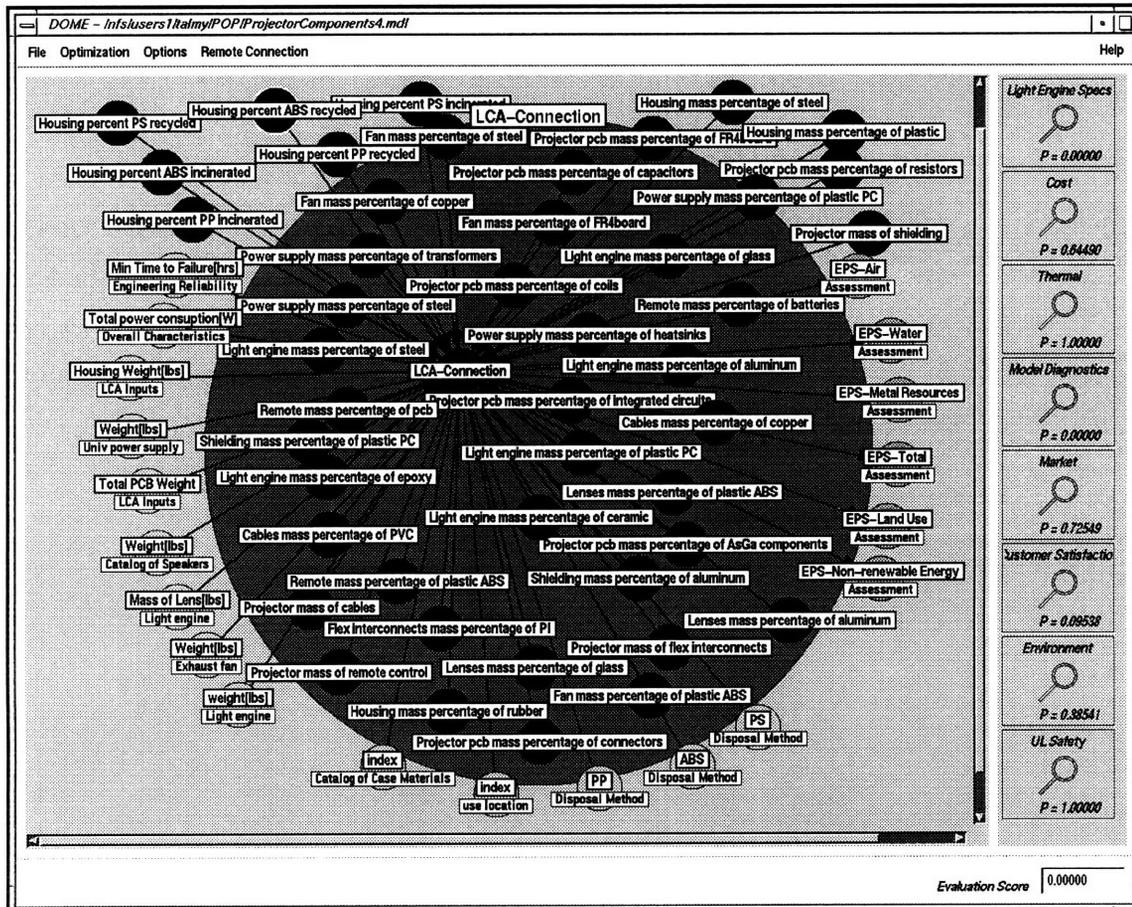


Figure 25. The LCA-connection module.

The LCA-connection node is placed in the center. The inputs are the index nodes from catalog modules, the parameter variables from the projector components, engineering reliability, overall characteristics and LCA inputs modules, and parameter variables previously assumed in the LCA model to have uncertainty associated. The later include percentages in mass of materials in each component, and percentages of housing plastic recycled and incinerated in the end-of-life scenarios. The six EPS metrics appear on the left side, corresponding to the meanwhile selection in the assessment module.

The uncertainty associated with parameter variables was implemented in the DOME model file through the definition, for each variable, of probability density functions, assuming the distributions to be uniform. The uncertainty, quantified within a range of $\pm 20\%$, was incorporated in the model to account for lack of information/understanding of the processes in the projector LCI model, data collected from different sources, components variability in projectors, and weight measurements. Appendix C provides the source code in Dome file for the LCA module, where these probability density functions were defined.

The assessment module, with the catalog option set to the EPS assessment method, is shown in Figure 26. This module contains the criteria, represented by the environmental evaluation browser on the right, through which environmental performances of the projector can be evaluated. Each environmental assessment metric performance, assumed in DOME framework to be a beta distribution, is evaluated against the corresponding specification, and an acceptance probability P is calculated. Appendix C provides the source code in Dome file for the assessment module.

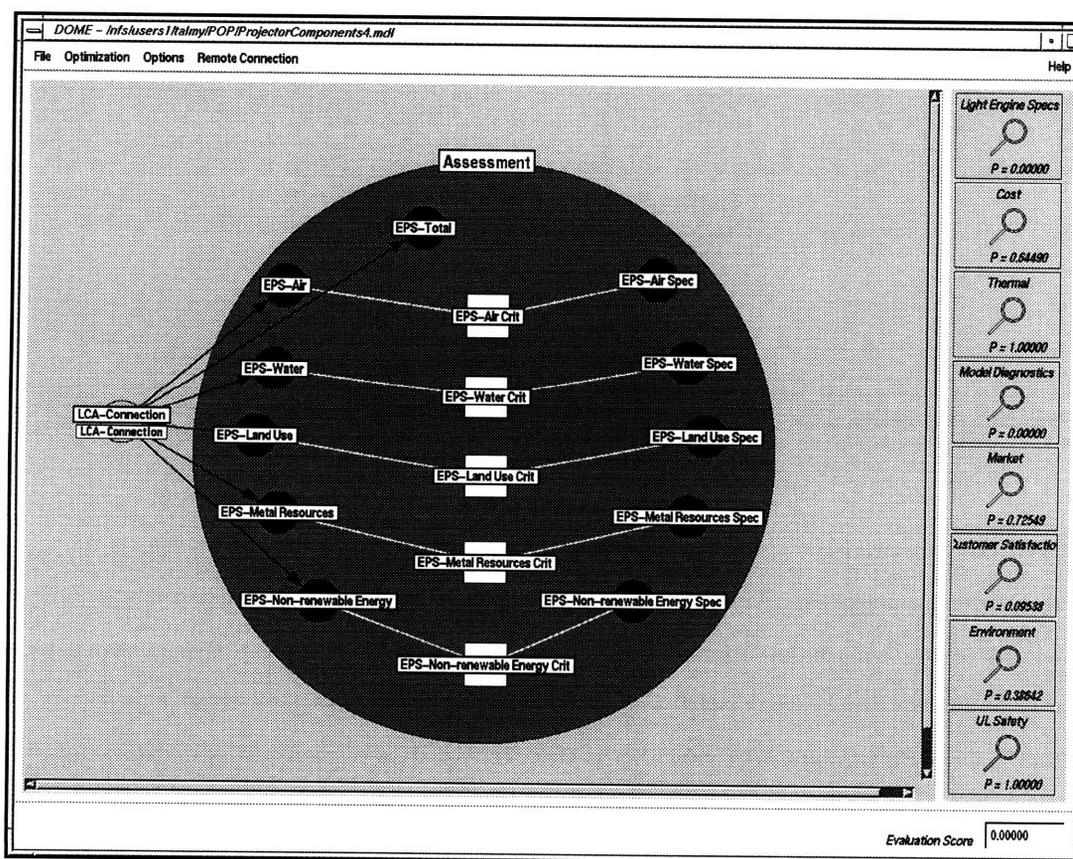


Figure 26. The assessment module for the EPS method.

Using this specification-based design decision model, a design evaluation is completely contingent upon the design specifications (Wallace, 1994). The environmental performance evaluations will depend highly on how environmental requirements were established, which in turn are not static and iteratively change as the company's understanding and goals in the design process evolve.

In the context of the present company's project with MIT concerning the design of a projector, it was decided to set the environmental specifications for this initial design phase based on the extreme-point method (Wallace, 1994). This estimation technique, characterized to be intuitive and straightforward, requires estimating only the extreme points at which there is a completely satisfactory or unacceptable design.

Figure 27 illustrates the technique used for estimate environmental specifications in the projector model. In the projector benchmarking design, considering the US electricity mix in the use phase and landfill as the disposal method, the specifications were established relatively to the environmental performance expected value, for each environmental assessment metric.

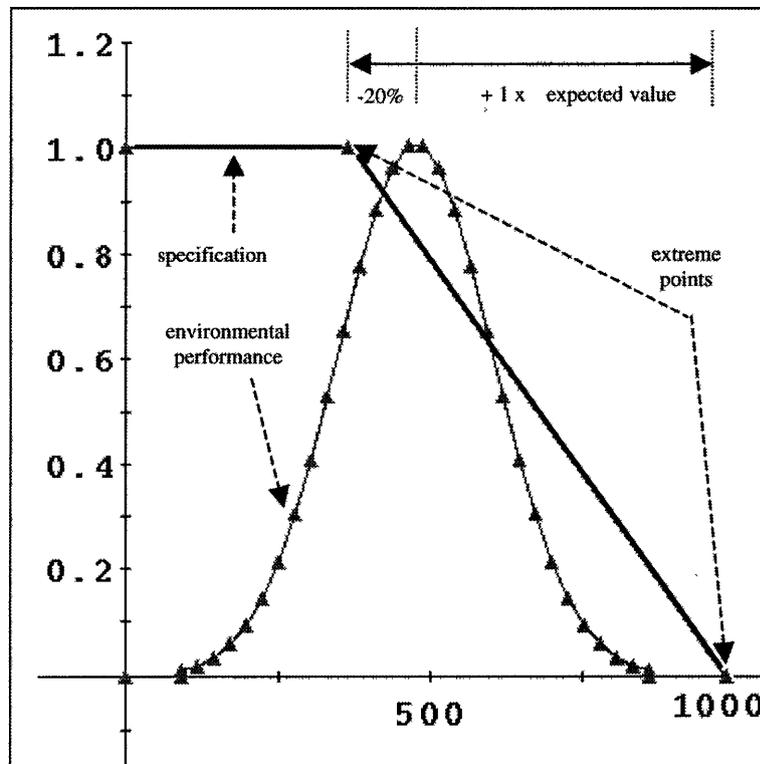


Figure 27. Setting approximately environmental specifications using the extreme point method.

In setting an initial goal of improving the projector environmental performance 20% relative to the benchmark design, the maximum metric value for which the environmental performance is completely satisfactory ($P = 1$) corresponds to 20% less than the environmental performance expected value in benchmarking design. The other extreme point from which the design should be rejected with a zero probability of acceptance ($P = 0$) was set to be twice the environmental performance expected value in benchmark design

The environmental performance values are obtained through the communication established between DOME and TEAM[®]. The data flow, in each update for the environmental evaluation process, can be described as follows, based on Kaufmann (1998). The process of data flow is schematically represented in Figure 28.

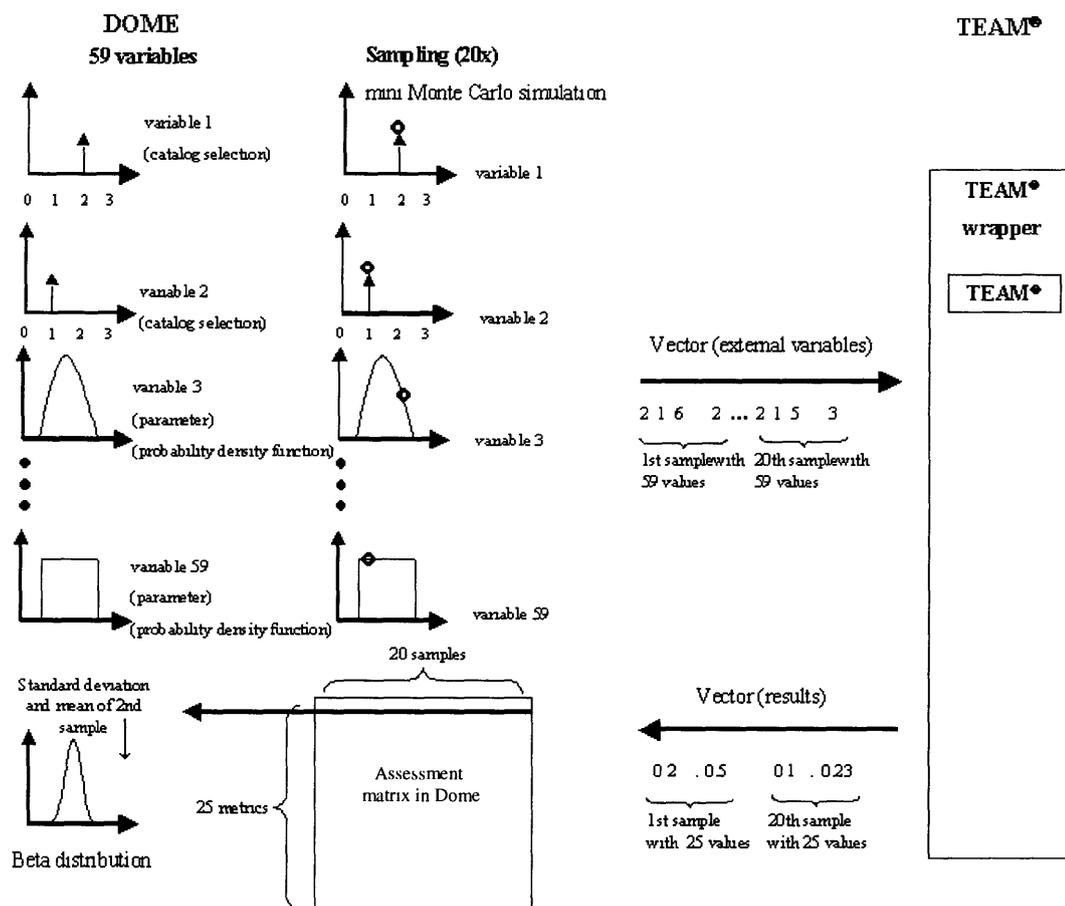


Figure 28. Environmental data flow. Adapted from Kaufmann (1998).

The projector LCA model is controlled by both parameter variables, which may be defined as probability density functions, and discrete choices. A mini Monte Carlo simulation is used to generate 20 samples of each parameter variable defined as a probability density function. The most cost-effective number of simulations to be used for resampling in DOME framework is currently being investigated by Nick Borland at the MIT CADlab.

The result vector, which contains 20 samples of all 59 controlling variables, is sent to the TEAM[®] software (meaning a data flow of 20×59 values). The TEAM[®] wrapper reads in the vector and runs 20 simulations, each with a different set of input variables. A result vector consisting of 20 sets of 25 environmental assessment metrics is sent back to the LCA-connection module in the DOME framework.

The LCA-connection node included in LCA-connection module represents a matrix of the size 25×20, as shown in Figure 29a. Each row represents the output of one simulation and each line corresponds to the outputs of 20 simulations for a given environmental assessment metric. In order to build the appropriate density functions, assuming the distributions to be beta (similar to normal distributions), the mean and the standard deviation are calculated for each environmental metric. The environmental performance distribution is displayed for each metric, as shown in Figure 29b.

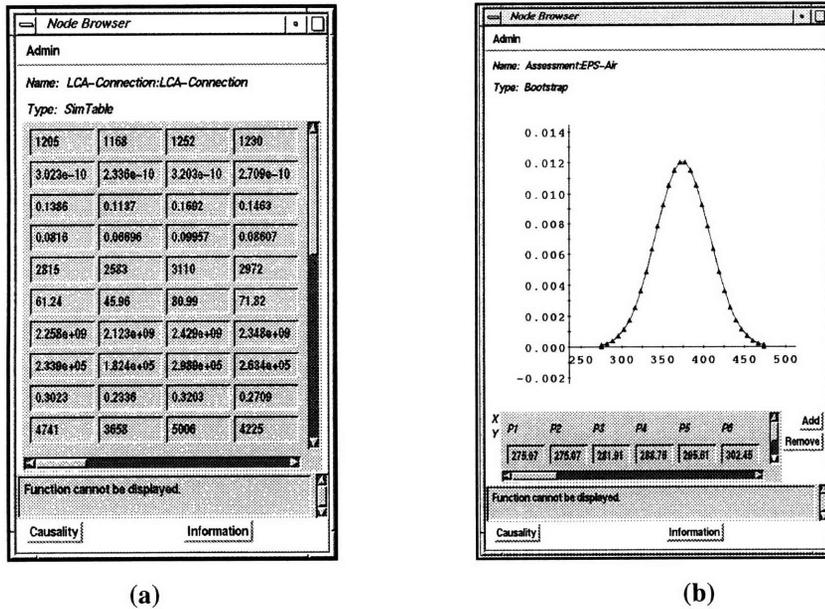


Figure 29. Environmental performance values.

(a) Assessment metric table (matrix 25×20); (b) EPS-air metric (beta distribution).

5.5. Using the integrated LCA model: integrated assessments and tradeoffs

The behavior of the integrated LCA model and its value in understanding interactions between traditional and environmental design goals were tested with illustrative scenarios. The design alternative used as the reference case was the benchmark design, considered to be used in the US and disposed of via landfill.

The following scenarios were defined for this purpose:

1. Light engine outsourced from different suppliers
2. Different locations where the projector is used
3. Distinct type of plastics in projector housing
4. Distinct end-of-life strategies for plastics in projector housing

It was not possible to test the more detailed version of the integrated LCA model due to TEAM[®] database errors that occurred upon implementation.

