

Modeling Time-dependent Resource Flows in a Product's Life-cycle
Integrating environmental and traditional design considerations

by

Paul Jackson

B.S., Mechanical Engineering

University of the Witwatersrand, Johannesburg, South Africa, 1994

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

at the


Massachusetts Institute of Technology

September 1997

© 1997 Massachusetts Institute of Technology
All rights reserved

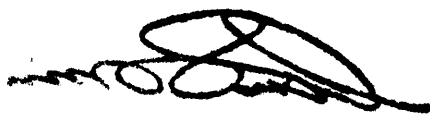
Signature of Author  Department of Mechanical Engineering
August 8, 1997

Certified by Esther and Harold E. Edgerton Assistant Professor of Mechanical Engineering
David Wallace
Thesis Supervisor

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

JAN 06 1998

LIBRARIES

A handwritten signature in black ink, consisting of several overlapping loops and a long horizontal stroke at the bottom.

Abstract

The integrated design of products requires that tradeoffs be made between many design requirements. Environmental and health impacts resulting from the production, use, recycling and disposal of consumer products are increasingly perceived as a product design issue. As a result, there has been a concerted research effort to develop procedures and tools to quantify environmental impact. This effort has focused on assessing the effects of products and their predefined life-cycles using static inventory data. However, environmental impact is often dependent upon time-dependent factors such as emission rates and material concentrations.

A method has been developed for calculating the time-dependent resource flows required to meet the demand placed on a product's life-cycle. The approach defines a generalized process module which is used to model the various components of a product's life-cycle network. Mathematical models are embedded within the process module to specify the relationship between its input and output flows. Numerical simulation is used to calculate the resource flows throughout a life-cycle network in response to a user-specified demand function. The generality of the process module allows sections of a network to be embedded within larger modules, thus facilitating the re-use of network sections in other product life-cycles. An example is presented to illustrate the implementation of the model and to validate its operation.

The research presented is part of an ongoing effort to develop a framework for integrated product design. A second example shows the use of this framework to create an integrated tool to design enclosures for electronic components. The modularized design tool considers electromagnetic radiation, heat transfer, environmental impact, cost and geometric interference in the evaluation of the enclosure. In addition to investigating the relationships inherent in the problem, the tool is used to optimize the design.

The modular life-cycle method is intended to be integrated into this type of design tool. However, limitations in the current implementation prevent it from being fully utilized. Suggestions are provided for future work which will increase the flexibility of the life-cycle implementation and expand its application as a design tool.

Acknowledgments

There are many people who have contributed to the development of this thesis.

First of all, my appreciation goes to my supervisor, Professor David Wallace, for his guidance and support throughout my time at MIT. His constructive criticism and persistent example have taught me many lessons which I will carry with me long after the completion of the research presented here.

My thanks to the Alliance for Global Sustainability for the funding of this research work.

I would like to thank those people who assisted in the conceptual development of the methods presented:

To Matthew Wall of the Mechanical Engineering Department at MIT, Andreas Moller of Hamburg GmbH and Frank Field III of the MIT Material Systems Laboratory who provided valuable input and constructive criticism for the work on product life-cycle modeling.

To Richard Schulz of the Boeing Company, Bill Hoffmann of Motorola and Mark Jarowoski of the United Technologies Research Center for their input into the electromagnetic shielding models used in the enclosure design problem.

Many thanks to Suzanne Weiner of the MIT Engineering Library for her assistance in compiling the literature used in this work.

Special thanks to my friends here in Boston and particularly to Amy Black and Adam Polcyn for walking many an "extra mile" alongside me. Their faithful comradeship and constant energy have helped me to maintain a balance to life which has made the journey thoroughly worthwhile. Special thanks also go to my colleagues in the MIT CADLab: Nicholas Borland, Jun Beom Kim, Kontong Pahng and Nicola Senin. This thesis is a tribute to the many hours we spent together in front of the computer terminal.