5.5.1. Changing light engine

The light engine, which is considered to be the core technology in the projector, is changed through the light engine catalog module to explore scenarios of different suppliers for this component. The possibilities of outsourcing the light engine were as follows:

- a) light engine PTL592U (reference case)
- b) light engine A (not specified due to confidentiality)
- c) light engine B (nor specified due to confidentiality)

These alternative designs were compared and possible tradeoffs were explored relative to environment, cost, and light engine specifications design goals. In Figure 30, the evaluation browsers for the reference case show that the cost performance is satisfactory, the environmental performance is less satisfactory as expected from the specifications setting method, and the technical performance is out of specification.

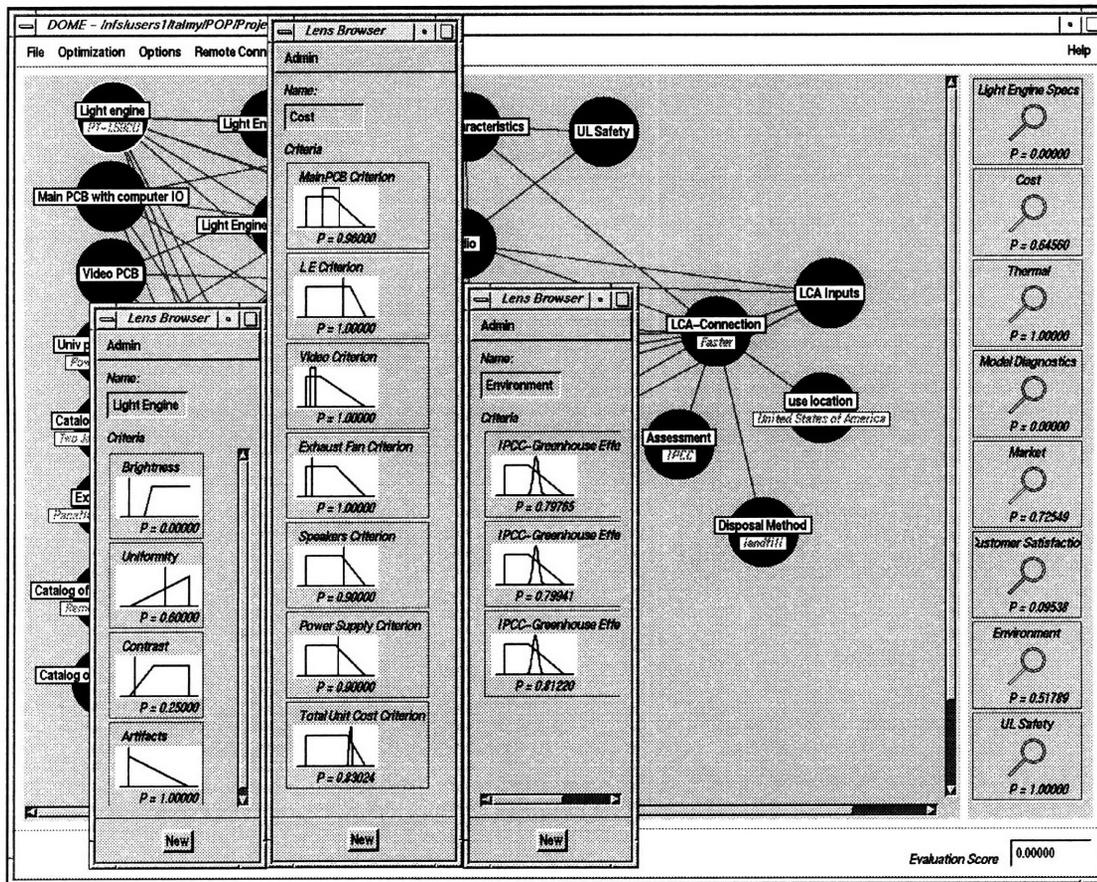
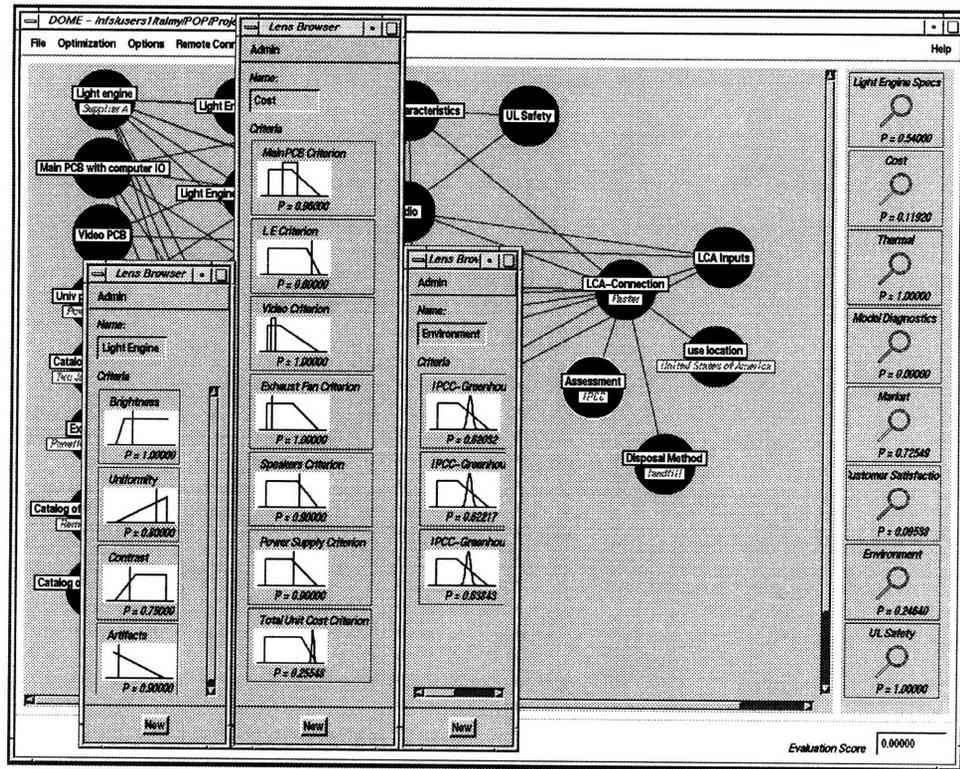


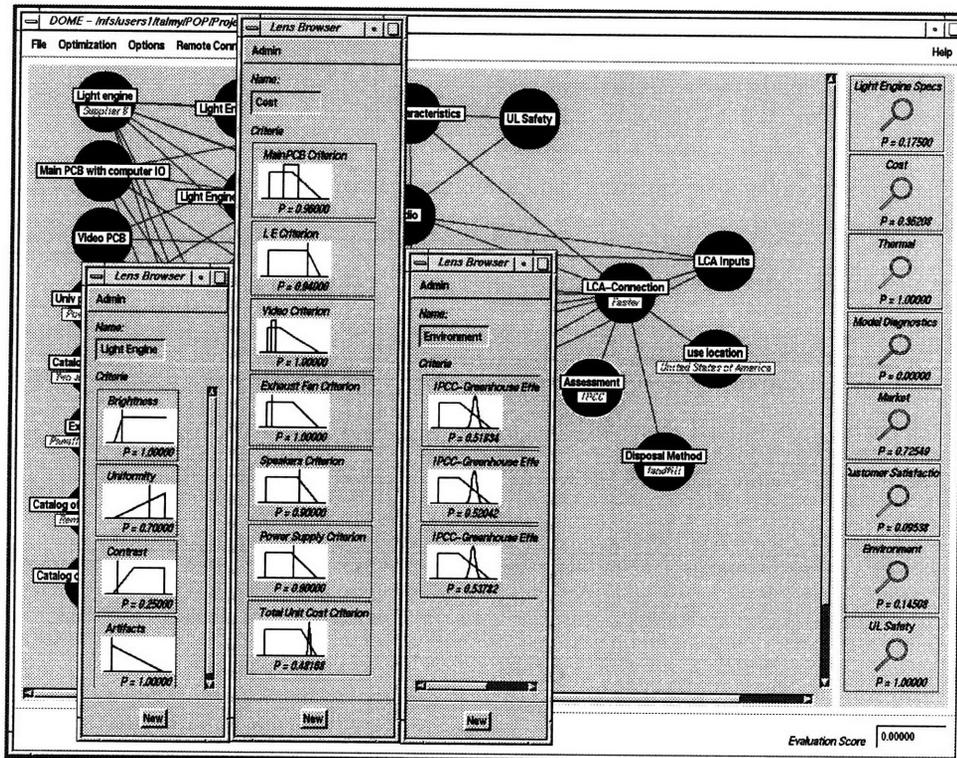
Figure 30. The reference case: environment, cost and light engine specification criteria. The IPCC metrics are the current selection in the environmental evaluation browser.

In order to improve both environmental and technical performances, the other light engine design alternatives may be explored through the catalog selections currently available. Figure 31 shows snapshots of DOME interface in selecting light engine A and light engine B.

According to the evaluation browsers in Figure 31, light engine A significantly improves the technical performance but worsens the environmental and cost performances. The selection of light engine B worsens less the cost performance than light engine A, but does not improve much the technical performance and decreases the environmental performance even more.



(a)



(b)

Figure 31. Selection of other light engine design alternatives: (a) light engine A; (b) light engine B. The IPCC metrics were used in the environmental evaluation browser.

The rank ordering obtained specifically for the environmental design goal selects first light engine PT PTL592U, then light engine A, and finally light engine B. Although the component weights decrease from light engine PT PTL592U to light engine B, the sequence corresponds inversely to a rank ordering based on power consumption. This result matches the initial assumption that the projector consumes electricity. The use phase gives a major contribution to the life-cycle impacts. An additional interpretation is that the weighting schemes supporting the different methods emphasize environmental impacts caused by emissions generated by energy production, rather than those originated by resource depletion.

A number of simulations were performed in order to explore simulation noise and the effects of different assessment methods. The simulations are graphically displayed in Figure 32.

The graphics in Figure 32 show that there is a trend to maintain the design rank ordering mentioned previously for all schemes. Although the selection between the light engine A and light engine B does not always have the same outcome, the preference for the benchmark design is constant using all these methods. Increasing the number of samples for each update in the environmental data flow process between TEAM[®] and DOME could promote a more constant assessment for the selection between light engine A and light engine B.

In the process of decision-making, a potential scenario could be the company considering the environment as a primary objective, although the best design score does not correspond to the design alternative with the best environmental performance. The company could change the design specifications according to a dynamic understanding and establishment of all goals in the design process, to iteratively test alternative design solutions. The company could also explore other light engine alternatives possibly available in the supplier chain and model them as new catalog selections.

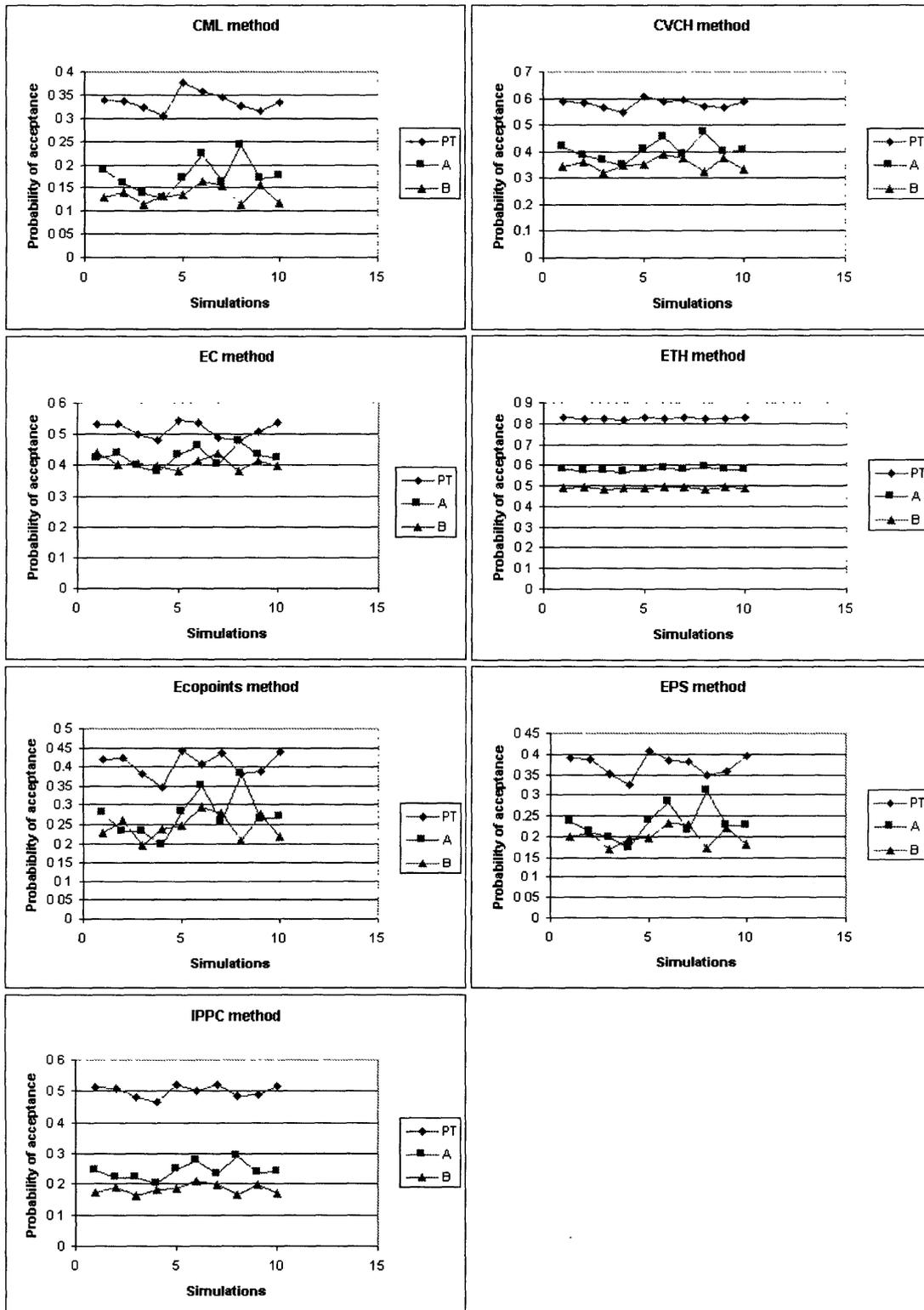


Figure 32. Simulations performed for the three options of light engine, using different impact assessment methods.

5.5.2. Impact of use location

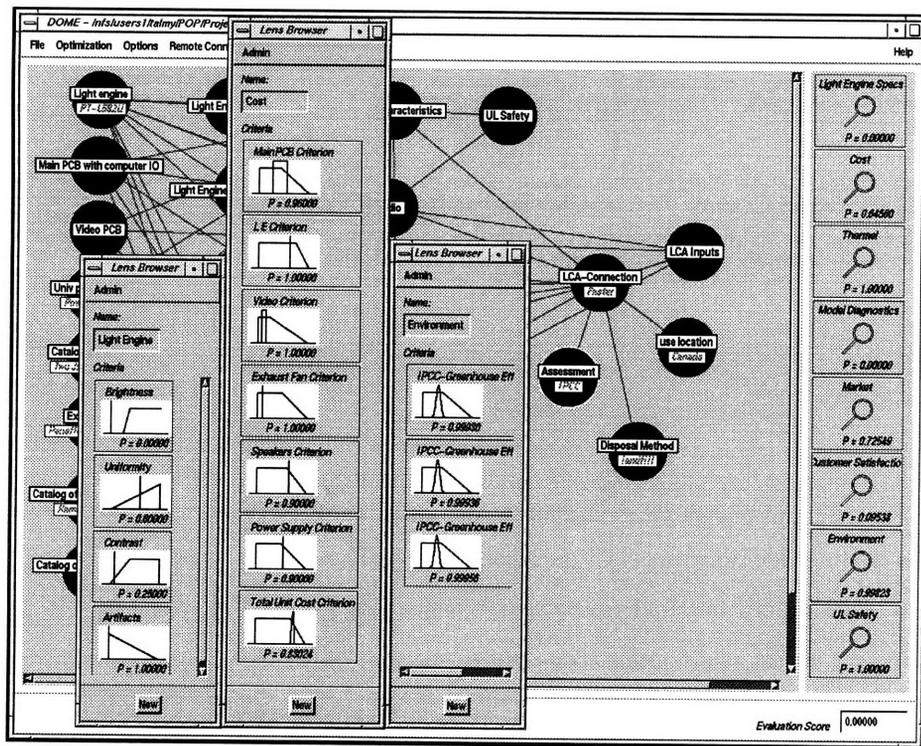
The importance given to the use phase leads to the exploration of what possible new trends would occur if the projector was considered to be used in a location other than the US. Again, the previous alternative designs were compared relatively to environment, cost, and light engine specifications design goals, but considering two possible scenarios:

- a) Projector is used during its life time in US (reference case)
- b) Projector is used during its life time in Canada

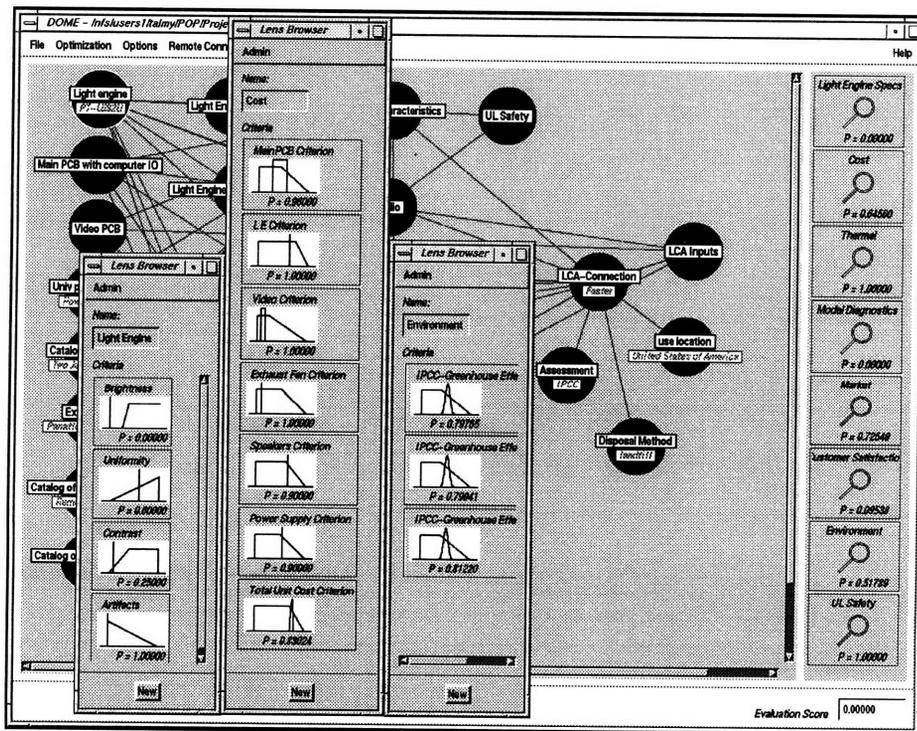
In Figure 33, the evaluation browsers show the same rank ordering for the cost and technical performances in both countries, as expected since these criteria are not affected by differences in electricity consumption, the controlling variable in changing use location. The rank ordering is also maintained, as the same components are being analyzed with the previous equal differences in power consumption.

The differences in the environmental evaluation browsers between each country are noticeable though. All the alternative designs are better accepted when the projector is used in Canada. This outcome, which was observed to be the same for all the assessment methods, is supported by differences in electricity mix. According to data collected from IEA (1997), Canada's electricity mix exhibits approximately 62% of hydro as a source in electricity generation. Distinctively, US presents approximately 53% of electricity generated by coal, which leads to a higher level of impacts to the environment, namely air emissions.

Again, the method applied for setting the specifications influences the results in evaluating different design alternatives. If the specifications had been initially set relatively to the environmental performance of the benchmark design in Canada, according to an hypothetical Canada oriented set of design goals, the differences in accepting design alternatives would be similar. However, using the projector in US would correspond to a scenario out of specification for all design alternatives.



(a)



(b)

Figure 33. The alternative design options when using the projector in (a) Canada and (b) US: environment, cost and light engine specification criteria. The IPCC metrics are the current selection in the environmental evaluation browser.

5.5.3. Impact of plastic type

To explore possible differences in evaluating design alternatives due to different plastic types used for the projector housing, the following scenarios were considered:

- a) ABS (reference case)
- b) PP
- c) PS

Figure 34 presents a graphical representation of results in the environmental evaluation browser produced by one simulation. Although the probability of acceptance in all three options are close values, it seems that there is a general trend for accepting first the plastic PP, then ABS, and finally PS.

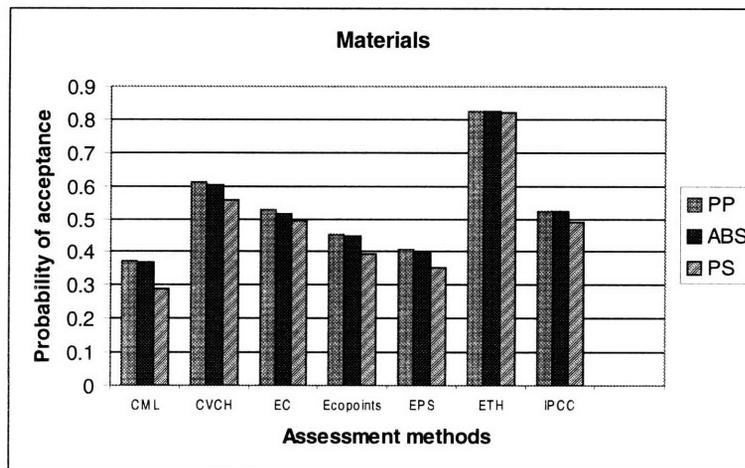


Figure 34. The alternative design options in selecting the plastic types for the projector housing.

This rank ordering, however, was observed to be different as more simulations were performed for all the three design options.

In running simulations, there was similarity in accepting these alternative designs relatively to cost. This outcome was expected, as the main cost driver in the projector was considered to be the light engine, and the projector housing materials were taking into account with minimal contribution to the projector cost.

Overall, the impact of the plastic type revealed to be inconsequential in this analysis.

5.5.4. Impact of end-of-life strategy

Finally, to explore possible differences in evaluating design alternatives due to distinct end-of-life strategies for the plastic used in the projector housing, the following scenarios were considered:

- a) landfill (reference case)
- b) 80% incineration and 20% landfill, approximately
- c) 80% recycling and 20% landfill, approximately

Figure 35 shows a graphical representation of results in the environmental evaluation browser produced by one simulation. It seems that there is a general trend for accepting first landfill, then incineration, and finally recycling.

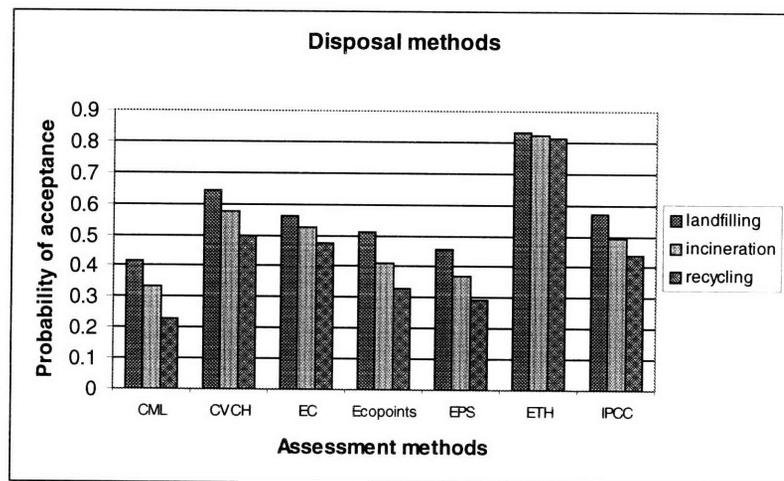


Figure 35. The alternative design options in selecting the end-of-life strategy for the plastics in the projector housing.

This ordering is not in accordance with what in general is considered to be an environmental optimization of the end-of-life system, where reusing products/components, recycling the materials or even incinerating with energy recovery may be environmentally preferred strategies to landfill activities. An interpretation for this distinct evaluation could stand on the observation of the databases used in the LCI model as well as recalling that the weighting schemes supporting the different methods influence highly the environmental scoring.

In the recycling databases, it can be observed that although credits are given to material flows in comparison with those in producing virgin material, the energy consumption involved in the

process is accounted for in much higher levels than in landfill and incineration. This fact, coupled with recognizing that the weighting schemes, in general, value environmental impacts caused by emissions more strongly rather than those originated by resource depletion, may drive to results favoring less recycling activities.

This rank ordering, however, was observed to be different as more simulations were performed for all the three design options.

An integrated assessment could be performed with other design goals, namely the projector cost, if a life-cycle cost model had been implemented in the projector system model.

5.6. Discussion

This section focuses on discussing experience gained with the process of creating and integrating a computer projector LCA model into a network-oriented design framework. The motivation was to achieve potential capabilities of real environmental improvement in the integrated design process of the product being designed.

In building the LCA model, the main focus goes to the process of data acquisition that strongly influenced the creation and implementation of the LCI model structure. The difficulties detected during this process of data gathering were mainly due to:

- The lack of detailed product/process data. This data scarcity is inherent to any early design phase of a new product, where the product is conceived mainly in conceptual terms and its structure is only generally determined. This phase, however, is the right opportunity for using LCA to perform a true green design, balancing all environmental implications of the product against alternatives as early in the design process as possible. Additionally, using LCA to provide final rankings and not as tool for performing a complete environmental characterization, the non-site-specific nature of the LCI and impact analysis is appropriate to this design stage.
- The specific situation of this project, where the company integrates the product design and major product components are outsourced. It became clear in the project that, because suppliers manufactured all the projector components, it would be difficult to

gather comprehensive information about components and manufacturing processes. In addition, the company exhibited particularities in its relation with potential suppliers that made totally impossible the acquisition of data for the main components, even involving confidential agreements on proprietary data. Therefore, it must be recognized the importance of having well established relations between companies, even with no contract signed up, for a cost-effective process in gathering data, in the early design phase, to accomplish successfully analytical goals initially set such as building an LCA model for the product being designed.

These difficulties were overcome by applying the methodology already described. It mainly involved building a streamlined, quantitative, and component/material-based LCI model based on a tear down of the benchmarking projector and weighting of the main components, and using a commercial software with general databases associated. To address the issues of lack of information/understanding, component variability in projectors, and weighting measurements, uncertainty in the form of probability distributions was associated with controlling variables of the model.

The process of establishing communication with the DOME system model and the design team presented also the following particularities worth mention:

- The definition of the interface between the different models involved in the project in terms of selecting the appropriate inputs and outputs for service exchange was not immediate and highly dependent on human interaction. At some point, it was a back and forward process pendant on data gathering, clarification of differences in model granularity and individual rhythms in structuring and implementing each model.
- The collaborative modeling approach experienced proved to be beneficial because allowed an independent development of the LCA model in content and usage of a specialized tool, while making possible a concurrent and integrated development of the system model in its several expertise areas.
- The publishing program revealed to be extremely useful for establishing the first connection of the LCA model with DOME system model in a timely and easy way.

In using the integrated model and exploring the distinct scenarios, important methodological outcomes were identified, namely the following:

- The method used for setting the design specifications in DOME framework showed to be a driving factor in the environmental evaluation browsers, influencing indirectly the possible tradeoffs involved with distinct design goals, other than environmental.
- The twenty samples used for each update in the environmental data flow process between TEAM[®] and DOME was not robust enough for handling uncertainty in exploring some scenarios.
- The weighting schemes supporting the different environmental assessment methods influenced highly the environmental scoring obtained when exploring the scenarios.

6. DOME integrated LCA model vs. qualitative matrices

6.1. Introduction

Several analysis methods have been used to incorporate DFE into product design. The integrated LCA model that was built and implemented using TEAM[®] and DOME framework may be also classified as a DFE analysis method.

In this chapter, the quantitative DOME integrated LCA model will be compared with qualitative environmental matrices. The comparison will be based upon data obtained from an informal survey completed by product development, manufacturing and environmental experts. The survey is intended to capture opinions about using the two methods in integrated product design to incorporate environmental criteria in decision-making.

Wallace (1994) presents a methodological comparison between qualitative matrices and the specification-based model supporting DOME framework, highlighting distinct approaches of these methods as decision tools and in dealing with data uncertainty. The comparison presented in this chapter will focus on how the LCA model integrated in the DOME framework and qualitative matrices may be differently perceived by experts.

In the following sections, an overview of main features of qualitative matrices is provided. The structure of the surveys will then be explained and an analysis of the survey data will be presented.

6.2. Qualitative matrices

Qualitative matrices were already introduced in Chapter 2 as a method currently used for DFE analysis. In this section, a qualitative matrix approach for environmental assessment proposed by Graedel and Allenby (1995) is described. Other matrix LCA approaches have been developed to meet different companies' needs (Eagan and Weinberg, 1997; O'Connor and Blythe, 1997). The goal in this section is to illustrate one of the qualitative matrix approaches.

Graedel and Allenby (1995) define four primary assessment matrices for evaluating each design alternative: a manufacturing matrix, a social political matrix, a toxicology/exposure matrix and an environmental matrix. The environmental matrix is shown in Figure 36.

	Initial production	Secondary processing	Packing	Transport	Consumer use	Reuse/recycle	Disposal
Local air impacts							
Water impacts							
Soil impacts							
Ocean impacts	+						
Atmospheric impacts						++	
Waste impacts						+	
Resource consumption							
Ancillary impacts	—	—	—	—	—	—	—
Significant externalities							

Matrix symbols: — not applicable; +, ++ positive

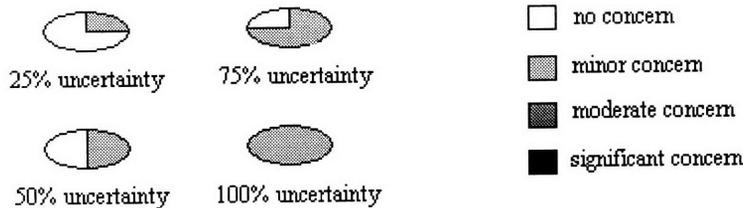


Figure 36. Environmental matrix.

The matrices are prepared using three possible entries for each matrix cell. A straight line represents a category inapplicable or inappropriate to the alternative under consideration. One or two plusses (“+” or “++”) means positive environmental effects from the design alternative and the relative degree of benefit. An oval indicates concern, with the degree of environmental concern keyed to the geometrical pattern in the oval. The extent to which the pattern fills the oval indicates the degree of uncertainty associated with a particular ranking.

Each matrix is given an overall degree of concern/certainty in the assessment. The matrix shown in Figure 38 summarizes these grouped assessments for comparing different design alternatives.

In assessing an individual matrix element, or in offering advice to designers exploring the rating of new design options, the environmental expert can refer to experience, appropriate checklists, design and manufacturing surveys and other protocols for guidance.

	Option A	Option B	Option C	Option D	Option E
Manufacturing					
Environmental					
Toxicity/exposure					
Social/political					

Figure 37. Summary matrix for comparing between design alternatives.

6.3. The survey

In order to compare the methods, it was felt that an informal survey might provide practical insight into how these methods may be differently perceived.

The survey was prepared to capture opinions from product development, manufacturing and environment related experts about using the methods in integrated product design. The experts were given the survey after a demonstration on the projector DOME system model and an explanation of main features of qualitative matrices for environmental assessment. The survey is provided in Appendix D.

The questions were intended to elicit insights and opinions from the experts on how both tools may be valued and credited in:

- Assessing the degree to which a design alternative meets environmental design goals.
- Performing trade offs in environmental performance with other design goals.
- Supporting decision making in the integrated product design process.
- Providing a helpful communication of uncertainty for making decisions.
- Performing the previous tasks without being too time consuming.

The survey was delivered with an initial review of the premises for both tools. For the projector DOME system model with the integrated LCA, the environmental impact assessment was:

- Provided by linking to an analytical life-cycle model created by an environmental expert using a commercial life-cycle analysis program and database.
- Performed in real time for each alternative explored by the designer using either a fast approximate model or a slower detailed model.
- Visualized using currently available environmental impact assessment methods (e.g., EPS, Eco-points) and quantitatively compared with benchmark performance goals.

For qualitative matrices, the environmental impact assessment was:

- Provided to the designer by an environmental expert.
- Prepared in advance for key benchmark designs; designers use the results to obtain insight and guide the exploration of new options, other than the benchmark designs
- Visualized with a qualitative summary matrix.

The number of surveys completed (10) was small but believed to be sufficient to provide a preliminary basis for studying trends.

6.4. Survey response analysis to compare methods

To statistically analyze trends in preferences in applying the methods for integrated product design, the survey responses of agreement with statements were quantified according to Table 3.

Table 3. Quantification of survey responses.

Agreement with statements	Strongly agree	Agree	Not sure	Disagree	Strongly disagree
Quantification	2	1	0	-1	-2

The measure used for evaluating the preferences between the two methods was the difference between the agreement levels for each method, on a given statement. The scale for measuring the preferences is shown in Figure 38. For statements 9 and 10, which address uncertainty related issues and do not imply preference for one of the two methods, the scale ranges from -2 to 2.

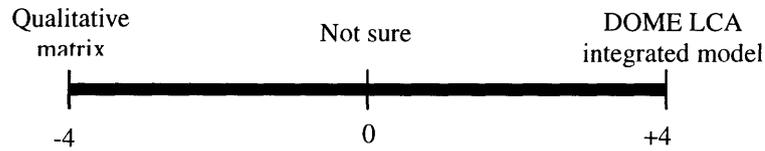


Figure 38. Scale for measuring preferences for one of the two methods

First, a simple descriptive statistical analysis was calculated. The goal was to evaluate the preferences for the methods according to the circumstances defined in each statement, while assessing the statistical significance of the data supporting those preferences. The statistics obtained, relevant to this analysis, are provided in Appendix E.

Figure 39 displays graphically the confidence intervals of the data. The preferences for one of the two methods for each statement were evaluated using mean values. The statistical significance was assessed using a one-sided T-test, comparing the T-statistic with the critical value of 1.37, for 10 degrees of freedom and 95% of confidence. This significance may be also visualized in Figure 39, observing the width of the confidence interval relative to the scale.