Finally, my deepest gratitude goes to my friends and family scattered around the globe and especially to my parents: David and Heidi, and my siblings: Helen, Ingrid and Michael. Your unwavering love and encouragement mean far more to me than my words could ever express. Thank you.

Psalm 121

A song of ascents.

I lift up my eyes to the hills-- where does my help come from?
My help comes from the LORD, the Maker of heaven and earth.
He will not let your foot slip-- he who watches over you will not slumber;
indeed, he who watches over Israel will neither slumber nor sleep.
The LORD watches over you-- the LORD is your shade at your right hand;
the sun will not harm you by day, nor the moon by night.
The LORD will keep you from all harm-- he will watch over your life;
the LORD will watch over your coming and going both now and forevermore.

Biography

Paul Jackson was born in Johannesburg, South Africa, on 10 May 1973.

His formal education was undertaken in Johannesburg at I. R. Griffith Primary School (1978-1985) and Hyde Park High School (1986-1990). He went on to complete a Bachelor of Science degree in Mechanical Engineering at the University of the Witwatersrand (WITS) in 1991 where he graduated *cum laude*. Among his awards at WITS, Paul received the Frederick Barnes Waldron Prize which is awarded "To the best student in final year Mechanical Engineering." At the end of each academic year he spent two months working at AECI (African Explosives and Chemical Industries) where he obtained practical engineering experience.

Balance has always been an important characteristic of Paul's life. He has consistently participated in extra-mural activities which have provided many opportunities to develop his inter-personal and leadership skills. At school he enjoyed being a member of many sports teams and cultural societies. As a Boy Scout he advanced to the level of Troop Leader and was awarded both the Springbok Scout and Chief Scout's Awards. He was also very active in his home church where he was involved in the leadership of a youth group for four years.

Upon completion of his undergraduate studies, Paul spent eight months touring in Europe and the USA before commencing his studies at the Massachusetts Institute of Technology (MIT) in Boston. He began his post-graduate studies in the MIT CADLab in September 1995. In addition to the courses which he has taken, he has carried out research work which resulted in the publishing of two papers:

- "An analytical method for integrating environmental and traditional design considerations."
 - Accepted for publication in the Annals of CIRP, 1997.
- "A modular method for representing product life-cycles."
 - Accepted for publication in the proceedings of the ASME Design Engineering Technical Conferences, 1997.

This thesis summarizes the research performed and completes the requirements for his Master of Science degree in Mechanical Engineering at MIT.

The Rolling Stone

by Robert Service

To scorn all strife and to view all life with the curious eyes of a child.
From the plangent sea to the prairie, from the slum to the heart of the wild;
From the red-rimmed star to the speck of sand, from the vast to the greatly small.
For I know that the whole for the good is planned and I want to see it all.

Contents

1. Introduction	11
1.1 Research Scope.....	11
2. Review of Related Work	13
2.1 Recent Developments in Environmental Life-Cycle Assessment (LCA).....	13
2.2 Process Modeling and Simulation	14
2.3 DOME Software - Fundamental concepts and principles.....	15
2.3.1 Problem decomposition into modules.....	15
2.3.2 Defining a module's embedded model.....	16
2.3.3 Catalogs of modules: facilitating reuse	16
2.3.4 Evaluating a design's performance.....	17
2.3.5 Problem integration: connecting modules.....	18
2.3.6 Overall design evaluation and optimization	18
2.3.7 Model Definition Language: facilitating the rapid construction of DOME models ...	18
3. Modeling Concepts	19
3.1 Terminology	19
3.2 Defining a Generic Process Module.....	20
3.3 Defining the Interactions between Input and Output Flows	21
3.4 Representing Product Life-cycle Networks.....	23
3.5 Developing a "Pull-System"	24
4. Model Implementation and Validation	26
4.1 General Problem Description	26
4.2 Implementing the Generalized Process Module	27
4.2.1 Definition of the standard process module	27
4.2.2 Customizing the standard process module	29
4.2.3 Representing processes with multiple resource inputs.....	30
4.2.4 Including additional functionality - Balancing inputs to minimize cost.....	31
4.3 Implementing Supporting Modules.....	32
4.4 Interpreting Results	34
4.4.1 Step response (Steady-state).....	34
4.4.2 Periodic demand curve (Saw tooth function).....	36
4.4.3 Mixed demand curve	37