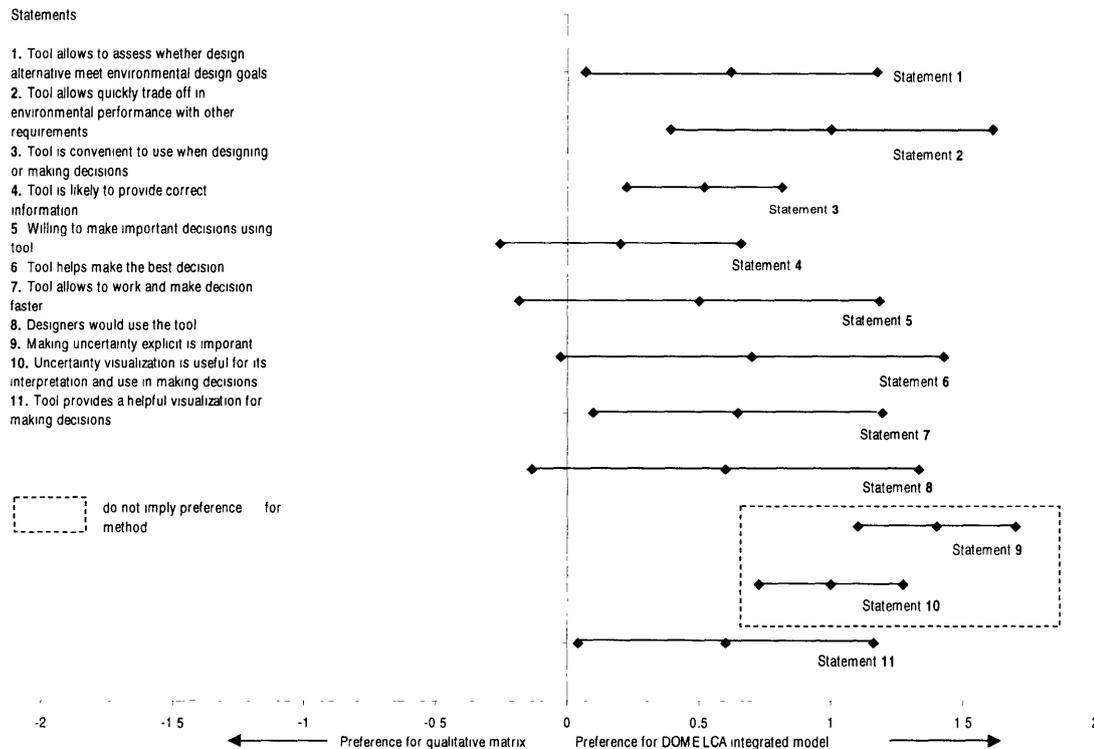


Figure 39. Graphical representation of the confidence intervals

The significance of outcomes from the preliminary survey is presented in Table 4. In observing the table, it seems that there is a general preference trend for using the DOME integrated LCA model. One may establish the preference as being relevant only when the measure value (mean) is equal or greater than 0.6. The data suggest that experts tend to prefer this tool for assessing design alternatives against environmental goals; quickly trading off in environmental performance with other design goals; conveniently making a decision; making decision faster; and for visualizing uncertainty when making decisions.

In statements 6 and 8, the results were not considered as representing a relevant preference because the statistical support was weak. This can be visualized in Figure 39, where the confidence interval encompasses zero, meaning that the preference for the DOME integrated LCA model is not certain.

Thus, there was no evidence in results for the experts finding preference for DOME tool in respect to: providing correct information; willingness to base an important decision on analysis; and ease of use for designers. Possible explanations based on comments provided by experts in the surveys suggest that a lack of clarification in the survey about the quality of data may have contributed to this result. Regarding opinions about the tool being used by designers, there was also lack of clarification on what was meant by a designer.

In a second step of the analysis, the goal was to identify the existence of possible correlations between agreements, in the sense that one agreement for one statement may be ‘linked’ to the agreement for another. For this purpose, a factor analysis (Cooper, 1983) was performed.

Table 5 presents the factors with corresponding factor loadings, selected as needed for interpreting the data using a cutoff rule of dropping the ones with eigenvalues greater than 1. Eigenvalues are a measure of how much variation each factor explains. The factor loadings quantify how much the original statements explain the factors. The factors and the correspondent eigenvalues and factor loadings are extensively listed in Appendix F.

Table 4. Preferences and statistical significance of data for each statement.

Statement	Preference	Statistical significance
1. Tool allows to assess design alternative meeting environmental design goals	Experts tend to prefer DOME method by 0.6 points in the defined scale	Preference is supported
2. Tool allows quickly trade off environment with other design goals	Experts tend to prefer DOME method by 1.0 points in the defined scale	Preference is supported
3. Tool is convenient to use for design, making decision	Experts tend to prefer DOME method by 0.5 points in the measuring scale	Preference is supported
4. Tool provides correct information	Experts tend to prefer DOME method by 0.2 points in the measuring scale	Preference is not supported
5. Willing make important decision using results from tool	Experts tend to prefer DOME method by 0.5 points in the measuring scale	Preference is not supported
6. Tool helps make the best decision	Experts tend to prefer DOME method by 0.7 points in the measuring scale	Preference is weakly supported
7. Tool allows to work and make decision faster	Experts tend to prefer DOME method by 0.6 points in the measuring scale	Preference is supported
8. Think designers would use tool	Experts tend to prefer DOME method by 0.6 points in the measuring scale	Preference is weakly supported
9. Make uncertainty explicit is important	Experts tend to agree with statement by 1.4 points in the measuring scale	Agreement is strongly supported
10. Uncertainty visualization useful for its interpretation, use in making decisions	Experts tend to agree with statement by 1.0 points in the measuring scale	Agreement is strongly supported
11. Tool provides helpful uncertainty visualization for making decisions	Experts tend to prefer DOME method by 0.6 points in the measuring scale	Preference is supported

Table 5. Factors selected for the analysis.

Agreement	Factor 1 factor loading	Factor 2 factor loading	Factor 3 factor loading	Factor 4 factor loading
S1	0.80281	-0.33107	0.02275	0.37730
S2	0.86748	0.04087	0.33319	-0.22557
S3	0.38172	0.74269	0.03822	-0.42947
S4	0.11443	0.27607	0.58126	0.71420
S5	0.94154	-0.20339	0.06201	0.03820
S6	0.93814	-0.28475	-0.08298	-0.03981
S7	0.46882	0.76248	-0.18973	0.24880
S8	0.86009	-0.45231	0.00372	-0.16398
S9	0.83300	0.15289	-0.18248	-0.04571
S10	0.40227	0.68067	-0.36092	0.10943
S11	0.01674	0.25556	0.83723	-0.30917

The “big” coefficients are emphasized in bold font in Table 5. The factors can be defined as follows:

$$F1 = .80 S1 + .86 S2 + .94 S5 + .94 S6 + .86 S8 + .83 S9$$

$$F2 = .74 S3 + .76 S7 + .68 S10$$

$$F3 = .84 S11$$

$$F4 = .71 S4$$

By looking at these factors, one may consider that:

- The agreements on statements 1, 2, 5, 6, 8, and 9 are correlated. One interpretation may be that the preference for DOME LCA tool to assess whether a particular design alternative will meet environmental design goals, to quickly trade off with other design goals, and to support making an important decision or the best decision, coupled with the agreement on the importance of making uncertainty explicit indirectly measure the agreement about better evaluation capabilities afforded by the DOME LCA tool. Responses to statements 5 and 6 could not be considered for interpretation, given their lack of or weak statistical support.

- The agreements on statements 3, 7, and 10 are correlated. One interpretation is that the agreements on the convenience of using DOME LCA tool when designing or making a decision, the capability of the tool to allow faster work and decision-making, and the usefulness of uncertainty visualization for its interpretation and making decisions are indirectly measuring the agreement about the DOME LCA tool being less time consuming for performing design and decision-making.
- The agreement on statement 11 as one factor may be interpreted as measuring a particular tool capability – visualization – distinct from the other tasks of assessment and decision making.
- Factor 4 may be considered as isolating the agreement on statement 4 due to strong lack of preference in choosing one of the methods.

The general preference trend for using the DOME integrated LCA model, as well as the identification of possible correlations in agreements, is encouraging but should also be tempered. An increased number of survey responses would have provided more robust data. Also, a more comprehensive comparison regarding the methodological capabilities of both tools would be possible through an in-depth study supported, for example, by a protocol analysis to help understand and analyze the practice of design activity, observing the use of these tools within everyday product design and related decision-making tasks.

Distinct data analysis and interpretations could have been performed for the data generated by the surveys. However, it is considered that these informal surveys and data analysis did provide some practical insight into how these methods may be differently perceived by some experts in application to integrated product design.

7. Conclusions

DFE is becoming an essential strategy for long-term success in today's industrial environment, as major market and regulation motivating forces are driving companies to see competitive advantage in incorporating environmental considerations into their procedures during early stages of product development. This design strategy allows an active practice of environmentally conscious product design while maintaining cost and performance relationships.

The goal of this thesis was to develop a quantitative LCA model of a new consumer electronics product, an LCD computer projector, and integrate it with other design models using DOME, believing that environmental issues must be incorporated into product design in balance with existing traditional design considerations. In doing so, the objective was to explore and discuss: (1) what is involved, methodologically and in terms of human interactions, in the process of developing such a collaborative modeling tool; (2) the behavior and value of the integrated LCA model in understanding interactions between traditional and environmental design goals. Ultimately, there was an attempt to draw insights, through a survey, into how the use of this DFE tool for assessing environmental performance against other design goals, in integrated product design, may be perceived by experts.

One important outcome was to realize that difficulties encountered during the process of data acquisition strongly influenced the creation and implementation of the LCA model structure. The lack of detailed product/process data, inherent to any early design phase of a new product, as well as the specific situation when major product components were outsourced, forced the adoption of a methodology involving the development of a streamlined, quantitative and component/material-based LCI model. To address the issue of lack of information/understanding, uncertainty in the form of probability distributions was associated with controlling variables of the model.

Another relevant outcome was experiencing the need to interact and collaborate with the other design team members to efficiently take advantage of the service exchange DOME capabilities for integrate environmental issues in the product design assessment. The definition of the interface between the different design models was not immediate and highly dependent on human interaction. In integrating the several design models needed to build the system model, the collaborative modeling approach using DOME framework proved to be beneficial, making the

integration possible in a timely and easy manner, while allowing independent development of the models, including the LCA model, using specialized tools.

In exploring the use of the model, it was important to notice that the method used for setting the design goal specifications in DOME framework influenced the possible tradeoffs involved in the evaluation. The weighting schemes supporting the environmental assessment methods affected highly the environmental scoring of design alternatives. It was also relevant observing that the resampling used for each update in the environmental data flow process between TEAM[®] and DOME was not robust enough for handling uncertainty in exploring some scenarios.

The interpretation of the survey results showing a general preference trend for using the DOME integrated LCA method was considered to be useful to provide some practical insight into how the methods may be differently perceived by some experts. However, more reliable results as well as a more comprehensive comparison regarding the methodological capabilities of both tools would be possible with an increased number of survey responses and an in-depth study to analyze the practice of design activity, and observe the use of these tools within everyday product design and related decision-making tasks.

This thesis work supports the idea that a human-centered, integrated approach is required to efficiently incorporate environmental issues into product design. It is also essential to be able to handle the lack of information/understanding of the processes involved in product life-cycle stages. This is a common issue when gathering data to assess product environmental performance in the early design phase using quantitative LCA methods.

The LCA model integrated through the DOME framework formed a consistent methodological basis for evaluating trade-offs between environmental criteria and other design goals. It facilitated data exchange and interoperability in a networked environment between specialized models and tools, including the LCA model, and provided the ability to address uncertainty associated with controlling variables of the model using probability distributions.

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Appendix A. External variables defined in the LCI model

A.1. The more approximate LCI model

NODE	NAME	VALUE	ERROR	MIN	MAX
incinerating_landfilling	% incinerated PS	0.8000	0.1600	0.6400	0.9600
recycling_landfilling	%recycled PS	0.8000	0.1600	0.6400	0.9600
disposal method	disposal method PS	catalog			
Fan	ABS fan	0.8000	0.1600	0.6400	0.9600
fan	copper fan	0.0300	0.0060	0.0240	0.0360
fan	steel fan	0.1500	0.0300	0.1200	0.1800
fan	FR4 fan	0.0200	0.0040	0.0160	0.0240
pcb	capacitor	0.0299	0.0060	0.0239	0.0359
pcb	integrated circuits	0.0498	0.0100	0.0398	0.0598
pcb	FR4	0.8305	0.1661	0.6644	0.9966
pcb	resistor	0.0030	0.0006	0.0024	0.0036
pcb	connector	0.0064	0.0013	0.0051	0.0077
pcb	AsGa	0.0010	0.0002	0.0008	0.0012
pcb	coil	0.0796	0.0159	0.0637	0.0955
assembly projector	cables	0.1763	0.0353	0.1411	0.2116
assembly projector	light engine	6.6407	1.3281	5.3125	7.9688
assembly projector	fan	0.7670	0.1534	0.6136	0.9204
assembly projector	pcb	2.2040	0.4408	1.7632	2.6448
assembly projector	lenses	2.7330	0.5466	2.1864	3.2796
assembly projector	shielding	0.4368	0.0874	0.3495	0.5242
assembly projector	power supply	3.2840	0.6568	2.6272	3.9408
assembly projector	speakers	0.0231	0.0046	0.0185	0.0278
assembly projector	housing	4.6654	0.9331	3.7323	5.5985
assembly projector	flex interconnects	0.0176	0.0035	0.0141	0.0212
assembly projector	remote control	0.2867	0.0573	0.2294	0.3441
lenses	ABS lenses	0.1600	0.0320	0.1280	0.1920
lenses	aluminum lenses	0.0300	0.0060	0.0240	0.0360
lenses	glass lenses	0.8100	0.1620	0.6480	0.9720
electricity distribution	use location	catalog			
use presentations	power consumption	800	160	640	960
use presentations	mean time before failure	3000	600	2400	3600
housing	plastic housing	0.8800	0.1760	0.7040	1.0560
housing	steel housing	0.1100	0.0220	0.0880	0.1320
housing	rubber housing	0.0100	0.0020	0.0080	0.0120
housing	type plastic	catalog			
cables	copper cables	0.7000	0.1400	0.5600	0.8400
cables	PVC cables	0.3000	0.0600	0.2400	0.3600
flex interconnects	PI flex interconnects	1.0000	0.2000	0.8000	1.2000
shielding	PC shielding	0.2500	0.0500	0.2000	0.3000
shielding	aluminum shielding	0.7500	0.1500	0.6000	0.9000
remote control	ABS remote	0.5700	0.1140	0.4560	0.6840
remote control	FR4 remote	0.2000	0.0400	0.1600	0.2400
remote control	batteries	0.2300	0.0460	0.1840	0.2760
recycling_landfilling	% recycled PP	0.8000	0.1600	0.6400	0.9600
disposal method	disposal method PP	catalog			
incinerating_landfilling	% incinerated PP	0.8000	0.1600	0.6400	0.9600
recycling_landfilling	% recycled ABS	0.8000	0.1600	0.6400	0.9600
disposal method	disposal method ABS	catalog			
incinerating_landfilling	% incinerated ABS	0.8000	0.1600	0.6400	0.9600
light engine	epoxy light engine	0.0060	0.0012	0.0048	0.0072
light engine	glass light engine	0.4050	0.0810	0.3240	0.4860
light engine	ceramic light engine	0.0100	0.0020	0.0080	0.0120
light engine	PC light engine	0.1300	0.0260	0.1040	0.1560
light engine	steel light engine	0.0600	0.0120	0.0480	0.0720
light engine	aluminum light engine	0.4000	0.0800	0.3200	0.4800
power supply	steel power supply	0.3800	0.0760	0.3040	0.4560
power supply	heatsinks power supply	0.0400	0.0080	0.0320	0.0480
power supply	transformers power supply	0.5200	0.1040	0.4160	0.6240
power supply	PC power supply	0.0600	0.0120	0.0480	0.0720

A.2. The more detailed LCI model

NODE	NAME	VALUE	ERROR	MIN	MAX
Coils management node	ratio coil_mass	200	20	180	220
FR4 management node	pcb board ratio area_mass	0.4000	0.0400	0.3600	0.4400
Capacitors management node	ratio capacitor_mass	8333	833	7500	9167
Resistors management node	ratio resistor_mass	3333	333	3000	3667
AsGa management node	ratio AsGa_mass	3333	333	3000	3667
IC management node	ratio ic_mass	2000	200	1800	2200
Connectors management node	ratio connector_mass	1250	125	1125	1375
Assembly PCB	capacitor_pcb	0.0299	0.0060	0.0239	0.0359
Assembly PCB	integrated circuit_pcb	0.0498	0.0100	0.0398	0.0598
Assembly PCB	FR4_pcb	0.8305	0.1661	0.6644	0.9966
Assembly PCB	resistor_pcb	0.0030	0.0006	0.0024	0.0036
Assembly PCB	connector_pcb	0.0064	0.0013	0.0051	0.0077
Assembly PCB	ratio area_mass	0.4000	0.0400	0.3600	0.4400
Assembly PCB	gallium arsenide_pcb	0.0010	0.0002	0.0008	0.0012
Assembly PCB	coil pcb	0.0796	0.0159	0.0637	0.0955
Assembly power supply	steel_power_supply	0.3800	0.0760	0.3040	0.4560
Assembly power supply	heatsinks_power_supply	0.0400	0.0080	0.0320	0.0480
Assembly power supply	transformers_power_supply	0.5200	0.1040	0.4160	0.6240
Assembly power supply	PC_power_supply	0.0600	0.0120	0.0480	0.0720
Transform. management node	ratio transformer_mass	7.2098	0.7210	6.4888	7.9308
Heatsinks management node	ratio heatsink_mass	60.976	6.098	54.878	67.073
Assembly shielding	PC shielding	0.2500	0.0500	0.2000	0.3000
Assembly shielding	aluminum shielding	0.7500	0.1500	0.6000	0.9000
Assembly fan	ABS_fan	0.8000	0.1600	0.6400	0.9600
Assembly fan	copper_fan	0.0300	0.0060	0.0240	0.0360
Assembly fan	steel_fan	0.1500	0.0300	0.1200	0.1800
Assembly fan	FR4_fan	0.0200	0.0040	0.0160	0.0240
Board sub. management node	fan board ratio area_mass	0.4000	0.0400	0.3600	0.4400
Assembly remote control	ABS_remote	0.5200	0.1040	0.4160	0.6240
Assembly remote control	silicon rubber_remote	0.0500	0.0100	0.0400	0.0600
Assembly remote control	pcb_remote	0.2000	0.0400	0.1600	0.2400
Assembly remote control	Batteries	0.2300	0.0460	0.1840	0.2760
recycling_landfilling	% recycled batteries	0.1000	0.0200	0.0800	0.1200
Resistors management node	ratio resistor_mass	3333	333	3000	3667
FR4 management node	pcb board ratio area_mass	0.4000	0.0400	0.3600	0.4400
AsGa management node	ratio AsGa_mass	3333	333	3000	3667
Assembly PCB	Capacitor_pcb	0.0299	0.0060	0.0239	0.0359
Assembly PCB	Integrated circuit_pcb	0.0498	0.0100	0.0398	0.0598
Assembly PCB	FR4_pcb	0.8305	0.1661	0.6644	0.9966
Assembly PCB	Resistor_pcb	0.0030	0.0006	0.0024	0.0036
Assembly PCB	Connector_pcb	0.0064	0.0013	0.0051	0.0077
Assembly PCB	ratio area_mass	0.4000	0.0400	0.3600	0.4400
Assembly PCB	Gallium arsenide_pcb	0.0010	0.0002	0.0008	0.0012
Assembly PCB	coil pcb	0.0796	0.0159	0.0637	0.0955
Coils management node	ratio coil_mass	200	20	180	220
Connectors management node	ratio connector_mass	1250	125	1125	1375
IC management node	ratio ic_mass	2000	200	1800	2200
Capacitors management node	ratio capacitor_mass	8333	833	7500	9167
Assembly lenses	Aluminum_lenses	0.0300	0.0060	0.0240	0.0360
Assembly lenses	ABS_lenses	0.1600	0.0320	0.1280	0.1920
Assembly lenses	Glass_lenses	0.8100	0.1620	0.6480	0.9720
Assembly light engine	Epoxy_light engine	0.0030	0.0006	0.0024	0.0036
Assembly light engine	Glass_light engine	0.4050	0.0810	0.3240	0.4860
Assembly light engine	Halide_light engine	0.0030	0.0006	0.0024	0.0036
Assembly light engine	Ceramic_light engine	0.0100	0.0020	0.0080	0.0120
Assembly light engine	Plastic PC_light engine	0.1300	0.0260	0.1040	0.1560
Assembly light engine	steel_light engine	0.0600	0.0120	0.0480	0.0720
Assembly light engine	Aluminum_light engine	0.4000	0.0800	0.3200	0.4800
Flex interconnects	PI_flex	1.0000	0.2000	0.8000	1.2000
Assembly cables	PVC cables	0.3000	0.0600	0.2400	0.3600
Assembly cables	Copper cables	0.7000	0.1400	0.5600	0.8400

Speakers management node	ratio speaker_mass	190	19	171	210
Assembly housing	Plastic_housing	0.8800	0.1760	0.7040	1.0560
Assembly housing	steel_housing	0.1100	0.0220	0.0880	0.1320
Assembly housing	Rubber_housing	0.0100	0.0020	0.0080	0.0120
Assembly housing	type plastic	catalog			
disposal method	Disposal method	catalog			
recycling_landfilling	% recycled	0.8000	0.1600	0.6400	0.9600
incinerating_landfilling	% incinerated	0.8000	0.1600	0.6400	0.9600
disposal method	disposal method	catalog			
recycling_landfilling	% recycled	0.8000	0.1600	0.6400	0.9600
incinerating_landfilling	% incinerated	0.8000	0.1600	0.6400	0.9600
disposal method	disposal method	catalog			
recycling_landfilling	% recycled	0.8000	0.1600	0.6400	0.9600
incinerating_landfilling	% incinerated	0.8000	0.1600	0.6400	0.9600
Assembly of projector	cables	0.1763	0.0353	0.1411	0.2116
Assembly of projector	light engine	6.6407	1.3281	5.3125	7.9688
Assembly of projector	fan	0.7670	0.1534	0.6136	0.9204
Assembly of projector	pcb	2.2040	0.4408	1.7632	2.6448
Assembly of projector	lenses	2.7330	0.5466	2.1864	3.2796
Assembly of projector	shielding	0.4368	0.0874	0.3495	0.5242
Assembly of projector	power supply	3.2840	0.6568	2.6272	3.9408
Assembly of projector	speakers	0.0231	0.0046	0.0185	0.0278
Assembly of projector	housing	4.6654	0.9331	3.7323	5.5985
Assembly of projector	flex interconnects	0.0176	0.0035	0.0141	0.0212
Assembly of projector	remote control	0.2867	0.0573	0.2294	0.3441
Use presentations	power consumption	800	160	640	960
Use presentations	min time bf	3000	600	2400	3600
Electricity distribution	use location	catalog			
Electricity distribution	%distribution losses	0.0700	0.0140	0.0560	0.0840
Electricity distribution	%coal	0.3400	0.0680	0.2720	0.4080
Electricity distribution	% lignite	0.0010	0.0002	0.0008	0.0012
Electricity distribution	%oil	0.1000	0.0200	0.0800	0.1200
Electricity distribution	%gas	0.1300	0.0260	0.1040	0.1560
Electricity distribution	%nuclear	0.2600	0.0520	0.2080	0.3120
Electricity distribution	%hydro	0.1400	0.0280	0.1120	0.1680

Appendix B. Weighting factors used in assessment methods

Assessment method	Articles	Units	Factor
CML-Air Acidification			/
	Sulphur Oxides (SOx as SO2)	g eq. H+	32
	Nitrogen Oxides (NOx as NO2)	g eq. H+	46
	Ammonia (NH3)	g eq. H+	17
	Hydrogen Chloride (HCl)	g eq. H+	36.5
	Hydrogen Fluoride (HF)	g eq. H+	20
	Chromic Acid (H2CrO4)	g eq. H+	29.5
	Sulphuric Acid (H2SO4)	g eq. H+	24.5
	Hydrogen Cyanide (HCN)	g eq. H+	27
	Hydrogen Sulphide (H2S)	g eq. H+	17
CML-Depletion of non ren.res.			/
	Oil (in ground)	frac. of reserve	2.39E+14
	Natural Gas (in ground)	frac. of reserve	1.298E+14
	Uranium (U, ore)	frac. of reserve	13400000000
	Copper (Cu, ore)	frac. of reserve	6.1E+11
	Lead (Pb, ore)	frac. of reserve	1.2E+11
	Nickel (Ni, ore)	frac. of reserve	1.1E+11
	Tin (Sn, ore)	frac. of reserve	10000000000
	Zinc (Zn, ore)	frac. of reserve	3.3E+11
	Bauxite (Al2O3, ore)	frac. of reserve	2.8E+13
	Gold (Au, ore)	frac. of reserve	61000000
	Iron (Fe, ore)	frac. of reserve	1E+14
	Manganese (Mn, ore)	frac. of reserve	5E+12
	Potassium Chloride (KCl, in ground)	frac. of reserve	1.7E+13
	Coal (in ground)	frac. of reserve	2.98E+15
CML-Depletion of oz. layer (high)			x
	CFC 11 (CFC13)	g eq. CFC-11	1
	CFC 12 (CCl2F2)	g eq. CFC-11	1.06
	CFC 114 (CF2ClCF2Cl)	g eq. CFC-11	0.82
	HCFC 22 (CHF2Cl)	g eq. CFC-11	0.08
	HCFC 123 (CHCl2CF3)	g eq. CFC-11	0.02
	Halon 1301 (CF3Br)	g eq. CFC-11	17.2
CML-Depletion of oz. layer (low)			x
	CFC 11 (CFC13)	g eq. CFC-11	1
	CFC 12 (CCl2F2)	g eq. CFC-11	0.88
	CFC 114 (CF2ClCF2Cl)	g eq. CFC-11	0.57
	HCFC 22 (CHF2Cl)	g eq. CFC-11	0.032
	HCFC 123 (CHCl2CF3)	g eq. CFC-11	0.013
	Halon 1301 (CF3Br)	g eq. CFC-11	10
CML-Eutrophication			x
	Nitrogen Oxides (NOx as NO2)	g eq. PO4	0.13
	Ammonia (NH4+, NH3, as N)	g eq. PO4	0.33
	Phosphorus (P)	g eq. PO4	3.06
	COD (Chemical Oxygen Demand)	g eq. PO4	0.022
	Nitrates (NO3-)	g eq. PO4	0.095
	Nitrogenous Matter (unspecified, as N)	g eq. PO4	0.42
	Phosphorous Matter (unspecified, as P)	g eq. PO4	3.06
	Nitrogen Dioxide (NO2)	g eq. PO4	0.13
	Nitrogen Oxide (NO)	g eq. PO4	0.2
	Nitrous Oxide (N2O)	g eq. PO4	0.27
CML-Eutrophication (water)			x
	Ammonia (NH4+, NH3, as N)	g eq. PO4	0.33
	Phosphorus (P)	g eq. PO4	3.06
	COD (Chemical Oxygen Demand)	g eq. PO4	0.022
	Nitrates (NO3-)	g eq. PO4	0.095
	Nitrogenous Matter (unspecified, as N)	g eq. PO4	0.42
	Phosphorous Matter (unspecified, as P)	g eq. PO4	3.06
	Nitrogen Dioxide (NO2)	g eq. PO4	0.13
	Nitrogen Oxide (NO)	g eq. PO4	0.2
CVCH-Air			/
	Particulates (unspecified)	m3	0.00007

	Carbon Dioxide (CO2, fossil)	m3	0.008
	Ammonia (NH3)	m3	0.0005
	Nitrogen Oxides (NOx as NO2)	m3	0.00003
	Hydrogen Chloride (HCl)	m3	0.0001
	Sulphur Oxides (SOx as SO2)	m3	0.00003
	Chlorine (Cl2)	m3	0.00002
	Hydrogen Fluoride (HF)	m3	0.00005
	Mercaptans	m3	0.00001
	Hydrogen Sulphide (H2S)	m3	0.00015
	Hydrocarbons (unspecified)	m3	0.015
	Methane (CH4)	m3	0.015
	Hydrocarbons (except methane)	m3	0.015
	Organic Matter (unspecified)	m3	0.00001
	Lead (Pb)	m3	0.000001
	Mercury (Hg)	m3	0.0000007
	(Cadmium (Cd)	m3	0.00000001
CVCH-Water			/
	Suspended Matter (unspecified)	l	0.02
	Lead (Pb++, Pb4+)	l	0.0005
	Cadmium (Cd++)	l	0.0001
	Iron (Fe++, Fe3+)	l	0.002
	Copper (Cu+, Cu++)	l	0.0005
	Mercury (Hg+, Hg++)	l	0.00001
	Ammonia (NH4+, NH3, as N)	l	0.001
	Chlorides (Cl-)	l	1
	Cyanides (CN-)	l	0.0001
	Fluorides (F-)	l	0.01
	Sulphides (S--)	l	0.0001
	Dissolved Organic Carbon (DOC)	l	0.01
	COD (Chemical Oxygen Demand)	l	0.03
	BOD5 (Biochemical Oxygen Demand)	l	0.02
	Saponifiable Oils and Fats	l	0.02
	Hydrocarbons	l	0.01
	Phenol (C6H6O)	l	0.00005
Ec(R)-Depletion of non ren. res.			/
	Oil (in ground)	frac. of reservex1e9	239000
	Natural Gas (in ground)	frac. of reservex1e9	130000
	Coal (in ground)	frac. of reservex1e9	2980000
	Iron (Fe, ore)	frac. of reservex1e9	100000
	Zinc (Zn, ore)	frac. of reservex1e9	330
	Lead (Pb, ore)	frac. of reservex1e9	120
	Bauxite (Al2O3, ore)	frac. of reservex1e9	28000
	Copper (Cu, ore)	frac. of reservex1e9	610
	Gold (Au, ore)	frac. of reservex1e9	0.061
	Manganese (Mn, ore)	frac. of reservex1e9	5000
	Nickel (Ni, ore)	frac. of reservex1e9	110
	Potassium Chloride (KCl, in ground)	frac. of reservex1e9	27000
	Tin (Sn, ore)	frac. of reservex1e9	10
	Uranium (U, ore)	frac. of reservex1e9	13.41
Ec(RxY)-Depletion of non ren. res.			x
	Oil (in ground)	frac. of reservex1e15/yr	0.0557
	Natural Gas (in ground)	frac. of reservex1e15/yr	0.117
	Coal (in ground)	frac. of reservex1e15/yr	0.0005037
	Bauxite (Al2O3, ore)	frac. of reservex1e15/yr	0.139
	Copper (Cu, ore)	frac. of reservex1e15/yr	26.3
	Gold (Au, ore)	frac. of reservex1e15/yr	591000
	Iron (Fe, ore)	frac. of reservex1e15/yr	0.0433
	Lead (Pb, ore)	frac. of reservex1e15/yr	194
	Manganese (Mn, ore)	frac. of reservex1e15/yr	0.292
	Nickel (Ni, ore)	frac. of reservex1e15/yr	76.03
	Potassium Chloride (KCl, in ground)	frac. of reservex1e15/yr	0.0572
	Tin (Sn, ore)	frac. of reservex1e15/yr	1800
	Uranium (U, ore)	frac. of reservex1e15/yr	181
	Zinc (Zn, ore)	frac. of reservex1e15/yr	64.9

Ec(Y)-Depletion of non ren. res.			/
	Oil (in ground)	kg/yr	75
	Natural Gas (in ground)	kg/yr	66
	Coal (in ground)	kg/yr	666
	Iron (Fe, ore)	kg/yr	231
	Zinc (Zn, ore)	kg/yr	47
	Lead (Pb, ore)	kg/yr	43
	Bauxite (Al ₂ O ₃ , ore)	kg/yr	257
	Copper (Cu, ore)	kg/yr	62
	Gold (Au, ore)	kg/yr	28
	Manganese (Mn, ore)	kg/yr	685
	Nickel (Ni, ore)	kg/yr	120
	Potassium Chloride (KCl, in ground)	kg/yr	649
	Tin (Sn, ore)	kg/yr	56
	Uranium (U, ore)	kg/yr	412
Ecopoints-Air			x
	Nitrogen Oxides (NO _x as NO ₂)	Ecopoint	42.3
	Sulphur Oxides (SO _x as SO ₂)	Ecopoint	23
	Carbon Dioxide (CO ₂ , fossil)	Ecopoint	0.036
	Hydrocarbons (unspecified)	Ecopoint	14.3
	Methane (CH ₄)	Ecopoint	14.3
	Hydrocarbons (except methane)	Ecopoint	14.3
	Hydrogen Chloride (HCl)	Ecopoint	42.3
	CFC 12 (CCl ₂ F ₂)	Ecopoint	4500
Ecopoints-Energy & Waste			x
	Waste (municipal and industrial)	Ecopoint	222
Ecopoints-Water			x
	Dissolved Organic Carbon (DOC)	Ecopoint	11.5
	COD (Chemical Oxygen Demand)	Ecopoint	3.83
	Phosphorus (P)	Ecopoint	756
	Chlorides (Cl ⁻)	Ecopoint	0.0262
	Nitrates (NO ₃ ⁻)	Ecopoint	0.905
	Sulphates (SO ₄ ⁻⁻)	Ecopoint	0.0766
	Ammonia (NH ₄ ⁺ , NH ₃ , as N)	Ecopoint	10.3
EPS-Air			x
	CFC 11 (CFCl ₃)	ELU	0.2163
	Methane (CH ₄)	ELU	0.0015577
	Carbon Dioxide (CO ₂ , fossil)	ELU	0.0000636
	Carbon Monoxide (CO)	ELU	0.0001912
	Ethylene (C ₂ H ₄)	ELU	0.003404
	Nitrogen Oxides (NO _x as NO ₂)	ELU	0.0003948
	Nitrous Oxide (N ₂ O)	ELU	0.020341
	Sulphur Oxides (SO _x as SO ₂)	ELU	0.0000545
	Particulates (unspecified)	ELU	0.0000071
	Arsenic (As)	ELU	0.01
	Cadmium (Cd)	ELU	0.0212
	Mercury (Hg)	ELU	0.17672
	Hydrogen Sulphide (H ₂ S)	ELU	0.0001418
	Lead (Pb)	ELU	0.2907
	Chromic Acid (H ₂ CrO ₄)	ELU	0.000353
EPS-Metal Resources			x
	Bauxite (Al ₂ O ₃ , ore)	ELU	0.164
	Gold (Au, ore)	ELU	850000
	Copper (Cu, ore)	ELU	57
	Iron (Fe, ore)	ELU	0.68
	Manganese (Mn, ore)	ELU	3.6
	Nickel (Ni, ore)	ELU	40
	Lead (Pb, ore)	ELU	240
	Tin (Sn, ore)	ELU	1480
	Zinc (Zn, ore)	ELU	49
	Uranium (U, ore)	ELU	1260
	Aldehydes	ELU	400000
EPS-Non Renewable Energy			x
	Natural Gas (in ground)	ELU	0.5

	Oil (in ground)	ELU	0.5
	Coal (in ground)	ELU	0.05
EPS-Water			x
	BOD5 (Biochemical Oxygen Demand)	ELU	0.000075
	COD (Chemical Oxygen Demand)	ELU	0.000006
	Phosphorus (P)	ELU	0.000075
	Ammonia (NH4+, NH3, as N)	ELU	0.000078
	Nitrates (NO3-)	ELU	0.000023
	Nitrogen Dioxide (NO2)	ELU	0.000003
	Nitrogen Oxide (NO)	ELU	0.000046
	Nitrogenous Matter (unspecified, as N)	ELU	0.00001
	Phosphorous Matter (unspecified, as P)	ELU	0.000075
ETH-Air Acidification			/
	CFC 11 (CFCl3)	g eq. H+	34.375
	HFC 125 (CF3CHF2)	g eq. H+	24
	Sulphur Oxides (SOx as SO2)	g eq. H+	32
	Hydrogen Chloride (HCl)	g eq. H+	36.5
	Nitrogen Oxides (NOx as NO2)	g eq. H+	46
	Ammonia (NH3)	g eq. H+	17
	Hydrogen Fluoride (HF)	g eq. H+	20
	Sulphuric Acid (H2SO4)	g eq. H+	24.5
	Hydrogen Cyanide (HCN)	g eq. H+	27
	Hydrogen Sulphide (H2S)	g eq. H+	17
IPCC-Greenhouse eff. (100 years)			x
	Carbon Dioxide (CO2, fossil)	g eq. CO2	1
	Methane (CH4)	g eq. CO2	24.5
	Nitrous Oxide (N2O)	g eq. CO2	320
	CFC 11 (CFCl3)	g eq. CO2	4000
	CFC 12 (CCl2F2)	g eq. CO2	8500
	CFC 13 (CF3Cl)	g eq. CO2	11700
	CFC 114 (CF2ClCF2Cl)	g eq. CO2	9300
	HCFC 22 (CHF2Cl)	g eq. CO2	1700
	HCFC 123 (CHCl2CF3)	g eq. CO2	93
	Halon 1301 (CF3Br)	g eq. CO2	5600
	HFC 125 (CF3CHF2)	g eq. CO2	3200
	Carbon Tetrafluoride (CF4)	g eq. CO2	6300
IPCC-Greenhouse eff. (20 years)			x
	Carbon Dioxide (CO2, fossil)	g eq. CO2	1
	Methane (CH4)	g eq. CO2	62
	Nitrous Oxide (N2O)	g eq. CO2	290
	CFC 11 (CFCl3)	g eq. CO2	5000
	CFC 12 (CCl2F2)	g eq. CO2	7900
	CFC 13 (CF3Cl)	g eq. CO2	8100
	CFC 114 (CF2ClCF2Cl)	g eq. CO2	6900
	HCFC 22 (CHF2Cl)	g eq. CO2	4300
	HCFC 123 (CHCl2CF3)	g eq. CO2	300
	Halon 1301 (CF3Br)	g eq. CO2	6200
	HFC 125 (CF3CHF2)	g eq. CO2	4800
	Carbon Tetrafluoride (CF4)	g eq. CO2	4100
IPCC-Greenhouse eff. (500 years)			x
	Carbon Dioxide (CO2, fossil)	g eq. CO2	1
	Methane (CH4)	g eq. CO2	7.5
	Nitrous Oxide (N2O)	g eq. CO2	180
	CFC 11 (CFCl3)	g eq. CO2	1400
	CFC 12 (CCl2F2)	g eq. CO2	4200
	CFC 13 (CF3Cl)	g eq. CO2	13600
	CFC 114 (CF2ClCF2Cl)	g eq. CO2	8300
	HCFC 22 (CHF2Cl)	g eq. CO2	520
	HCFC 123 (CHCl2CF3)	g eq. CO2	29
	Halon 1301 (CF3Br)	g eq. CO2	2200
	HFC 125 (CF3CHF2)	g eq. CO2	1100
	Carbon Tetrafluoride (CF4)	g eq. CO2	9800

Appendix C. DOME source code files

C.1. LCA modules code in ProjectorComponents4.mdl file:

```
Module "Faster"
(
  UpdateFile "quickUpdate"
  SimTable "LCA-Connection" { 25 20 }
  (
    URL "Remote"
    UpdateFunction "updateQuickTEAM"
    Dependency "%_incinerated_PS"
      (ConnectedTo "Housing percent PS incinerated")
    Dependency "%recycled_PS"
      (ConnectedTo "Housing percent PS recycled")
    Dependency "PS_disposal_method"
    Dependency "ABS_fan"
      (ConnectedTo "Fan mass percentage of plastic ABS")
    Dependency "copper_fan"
      (ConnectedTo "Fan mass percentage of copper")
    Dependency "steel_fan"
      (ConnectedTo "Fan mass percentage of steel")
    Dependency "FR4_fan_"
      (ConnectedTo "Fan mass percentage of FR4board")
    Dependency "capacitor"
      (ConnectedTo "Projector pcb mass percentage of capacitors")
    Dependency "integrated_circuits"
      (ConnectedTo "Projector pcb mass percentage of integrated
circuits")
    Dependency "FR4"
      (ConnectedTo "Projector pcb mass percentage of FR4board")
    Dependency "resistor"
      (ConnectedTo "Projector pcb mass percentage of resistors")
    Dependency "connector"
      (ConnectedTo "Projector pcb mass percentage of connectors")
    Dependency "AsGa"
      (ConnectedTo "Projector pcb mass percentage of AsGa components")
    Dependency "coil"
      (ConnectedTo "Projector pcb mass percentage of coils")
    Dependency "cables"
      (ConnectedTo "Projector mass of cables")
    Dependency "light_engine"
    Dependency "fan"
    Dependency "pcb"
    Dependency "lenses"
    Dependency "shielding"
      (ConnectedTo "Projector mass of shielding")
    Dependency "power_supply"
    Dependency "speakers"
    Dependency "housing"
    Dependency "flex_interconnects"
      (ConnectedTo "Projector mass of flex interconnects")
    Dependency "remote_control"
      (ConnectedTo "Projector mass of remote control")
    Dependency "ABS_lenses"
      (ConnectedTo "Lenses mass percentage of plastic ABS")
    Dependency "aluminum_lenses"
      (ConnectedTo "Lenses mass percentage of aluminum")
    Dependency "glass_lenses_"
      (ConnectedTo "Lenses mass percentage of glass")
    Dependency "use_location"
    Dependency "power_consumption"
    Dependency "mean_time_bf"
    Dependency "plastic_housing"
      (ConnectedTo "Housing mass percentage of plastic")
    Dependency "steel_housing"
      (ConnectedTo "Housing mass percentage of steel")
    Dependency "rubber_housing"
```

```

        (ConnectedTo "Housing mass percentage of rubber")
    Dependency "type_plastic"
    Dependency "copper_cables"
        (ConnectedTo "Cables mass percentage of copper")
    Dependency "PVC_cables"
        (ConnectedTo "Cables mass percentage of PVC")
    Dependency "PI_flex_interconnects"
        (ConnectedTo "Flex interconnects mass percentage of PI")
    Dependency "PC_shielding"
        (ConnectedTo "Shielding mass percentage of plastic PC")
    Dependency "aluminum_shielding"
        (ConnectedTo "Shielding mass percentage of aluminum")
    Dependency "ABS_remote"
        (ConnectedTo "Remote mass percentage of plastic ABS")
    Dependency "FR4_remote"
        (ConnectedTo "Remote mass percentage of pcb")
    Dependency "batteries_"
        (ConnectedTo "Remote mass percentage of batteries")
    Dependency "%_recycled_PP"
        (ConnectedTo "Housing percent PP recycled")
    Dependency "PP_disposal_method"
    Dependency "%_incinerated_PP"
        (ConnectedTo "Housing percent PP incinerated")
    Dependency "%_recycled_ABS"
        (ConnectedTo "Housing percent ABS recycled")
    Dependency "ABS_disposal_method"
    Dependency "%_incinerated_ABS"
        (ConnectedTo "Housing percent ABS incinerated")
    Dependency "epoxy_light_engine"
        (ConnectedTo "Light engine mass percentage of epoxy")
    Dependency "glass_light_engine"
        (ConnectedTo "Light engine mass percentage of glass")
    Dependency "ceramic_light_engine"
        (ConnectedTo "Light engine mass percentage of ceramic")
    Dependency "PC_light_engine"
        (ConnectedTo "Light engine mass percentage of plastic PC")
    Dependency "steel_light_engine"
        (ConnectedTo "Light engine mass percentage of steel")
    Dependency "aluminum_light_engine"
        (ConnectedTo "Light engine mass percentage of aluminum")
    Dependency "steel_power_supply"
        (ConnectedTo "Power supply mass percentage of steel")
    Dependency "heatsinks_power_suppy"
        (ConnectedTo "Power supply mass percentage of heatsinks")
    Dependency "transformers_power_supply"
        (ConnectedTo "Power supply mass percentage of transformers")
    Dependency "PC_power_supply"
        (ConnectedTo "Power supply mass percentage of plastic PC")
)
Variable "Housing percent PS incinerated"
(
    Uniform { 0.72 0.88 }
)
Variable "Housing percent PS recycled"
(
    Uniform { 0.72 0.88 }
)
Variable "Fan mass percentage of plastic ABS"
(
    Uniform { 0.64 0.96 }
)
Variable "Fan mass percentage of copper"
(
    Uniform { 0.024 0.036 }
)
Variable "Fan mass percentage of steel"
(
    Uniform { 0.12 0.18 }
)
Variable "Fan mass percentage of FR4board"
(

```

```

    Uniform { 0.016 0.024 }
)
Variable "Projector pcb mass percentage of capacitors"
(
    Uniform { 0.0239 0.0359 }
)
Variable "Projector pcb mass percentage of integrated circuits"
(
    Uniform { 0.0398 0.0598 }
)
Variable "Projector pcb mass percentage of FR4board"
(
    Uniform { 0.6644 0.9966 }
)
Variable "Projector pcb mass percentage of resistors"
(
    Uniform { 0.0024 0.0036 }
)
Variable "Projector pcb mass percentage of connectors"
(
    Uniform { 0.0051 0.0077 }
)
Variable "Projector pcb mass percentage of AsGa components"
(
    Uniform { 0.00008 0.00012 }
)
Variable "Projector pcb mass percentage of coils"
(
    Uniform { 0.0637 0.0955 }
)
Variable "Projector mass of cables"
(
    Delta {0.1763}
)
Variable "Projector mass of shielding"
(
    Delta {0.4368}
)
Variable "Projector mass of flex interconnects"
(
    Delta {0.0176 }
)
Variable "Projector mass of remote control"
(
    Uniform { 0.258 0.3154 }
)
Variable "Lenses mass percentage of plastic ABS"
(
    Uniform { 0.128 0.192 }
)
Variable "Lenses mass percentage of aluminum"
(
    Uniform { 0.024 0.036 }
)
Variable "Lenses mass percentage of glass"
(
    Uniform { 0.648 0.972 }
)
Variable "Housing mass percentage of plastic"
(
    Uniform { 0.70 0.9 }
)
Variable "Housing mass percentage of steel"
(
    Uniform { 0.088 0.132 }
)
Variable "Housing mass percentage of rubber"
(
    Uniform { 0.008 0.012 }
)
Variable "Cables mass percentage of copper"

```

```

(
    Uniform { 0.56 0.84 }
)
Variable "Cables mass percentage of PVC"
(
    Uniform { 0.24 0.36 }
)
Variable "Flex interconnects mass percentage of PI"
(
    Uniform { 0.8 1 }
)
Variable "Shielding mass percentage of plastic PC"
(
    Uniform { 0.2 0.3 }
)
Variable "Shielding mass percentage of aluminum"
(
    Uniform { 0.6 0.9 }
)
Variable "Remote mass percentage of plastic ABS"
(
    Uniform { 0.456 0.684 }
)
Variable "Remote mass percentage of pcb"
(
    Uniform { 0.16 0.24 }
)
Variable "Remote mass percentage of batteries"
(
    Uniform { 0.184 0.276 }
)
Variable "Housing percent PP recycled"
(
    Uniform { 0.72 0.88 }
)
Variable "Housing percent PP incinerated"
(
    Uniform { 0.72 0.88 }
)
Variable "Housing percent ABS recycled"
(
    Uniform { 0.72 0.88 }
)
Variable "Housing percent ABS incinerated"
(
    Uniform { 0.72 0.88 }
)
Variable "Light engine mass percentage of epoxy"
(
    Uniform { 0.0048 0.0072 }
)
Variable "Light engine mass percentage of glass"
(
    Uniform { 0.324 0.486 }
)
Variable "Light engine mass percentage of ceramic"
(
    Uniform { 0.008 0.012 }
)
Variable "Light engine mass percentage of plastic PC"
(
    Uniform { 0.104 0.156 }
)
Variable "Light engine mass percentage of steel"
(
    Uniform { 0.048 0.072 }
)
Variable "Light engine mass percentage of aluminum"
(
    Uniform { 0.32 0.48 }
)
)

```

```

Variable "Power supply mass percentage of steel"
(
    Uniform { 0.304 0.456 }
)
Variable "Power supply mass percentage of heatsinks"
(
    Uniform { 0.032 0.048 }
)
Variable "Power supply mass percentage of transformers"
(
    Uniform { 0.416 0.624 }
)
Variable "Power supply mass percentage of plastic PC"
(
    Uniform { 0.048 0.072 }
)
)

Module "Detailed"
(
    UpdateFile "polarfUpdate"
    SimTable "LCA-Connection" { 25 4 }
    (
        UpdateFunction "updatePolarfTEAM"

        URL "Remote"

        Dependency "Pratio_coil_mass"
            (ConnectedTo "Projector pcb coil/mass ratio")
        Dependency "Ppcb_board_ratio_area_mass"
            (ConnectedTo "Projector pcb area/mass ratio")
        Dependency "Pratio_capacitor_mass"
            (ConnectedTo "Projector pcb capacitor/mass ratio")
        Dependency "Pratio_resistor_mass"
            (ConnectedTo "Projector pcb resistor/mass ratio")
        Dependency "Pratio_AsGa_mass"
            (ConnectedTo "Projector pcb AsGa component/mass ratio")
        Dependency "Pratio_ic_mass"
            (ConnectedTo "Projector pcb integrated circuits/mass ratio")
        Dependency "Pratio_connector_mass"
            (ConnectedTo "Projector pcb connector/mass ratio")
        Dependency "Pcapacitor_pcb"
            (ConnectedTo "Projector pcb mass percentage of capacitors")
        Dependency "Pintegrated_circuit_pcb"
            (ConnectedTo "Projector pcb mass percentage of integrated
circuits")
        Dependency "PFR4_pcb"
            (ConnectedTo "Projector pcb mass percentage of FR4board")
        Dependency "Presistor_pcb"
            (ConnectedTo "Projector pcb mass percentage of resistors")
        Dependency "Pconnector_pcb"
            (ConnectedTo "Projector pcb mass percentage of connectors")
        Dependency "Pratio_area_mass"
            (ConnectedTo "Projector pcb surface processed area/mass")
        Dependency "Pgallium_arsenide_pcb"
            (ConnectedTo "Projector pcb mass percentage of AsGa components")
        Dependency "Pcoil_pcb"
            (ConnectedTo "Projector pcb mass percentage of coils")
        Dependency "steel_power_supply"
            (ConnectedTo "Power supply mass percentage of steel")
        Dependency "heatsinks_power_supply"
            (ConnectedTo "Power supply mass percentage of heatsinks")
        Dependency "transformers_power_supply"
            (ConnectedTo "Power supply mass percentage of transformers")
        Dependency "PC_power_supply"
            (ConnectedTo "Power supply mass percentage of plastic PC")
        Dependency "ratio_transformer_mass"
            (ConnectedTo "Power supply transformer/mass ratio")
        Dependency "ratio_heatsink_mass"
            (ConnectedTo "Power supply heatsink/mass ratio")
    )
)

```

Dependency "PC_shielding"
 (ConnectedTo "Shielding mass percentage of plastic PC")
 Dependency "aluminum_shielding"
 (ConnectedTo "Shielding mass percentage of aluminum")
 Dependency "ABS_fan"
 (ConnectedTo "Fan mass percentage of plastic ABS")
 Dependency "copper_fan"
 (ConnectedTo "Fan mass percentage of copper")
 Dependency "steel_fan"
 (ConnectedTo "Fan mass percentage of steel")
 Dependency "FR4_fan"
 (ConnectedTo "Fan mass percentage of FR4board")
 Dependency "fan_board_ratio_area_mass"
 (ConnectedTo "Fan FR4board area/mass ratio")
 Dependency "ABS_remote"
 (ConnectedTo "Remote mass percentage of plastic ABS")
 Dependency "silicon_rubber_remote"
 (ConnectedTo "Remote mass percentage of silicon rubber")
 Dependency "pcb_remote"
 (ConnectedTo "Remote mass percentage of pcb")
 Dependency "batteries"
 (ConnectedTo "Remote mass percentage of batteries")
 Dependency "%_recycled_batteries"
 (ConnectedTo "Remote percent recycled batteries")
 Dependency "Rratio_resistor_mass"
 (ConnectedTo "Remote pcb resistor/mass ratio")
 Dependency "Rpcb_board_ratio_area_mass"
 (ConnectedTo "Remote pcb area/mass ratio")
 Dependency "Rratio_AsGa_mass"
 (ConnectedTo "Remote pcb AsGa component/mass ratio")
 Dependency "Rcapacitor_pcb"
 (ConnectedTo "Remote pcb mass percentage of capacitors")
 Dependency "Rintegrated_circuit_pcb"
 (ConnectedTo "Remote pcb mass percentage of integrated circuits")
 Dependency "RFR4_pcb"
 (ConnectedTo "Remote pcb mass percentage of FR4board")
 Dependency "Rresistor_pcb"
 (ConnectedTo "Remote pcb mass percentage of resistors")
 Dependency "Rconnector_pcb"
 (ConnectedTo "Remote pcb mass percentage of connectors")
 Dependency "Rratio_area_mass"
 (ConnectedTo "Remote pcb surface processed area/mass")
 Dependency "Rgallium_arsenide_pcb"
 (ConnectedTo "Remote pcb mass percentage of AsGa components")
 Dependency "Rcoil_pcb"
 (ConnectedTo "Remote pcb mass percentage of coils")
 Dependency "Rratio_coil_mass"
 (ConnectedTo "Remote pcb coil/mass ratio")
 Dependency "Rratio_connector_mass"
 (ConnectedTo "Remote pcb connector/mass ratio")
 Dependency "Rratio_ic_mass"
 (ConnectedTo "Remote pcb integrated circuits/mass ratio")
 Dependency "Rratio_capacitor_mass"
 (ConnectedTo "Remote pcb capacitor/mass ratio")
 Dependency "aluminum_lenses"
 (ConnectedTo "Lenses mass percentage of aluminum")
 Dependency "ABS_lenses"
 (ConnectedTo "Lenses mass percentage of plastic ABS")
 Dependency "glass_lenses"
 (ConnectedTo "Lenses mass percentage of glass")
 Dependency "epoxy_light_engine"
 (ConnectedTo "Light engine mass percentage of epoxy")
 Dependency "glass_light_engine"
 (ConnectedTo "Light engine mass percentage of glass")
 Dependency "halide_light_engine"
 (ConnectedTo "Light engine mass percentage of halide")
 Dependency "ceramic_light_engine"
 (ConnectedTo "Light engine mass percentage of ceramic")
 Dependency "plastic_PC_light_engine"
 (ConnectedTo "Light engine mass percentage of plastic PC")
 Dependency "steel_light_engine"

```

        (ConnectedTo "Light engine mass percentage of steel")
Dependency "aluminum_light_engine"
        (ConnectedTo "Light engine mass percentage of aluminum")
Dependency "PI_flex"
        (ConnectedTo "Flex interconnects mass percentage of PI")
Dependency "PVC_cables"
        (ConnectedTo "Cables mass percentage of PVC")
Dependency "copper_cables"
        (ConnectedTo "Cables mass percentage of copper")
Dependency "ratio_speaker_mass"
        (ConnectedTo "Speaker/mass ratio")
Dependency "plastic_housing"
        (ConnectedTo "Housing mass percentage of plastic")
Dependency "steel_housing"
        (ConnectedTo "Housing mass percentage of steel")
Dependency "rubber_housing"
        (ConnectedTo "Housing mass percentage of rubber")
Dependency "type_plastic"
Dependency "ABS_disposal_method"
Dependency "ABS_%_recycled"
        (ConnectedTo "Housing percent ABS recycled")
Dependency "ABS_%_incinerated"
        (ConnectedTo "Housing percent ABS incinerated")
Dependency "PS_disposal_method"
Dependency "PS_%_recycled"
        (ConnectedTo "Housing percent PS recycled")
Dependency "PS_%_incinerated"
        (ConnectedTo "Housing percent PS incinerated")
Dependency "PP_disposal_method"
Dependency "PP_%_recycled"
        (ConnectedTo "Housing percent PP recycled")
Dependency "PP_%_incinerated"
        (ConnectedTo "Housing percent PP incinerated")
Dependency "cables"
        (ConnectedTo "Projector mass of cables")
Dependency "light_engine"
Dependency "fan"
Dependency "pcb"
Dependency "lenses"
Dependency "shielding"
        (ConnectedTo "Projector mass of shielding")
Dependency "power_supply"
Dependency "speakers"
Dependency "housing"
Dependency "flex_inteconnects"
        (ConnectedTo "Projector mass of flex interconnects")
Dependency "remote_control"
        (ConnectedTo "Projector mass of remote control")
Dependency "power_consumption"
Dependency "mean_time_bf_in_sec"
        (ConnectedTo "Projector mean time before failure[sec]")
Dependency "use_location"
Dependency "%distribution_losses"
        (ConnectedTo "Percentage of losses in electricity distribution")
Dependency "%coal"
        (ConnectedTo "Percentage of coal in electricity production")
Dependency "%_lignite"
        (ConnectedTo "Percentage of lignite in electricity production")
Dependency "%oil"
        (ConnectedTo "Percentage of oil in electricity production")
Dependency "%gas"
        (ConnectedTo "Percentage of gas in electricity production")
Dependency "%nuclea"
        (ConnectedTo "Percentage of nuclear in electricity production")
Dependency "%hydr"
        (ConnectedTo "Percentage of hydro in electricity production")
)
Variable "Projector pcb coil/mass ratio"
(
    Beta { 3 3 180 220 }
)

```

```

Variable "Projector pcb area/mass ratio"
(
  Beta { 3 3 0.36 0.44 }
)
Variable "Projector pcb capacitor/mass ratio"
(
  Beta { 3 3 7500 9167 }
)
Variable "Projector pcb resistor/mass ratio"
(
  Beta { 3 3 3000 3667 }
)
Variable "Projector pcb AsGa component/mass ratio"
(
  Beta { 3 3 3000 3667 }
)
Variable "Projector pcb integrated circuits/mass ratio"
(
  Beta { 3 3 1800 2200 }
)
Variable "Projector pcb connector/mass ratio"
(
  Beta { 3 3 1125 1375 }
)
Variable "Projector pcb mass percentage of capacitors"
(
  Uniform { 0.0239 0.0359 }
)
Variable "Projector pcb mass percentage of integrated circuits"
(
  Uniform { 0.0398 0.0598 }
)
Variable "Projector pcb mass percentage of FR4board"
(
  Uniform { 0.6644 0.9966 }
)
Variable "Projector pcb mass percentage of resistors"
(
  Uniform { 0.0024 0.0036 }
)
Variable "Projector pcb mass percentage of connectors"
(
  Uniform { 0.0051 0.0077 }
)
Variable "Projector pcb surface processed area/mass"
(
  Beta { 3 3 0.36 0.44 }
)
Variable "Projector pcb mass percentage of AsGa components"
(
  Uniform { 0.00008 0.00012 }
)
Variable "Projector pcb mass percentage of coils"
(
  Uniform { 0.0637 0.0955 }
)
Variable "Power supply mass percentage of steel"
(
  Uniform { 0.304 0.456 }
)
Variable "Power supply mass percentage of heatsinks"
(
  Uniform { 0.032 0.048 }
)
Variable "Power supply mass percentage of transformers"
(
  Uniform { 0.416 0.624 }
)
Variable "Power supply mass percentage of plastic PC"
(
  Uniform { 0.048 0.072 }
)

```

```

)
Variable "Power supply transformer/mass ratio"
(
    Beta { 3 3 6.5 7.9 }
)
Variable "Power supply heatsink/mass ratio"
(
    Beta { 3 3 54.9 67.1 }
)
Variable "Shielding mass percentage of plastic PC"
(
    Uniform { 0.2 0.3 }
)
Variable "Shielding mass percentage of aluminum"
(
    Uniform { 0.6 0.9 }
)
Variable "Fan mass percentage of plastic ABS"
(
    Uniform { 0.64 0.96 }
)
Variable "Fan mass percentage of copper"
(
    Uniform { 0.024 0.036 }
)
Variable "Fan mass percentage of steel"
(
    Uniform { 0.12 0.18 }
)
Variable "Fan mass percentage of FR4board"
(
    Uniform { 0.016 0.024 }
)
Variable "Fan FR4board area/mass ratio"
(
    Beta { 3 3 0.36 0.44 }
)
Variable "Remote mass percentage of plastic ABS"
(
    Uniform { 0.416 0.624 }
)
Variable "Remote mass percentage of silicon rubber"
(
    Uniform { 0.04 0.06 }
)
Variable "Remote mass percentage of pcb"
(
    Uniform { 0.16 0.24 }
)
Variable "Remote mass percentage of batteries"
(
    Uniform { 0.184 0.276 }
)
Variable "Remote percent recycled batteries"
(
    Uniform { 0.08 0.12 }
)
Variable "Remote pcb resistor/mass ratio"
(
    Beta { 3 3 3000 3667 }
)
Variable "Remote pcb area/mass ratio"
(
    Beta { 3 3 0.36 0.44 }
)
Variable "Remote pcb AsGa component/mass ratio"
(
    Beta { 3 3 3000 3667 }
)
Variable "Remote pcb mass percentage of capacitors"
(

```

```

    Uniform { 0.0239 0.0359 }
  )
Variable "Remote pcb mass percentage of integrated circuits"
(
  Uniform { 0.0398 0.05976 }
)
Variable "Remote pcb mass percentage of FR4board"
(
  Uniform { 0.6644 0.9966 }
)
Variable "Remote pcb mass percentage of resistors"
(
  Uniform { 0.0024 0.0036 }
)
Variable "Remote pcb mass percentage of connectors"
(
  Uniform { 0.0051 0.0077 }
)
Variable "Remote pcb surface processed area/mass"
(
  Beta { 3 3 0.32 0.48 }
)
Variable "Remote pcb mass percentage of AsGa components"
(
  Uniform { 0.00008 0.00012 }
)
Variable "Remote pcb mass percentage of coils"
(
  Uniform { 0.0637 0.0955 }
)
Variable "Remote pcb coil/mass ratio"
(
  Beta { 3 3 150 183 }
)
Variable "Remote pcb connector/mass ratio"
(
  Beta { 3 3 1125 1375 }
)
Variable "Remote pcb integrated circuits/mass ratio"
(
  Beta { 3 3 1800 2200 }
)
Variable "Remote pcb capacitor/mass ratio"
(
  Beta { 3 3 7500 9167 }
)
Variable "Lenses mass percentage of aluminum"
(
  Uniform { 0.024 0.036 }
)
Variable "Lenses mass percentage of plastic ABS"
(
  Uniform { 0.128 0.192 }
)
Variable "Lenses mass percentage of glass"
(
  Uniform { 0.648 0.972 }
)
Variable "Light engine mass percentage of epoxy"
(
  Uniform { 0.0024 0.0036 }
)
Variable "Light engine mass percentage of glass"
(
  Uniform { 0.324 0.486 }
)
Variable "Light engine mass percentage of halide"
(
  Uniform { 0.0024 0.0036 }
)
Variable "Light engine mass percentage of ceramic"

```

```

(
    Uniform { 0.008 0.012 }
)
Variable "Light engine mass percentage of plastic PC"
(
    Uniform { 0.104 0.156 }
)
Variable "Light engine mass percentage of steel"
(
    Uniform { 0.048 0.072 }
)
Variable "Light engine mass percentage of aluminum"
(
    Uniform { 0.32 0.48 }
)
Variable "Flex interconnects mass percentage of PI"
(
    Uniform { 0.8 1 }
)
Variable "Cables mass percentage of PVC"
(
    Uniform { 0.24 0.36 }
)
Variable "Cables mass percentage of copper"
(
    Uniform { 0.56 0.84 }
)
Variable "Speaker/mass ratio"
(
    Beta { 3 3 171 210 }
)
Variable "Housing mass percentage of plastic"
(
    Uniform { 0.70 0.9 }
)
Variable "Housing mass percentage of steel"
(
    Uniform { 0.088 0.132 }
)
Variable "Housing mass percentage of rubber"
(
    Uniform { 0.008 0.012 }
)
Variable "Housing percent ABS recycled"
(
    Uniform { 0.72 0.88 }
)
Variable "Housing percent ABS incinerated"
(
    Uniform { 0.72 0.88 }
)
Variable "Housing percent PS recycled"
(
    Uniform { 0.72 0.88 }
)
Variable "Housing percent PS incinerated"
(
    Uniform { 0.72 0.88 }
)
Variable "Housing percent PP recycled"
(
    Uniform { 0.72 0.88 }
)
Variable "Housing percent PP incinerated"
(
    Uniform { 0.72 0.88 }
)
Variable "Projector mass of cables"
(
    Delta { 0.1763 }
)
)

```

```

Variable "Projector mass of shielding"
(
    Delta { 0.4368 }
)
Variable "Projector mass of flex interconnects"
(
    Delta { 0.0176 }
)
Variable "Projector mass of remote control"
(
    Uniform { 0.258 0.3154 }
)
Variable "Projector mean time before failure[hrs]"
(
    Beta { 3 3 2700 3300 }
)
SimVariable "Projector mean time before failure[sec]"
(
    Dependency "mean_time_bf"
    DefineUpdateFunction "updateProjectorMeanBeforeF"
    (
        output = mean_time_bfx3600;
    )
)
Variable "Percentage of losses in electricity distribution"
(
    Uniform { 0.063 0.077 }
)
Variable "Percentage of coal in electricity production"
(
    Uniform { 0.306 0.374 }
)
Variable "Percentage of lignite in electricity production"
(
    Uniform { 0.0009 0.0011 }
)
Variable "Percentage of oil in electricity production"
(
    Uniform { 0.09 0.11 }
)
Variable "Percentage of gas in electricity production"
(
    Uniform { 0.117 0.143 }
)
Variable "Percentage of nuclear in electricity production"
(
    Uniform { 0.234 0.286 }
)
Variable "Percentage of hydro in electricity production"
(
    Uniform { 0.126 0.154 }
)

Catalog "LCA-Connection"
(

Module "Faster"()
(
    "type_plastic" "type_plastic"
    "ABS_disposal_method" "ABS_disposal_method"
    "PS_disposal_method" "PS_disposal_method"
    "PP_disposal_method" "PP_disposal_method"
    "use_location" "use_location"
    "LCA-Connection" "LCA-Connection"
    "light_engine" "light_engine"
    "fan" "fan"
    "pcb" "pcb"
    "power_supply" "power_supply"
    "speakers" "speakers"
    "housing" "housing"
    "power_consumption" "power_consumption"
)
)

```

```

        "mean_time_bf" "mean_time_bf"
        "lenses" "lenses"
    )
Module "Detailed"()
(
    "type_plastic" "type_plastic"
    "ABS_disposal_method" "ABS_disposal_method"
    "PS_disposal_method" "PS_disposal_method"
    "PP_disposal_method" "PP_disposal_method"
    "use_location" "use_location"
    "LCA-Connection" "LCA-Connection"
    "light_engine" "light_engine"
    "fan" "fan"
    "pcb" "pcb"
    "power_supply" "power_supply"
    "speakers" "speakers"
    "housing" "housing"
    "power_consumption" "power_consumption"
    "mean_time_bf" "mean_time_bf"
    "lenses" "lenses"
)

```

C.2. Assessment catalog file

Catalog "Assessment"

```

(
    Module "CML"
    (
        Bootstrap "CML-Air" { 0 1000 }
        (
            Dependency "TEAM_Assessment"
        )
        Specification "CML-Air Spec"
        (
            SegmentedAF { 0 0 0 1 945 1 2362 0 }
        )
        Criterion "CML-Air Crit"
        (
            Bootstrap "CML-Air"
            Specification "CML-Air Spec"
        )

        Bootstrap "CML-Resources" { 1 1000 }
        (
            Dependency "TEAM_Assessment"
        )
        Specification "CML-Resources Spec"
        (
            SegmentedAF { 0 0 0 1 9e-10 1 5e-9 0 }
        )
        Criterion "CML-Resources Crit"
        (
            Bootstrap "CML-Resources"
            Specification "CML-Resources Spec"
        )

        Bootstrap "CML-Ozone-high" { 2 1000 }
    )
)

```

```

(
  Dependency "TEAM_Assessment"
)
Specification "CML-Ozone-high Spec"
(
  SegmentedAF { 0 0 0 1 0.108 1 0.27 0 }
)
Criterion "CML-Ozone-high Crit"
(
  Bootstrap "CML-Ozone-high"
  Specification "CML-Ozone-high Spec"
)

Bootstrap "CML-Ozone-low" { 3 1000 }
(
  Dependency "TEAM_Assessment"
)
Specification "CML-Ozone-low Spec"
(
  SegmentedAF { 0 0 0 1 0.064 1 0.16 0 }
)
Criterion "CML-Ozone-low Crit"
(
  Bootstrap "CML-Ozone-low"
  Specification "CML-Ozone-low Spec"
)

Bootstrap "CML-Eutrophication" { 4 1000 }
(
  Dependency "TEAM_Assessment"
)
Specification "CML-Eutrophication Spec"
(
  SegmentedAF { 0 0 0 1 2130 1 5324 0 }
)
Criterion "CML-Eutrophication Crit"
(
  Bootstrap "CML-Eutrophication"
  Specification "CML-Eutrophication Spec"
)

Bootstrap "CML-Eutrophication (water)" { 5 1000 }
(
  Dependency "TEAM_Assessment"
)
Specification "CML-Eutrophication (water) Spec"
(
  SegmentedAF { 0 0 0 1 41 1 102 0 }
)
Criterion "CML-Eutrophication (water) Crit"
(
  Bootstrap "CML-Eutrophication (water)"
  Specification "CML-Eutrophication (water) Spec"
)

Lens "Environment"
(
  Criterion "CML-Air Crit"
  Criterion "CML-Resources Crit"
  Criterion "CML-Ozone-high Crit"
  Criterion "CML-Ozone-low Crit"
  Criterion "CML-Eutrophication Crit"
  Criterion "CML-Eutrophication (water) Crit"
)

)
( "TEAM_Assessment" = "TEAM_Assessment" )

```

```

Module "CVCH"
(
  Bootstrap "CVCH-Air" { 6 1000 }
  (
    Dependency "TEAM_Assessment"
  )
  Specification "CVCH-Air Spec"
  (
    SegmentedAF { 0 0 0 1 1680000000 1 4.2e9 0 }
  )
  Criterion "CVCH-Air Crit"
  (
    Bootstrap "CVCH-Air"
    Specification "CVCH-Air Spec"
  )
)

  Bootstrap "CVCH-Water" { 7 1000 }
  (
    Dependency "TEAM_Assessment"
  )
  Specification "CVCH-Water Spec"
  (
    SegmentedAF { 0 0 0 1 160000 1 400000 0 }
  )
  Criterion "CVCH-Water Crit"
  (
    Bootstrap "CVCH-Water"
    Specification "CVCH-Water Spec"
  )
)

  Lens "Environment"
  (
    Criterion "CVCH-Air Crit"
    Criterion "CVCH-Water Crit"
  )
)
( "TEAM_Assessment" = "TEAM_Assessment" )
Module "EC"
(
  Bootstrap "EC(R)" { 8 1000 }
  (
    Dependency "TEAM_Assessment"
  )
  Specification "EC(R) Spec"
  (
    SegmentedAF { 0 0 0 1 0.216 1 0.54 0 }
  )
  Criterion "EC(R) Crit"
  (
    Bootstrap "EC(R)"
    Specification "EC(R) Spec"
  )
)

  Bootstrap "EC(RxY)" { 9 1000 }
  (
    Dependency "TEAM_Assessment"
  )
  Specification "EC(RxY) Spec"
  (
    SegmentedAF { 0 0 0 1 3406 1 8516 0 }
  )
  Criterion "EC(RxY) Crit"
  (
    Bootstrap "EC(RxY)"
    Specification "EC(RxY) Spec"
  )
)

  Bootstrap "EC(Y)" { 10 1000 }

```

```

(
    Dependency "TEAM_Assessment"
)
Specification "EC(Y) Spec"
(
    SegmentedAF { 0 0 0 1 11 1 28 0 }
)
Criterion "EC(Y) Crit"
(
    Bootstrap "EC(Y)"
    Specification "EC(Y) Spec"
)

Lens "Environment"
(
    Criterion "EC(R) Crit"
    Criterion "EC(RxY) Crit"
    Criterion "EC(Y) Crit"
)
)
( "TEAM_Assessment" = "TEAM_Assessment" )
Module "Ecopoints"
(
    Bootstrap "Ecopoints-Total" { 11 1000 }
    (
        Dependency "TEAM_Assessment"
    )

    Bootstrap "Ecopoints-Air" { 12 1000 }
    (
        Dependency "TEAM_Assessment"
    )
    Specification "Ecopoints-Air Spec"
    (
        SegmentedAF { 0 0 0 1 1704000 1 4260000 0 }
    )
    Criterion "Ecopoints-Air Crit"
    (
        Bootstrap "Ecopoints-Air"
        Specification "Ecopoints-Air Spec"
    )

    Bootstrap "Ecopoints-Energy & Waste" { 13 1000 }
    (
        Dependency "TEAM_Assessment"
    )
    Specification "Ecopoints-Energy & Waste Spec"
    (
        SegmentedAF { 0 0 0 1 5934 1 14834 0 }
    )
    Criterion "Ecopoints-Energy & Waste Crit"
    (
        Bootstrap "Ecopoints-Energy & Waste"
        Specification "Ecopoints-Energy & Waste Spec"
    )

    Bootstrap "Ecopoints-Water" { 14 1000 }
    (
        Dependency "TEAM_Assessment"
    )
    Specification "Ecopoints-Water Spec"
    (
        SegmentedAF { 0 0 0 1 1821 1 4552 0 }
    )
    Criterion "Ecopoints-Water Crit"
    (
        Bootstrap "Ecopoints-Water"

```

```

        Specification "Ecopoints-Water Spec"
    )
    Lens "Environment"
    (
        Criterion "Ecopoints-Air Crit"
        Criterion "Ecopoints-Energy & Waste Crit"
        Criterion "Ecopoints-Water Crit"
    )
)
("TEAM_Assessment" = "TEAM_Assessment")
Module "EPS"
(
    Bootstrap "EPS-Total" { 15 1000 }
    (
        Dependency "TEAM_Assessment"
    )

    Bootstrap "EPS-Air" { 16 1000 }
    (
        Dependency "TEAM_Assessment"
    )
    Specification "EPS-Air Spec"
    (
        SegmentedAF { 0 0 0 1 289 1 722 0 }
    )
    Criterion "EPS-Air Crit"
    (
        Bootstrap "EPS-Air"
        Specification "EPS-Air Spec"
    )

    Bootstrap "EPS-Land Use" { 17 1000 }
    (
        Dependency "TEAM_Assessment"
    )
    Specification "EPS-Land Use Spec"
    (
        SegmentedAF { 0 0 0 1 1 0 }
    )
    Criterion "EPS-Land Use Crit"
    (
        Bootstrap "EPS-Land Use"
        Specification "EPS-Land Use Spec"
    )

    Bootstrap "EPS-Metal Resources" { 18 1000 }
    (
        Dependency "TEAM_Assessment"
    )
    Specification "EPS-Metal Resources Spec"
    (
        SegmentedAF { 0 0 0 1 7283 1 18208 0 }
    )
    Criterion "EPS-Metal Resources Crit"
    (
        Bootstrap "EPS-Metal Resources"
        Specification "EPS-Metal Resources Spec"
    )

    Bootstrap "EPS-Non-renewable Energy" { 19 1000 }
    (
        Dependency "TEAM_Assessment"
    )
    Specification "EPS-Non-renewable Energy Spec"
    (
        SegmentedAF { 0 0 0 1 310 1 776 0 }
    )
)

```

```

)
Criterion "EPS-Non-renewable Energy Crit"
(
    Bootstrap "EPS-Non-renewable Energy"
    Specification "EPS-Non-renewable Energy Spec"
)

Bootstrap "EPS-Water" { 20 1000 }
(
    Dependency "TEAM_Assessment"
)
Specification "EPS-Water Spec"
(
    SegmentedAF { 0 0 0 1 0.00256 1 0.0064 0 }
)
Criterion "EPS-Water Crit"
(
    Bootstrap "EPS-Water"
    Specification "EPS-Water Spec"
)

Lens "Environment"
(
    Criterion "EPS-Air Crit"
    Criterion "EPS-Land Use Crit"
    Criterion "EPS-Metal Resources Crit"
    Criterion "EPS-Non-renewable Energy Crit"
    Criterion "EPS-Water Crit"
)
)
( "TEAM_Assessment" = "TEAM_Assessment" )
Module "ETH"
(
    Bootstrap "ETH-Air Acidification" { 21 1000 }
    (
        Dependency "TEAM_Assessment"
    )
    Specification "ETH-Air Acidification Spec"
    (
        SegmentedAF { 0 0 0 1 945 1 2362 0 }
    )
    Criterion "ETH-Air Acidification Crit"
    (
        Bootstrap "ETH-Air Acidification"
        Specification "ETH-Air Acidification Spec"
    )
)

Lens "Environment"
(
    Criterion "ETH-Air Acidification Crit"
)
)
( "TEAM_Assessment" = "TEAM_Assessment" )
Module "IPCC"
(
    Bootstrap "IPCC-Greenhouse Effect 100 years" { 22 1000 }
    (
        Dependency "TEAM_Assessment"
    )
    Specification "IPCC-Greenhouse Effect 100 years Spec"
    (
        SegmentedAF { 0 0 0 1 4320000 1 10800000 0 }
    )
    Criterion "IPCC-Greenhouse Effect 100 years Crit"
    (
        Bootstrap "IPCC-Greenhouse Effect 100 years"
        Specification "IPCC-Greenhouse Effect 100 years Spec"
    )
)

```

```

Bootstrap "IPCC-Greenhouse Effect 20 years" { 23 1000 }
(
  Dependency "TEAM_Assessment"
)
Specification "IPCC-Greenhouse Effect 20 years Spec"
(
  SegmentedAF { 0 0 0 1 4400000 1 11000000 0 }
)
Criterion "IPCC-Greenhouse Effect 20 years Crit"
(
  Bootstrap "IPCC-Greenhouse Effect 20 years"
  Specification "IPCC-Greenhouse Effect 20 years Spec"
)

Bootstrap "IPCC-Greenhouse Effect 500 years" { 24 1000 }
(
  Dependency "TEAM_Assessment"
)
Specification "IPCC-Greenhouse Effect 500 years Spec"
(
  SegmentedAF { 0 0 0 1 4320000 1 10800000 0 }
)
Criterion "IPCC-Greenhouse Effect 500 years Crit"
(
  Bootstrap "IPCC-Greenhouse Effect 500 years"
  Specification "IPCC-Greenhouse Effect 500 years Spec"
)

Lens "Environment"
(
  Criterion "IPCC-Greenhouse Effect 100 years Crit"
  Criterion "IPCC-Greenhouse Effect 20 years Crit"
  Criterion "IPCC-Greenhouse Effect 500 years Crit"
)
)
( "TEAM_Assessment" = "TEAM_Assessment" )
)

```

Appendix D. Survey

Methods for integrating Design-for-the-Environment with traditional product design

In the previous DOME projector demonstration, environmental impact assessment was:

- provided by linking to an analytical life-cycle model created by an environmental expert who uses a commercial life-cycle analysis program and database.
- performed in real time for each alternative explored by the designer using either a fast approximate model or a slower (10 minute response) detailed model.
- visualized using standard impact assessment criteria (e.g., EPS or Ecopoints) and quantitatively compared with benchmark performance goals.

An alternative approach for providing the designer with impact assessment is a qualitative matrix.

	Option A	Option B	Option C	Option D	Option E
Manufacturing	0	+	—	+	—
Environmental	0	—	0	+	0
Toxicity/exposure	0	+	+	—	0
Social/political	0	—	+	—	+

This summary matrix is derived from more detailed matrices for each concept like the manufacturing matrix below.

<i>Option A - Manufacturing</i>	Production	Consumer use	Disposal method	Summary
Process compatibility	0	+	0	+
Materials compatibility	0	—	—	—
Performance	0	—	0	—
Energy consumption	0	—	—	—
Resource consumption	0	++	0	+
Availability	0	0	0	0
Cost	0	0	0	0
Competitive implications	0	—	0	—
Environment of use	0	0	0	0

Using qualitative matrices, environmental impact assessment is:

- provided to the designer by an environmental expert.
- prepared in advance for key benchmark designs; designers use the results to obtain insight and guide the exploration of new options (other than the benchmark designs).
- visualized with a qualitative summary matrix.

Your Job Description: _____

Please indicate your agreement with the following statements.

1. The tool allows me to assess whether a particular design alternative will meet environmental design goals.

DOME model strongly agree ___ agree ___ disagree ___ strongly disagree ___ not sure ___
Qualitative matrix strongly agree ___ agree ___ disagree ___ strongly disagree ___ not sure ___

Please provide a brief explanation if you feel one is needed:

2. Using the tool, I will be able to quickly trade off in environmental performance with other requirements, such as cost or customer preferences.

DOME model strongly agree ___ agree ___ disagree ___ strongly disagree ___ not sure ___
Qualitative matrix strongly agree ___ agree ___ disagree ___ strongly disagree ___ not sure ___

Please provide a brief explanation if you feel one is needed:

3. The tool would be convenient to use when I am designing or making a decision.

DOME model strongly agree ___ agree ___ disagree ___ strongly disagree ___ not sure ___
Qualitative matrix strongly agree ___ agree ___ disagree ___ strongly disagree ___ not sure ___

Please provide a brief explanation if you feel one is needed:

4. The tool is likely to provide me with correct information.

DOME model strongly agree ___ agree ___ disagree ___ strongly disagree ___ not sure ___
Qualitative matrix strongly agree ___ agree ___ disagree ___ strongly disagree ___ not sure ___

Please provide a brief explanation if you feel one is needed:

5. I would be willing to make an important decision using results from the tool.

DOME model strongly agree ___ agree ___ disagree ___ strongly disagree ___ not sure ___
Qualitative matrix strongly agree ___ agree ___ disagree ___ strongly disagree ___ not sure ___

Please provide a brief explanation if you feel one is needed:

6. The tool will help me make the best decision.

DOME model strongly agree ___ agree ___ disagree ___ strongly disagree ___ not sure ___
 Qualitative matrix strongly agree ___ agree ___ disagree ___ strongly disagree ___ not sure ___

Please provide a brief explanation if you feel one is needed:

7. The tool would allow me to work and make decision faster.

DOME model strongly agree ___ agree ___ disagree ___ strongly disagree ___ not sure ___
 Qualitative matrix strongly agree ___ agree ___ disagree ___ strongly disagree ___ not sure ___

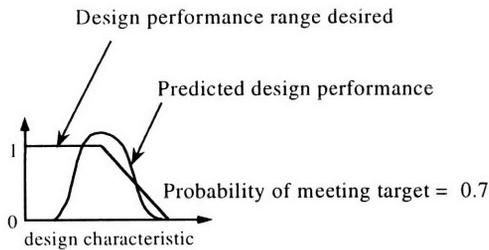
Please provide a brief explanation if you feel one is needed:

8. I think designers would use the tool.

DOME model strongly agree ___ agree ___ disagree ___ strongly disagree ___ not sure ___
 Qualitative matrix strongly agree ___ agree ___ disagree ___ strongly disagree ___ not sure ___

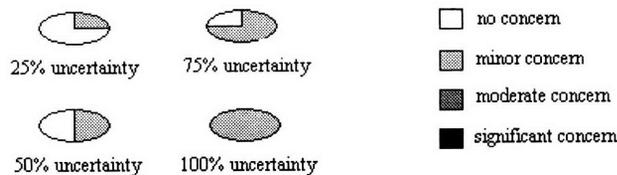
Please provide a brief explanation if you feel one is needed:

In the DOME model, simulation techniques are used to provide distributions for possible outcomes:



In qualitative matrices, symbols for uncertainty can be incorporated as illustrated below.

	Option A	Option B	Option C	Option D	Option E
Manufacturing	0	+	-	+	-
Environmental	0	-	0	+	0
Toxicity/exposure	0	+	+	-	0
Social/political	0	-	+	-	+



9. Making uncertainty explicit is important.

strongly agree ____ agree ____ disagree ____ strongly disagree ____ not sure ____

Please provide a brief explanation if you feel one is needed:

10. The visualization of uncertainty is useful for its interpretation and use in making decisions.

strongly agree ____ agree ____ disagree ____ strongly disagree ____ not sure ____

Please provide a brief explanation if you feel one is needed:

11. The tool provides a helpful visualization of uncertainty for making decisions.

DOME model strongly agree ____ agree ____ disagree ____ strongly disagree ____ not sure ____

Qualitative matrix strongly agree ____ agree ____ disagree ____ strongly disagree ____ not sure ____

Please provide a brief explanation if you feel one is needed:

Appendix E. Statistics for the survey analysis

Statements	Mean	Standard error	T Stat	Confidence level (90%)	Confidence interval (90%)
1	0.62	0.30	2.05	0.55	0.355 ± 0.302
2	1.00	0.33	3.00	0.61	0.778 ± 0.156
3	0.52	0.16	3.22	0.29	0.555 ± 0.327
4	0.20	0.25	0.80	0.46	0.111 ± 0.484
5	0.50	0.37	1.34	0.68	0.222 ± 0.516
6	0.70	0.39	1.77	0.72	0.444 ± 0.628
7	0.65	0.30	2.16	0.55	0.667 ± 0.620
8	0.60	0.40	1.50	0.73	0.333 ± 0.620
9	1.40	0.16	8.57	0.30	1.333 ± 0.310
10	1.00	0.15	6.71	0.27	1.000 ± 0.310
11	0.60	0.30	1.96	0.56	0.555 ± 0.628

Appendix F. Factor analysis

The factor analysis was conducted using STATA[®]. The outputs obtained are listed below.

```
Factor q1 q2 q3 q4 q5 q6 q7 q8 q9 q10 q11
(obs=10)
(collinear variables specified)
```

(principal factors; 9 factors retained)

Factor	Eigenvalue	Difference	Proportion	Cumulative
1	5.13797	2.93848	0.4671	0.4671
2	2.19949	0.83738	0.2000	0.6670
3	1.36211	0.27286	0.1238	0.7909
4	1.08925	0.52406	0.0990	0.8899
5	0.56519	0.22601	0.0514	0.9413
6	0.33918	0.14822	0.0308	0.9721
7	0.19097	0.11380	0.0174	0.9895
8	0.07717	0.03851	0.0070	0.9965
9	0.03866	0.03866	0.0035	1.0000
10	0.00000	0.00000	0.0000	1.0000
11	-0.00000	.	-0.0000	1.0000

Variable	Factor Loadings					
	1	2	3	4	5	6
q1	0.80281	-0.33107	0.02275	0.37730	0.24072	0.02203
q2	0.86748	0.04087	0.33319	-0.22557	-0.01131	-0.12448
q3	0.38172	0.74269	0.03822	-0.42947	-0.30528	-0.00008
q4	0.11443	0.27607	0.58126	0.71420	-0.23282	0.06684
q5	0.94154	-0.20339	0.06201	0.03820	-0.04700	-0.04895
q6	0.93814	-0.28475	-0.08298	-0.03981	-0.02923	-0.08670
q7	0.46882	0.76248	-0.18973	0.24880	-0.06773	-0.26288
q8	0.86009	-0.45231	0.00372	-0.16398	-0.03589	-0.09362
q9	0.83300	0.15289	-0.18248	-0.04571	-0.12194	0.47478
q10	0.40227	0.68067	-0.36092	0.10943	0.47229	0.04318
q11	0.01674	0.25556	0.83723	-0.30917	0.33594	0.06051

Variable	Factor Loadings			Uniqueness
	7	8	9	
q1	-0.19983	0.05675	-0.03775	0.00000
q2	-0.23016	-0.11769	-0.03825	0.00000
q3	-0.12173	0.07298	0.05876	0.00000
q4	-0.00928	0.03284	0.05401	-0.00000
q5	0.16943	-0.16738	0.07417	0.00000
q6	0.10955	0.09966	-0.00652	0.00000
q7	0.13006	0.00228	-0.10158	0.00000
q8	0.05365	0.11850	0.04222	0.00000
q9	0.05492	-0.01724	-0.06114	0.00000
q10	-0.02451	-0.00059	0.08429	0.00000
q11	0.13798	0.03741	-0.03027	-0.00000