5. Integrated Design Example	39
5.1 Breaking Problem into Modules	39
5.2 Definition of Individual Processes.....	40
5.2.1 Electronic component.....	40
5.2.2 Electromagnetic (EM) shielding calculations	42
5.2.3 Heat transfer	43
5.2.4 Environmental impact assessment	44
5.3 Assembling the Integrated Model	45
5.4 Exploring the Enclosure Design Problem.....	45
5.5 Optimization.....	50
5.6 Incorporating Time-based Inventory Information.....	53
6. Conclusions	55
7. Future Work on the Representation of Product Life-cycles	56
7.1 Vector Mathematics in DOME	56
7.2 Developing Material-Specific Definitions of Process Modules.....	56
7.3 Developing Resource Modules	57
7.4 Compiling Data for the Modular Representation.....	58
7.5 Integrating Time-based Life-cycle Models and LCA Tools.....	58
8. References	59
Appendix A : Definition of Equations for Generalized Process Module.	62
Appendix B : Development of Electromagnetic Shielding Models.	65
Appendix C : Development of Heat Transfer Models.	74

List of Figures

Figure 1: A Simplified Motor Module - Interface and Embedded Model.	15
Figure 2: Embedded Relationships between Parameters.....	16
Figure 3: Partial Engineering Material Catalog.....	16
Figure 4: Acceptability-based Evaluation.	17
Figure 5: Battery Modules (Interchangeable with respect to the motor module).	18
Figure 6. External View of the Generic Process Module.....	20
Figure 7. Schematic Representation of the Basic Process Module.....	22
Figure 8. Modular Representation of a Generic Product Life-cycle Network.....	23
Figure 9. Flow Chart Representing the Information Flow for a “Pull System”.	24
Figure 10. Schematic Representation of the Generalized Process Module.	25
Figure 11. Modular Representation of a Generic Product Life-cycle Network.	26
Figure 12. Implementation of the Product Life-cycle Network.....	27
Figure 13: Visualization of the Generalized Process Module in DOME.....	28
Figure 14: Visualization of the Assembly Module (Multiple Resource Inputs).	30
Figure 15: Generalized Process Module with Cost-related Parameters.....	31
Figure 16: Clock Module Visualization (Controls the time-based numerical simulation).32	
Figure 17: Graphical Representation of the User Module.....	33
Figure 18: Visualization of Support Modules for Product Life-cycle Network.	33
Figure 19: Response of the Network to a Unit Step in the Overall Demand.	34
Figure 20: Comparison of New Input Required for different Recycling Potentials.....	35
Figure 21: Response of the Network to a Periodic Demand Curve (Saw Tooth).	36
Figure 22: Effect of Recycling on the New Inputs Required (Periodic Demand Curve).36	
Figure 23: Comparison of the Network’s Total Demand and Total Product Flow.....	37
Figure 24: Response of the Network to a Mixed Demand Curve.	37
Figure 25: Effect of Recycling on the New Inputs Required (Mixed Demand Curve)...	38
Figure 26: Enclosure for Computer Components.....	39
Figure 27: Contents of a Module Representing an Electronic Component.....	40
Figure 28: Probabilistic Data for the Component’s Operating Temperature.....	41
Figure 29: Component’s Evaluation Lens.	41
Figure 30: DOME Representation of the Module for EM Shielding Calculations.	42
Figure 31: DOME Representation of the Heat Transfer Module	43

Figure 32: Environment Module and Evaluation Lens.....	44
Figure 33: Integrated Enclosure Design Tool.	45
Figure 34: Design Visualization: Steel Enclosure.	46
Figure 35: Catalog Browser for Enclosure Materials.....	47
Figure 36: Enclosure Design: Plastic Enclosure (ABS).....	47
Figure 37: Enclosure Design: Plastic Enclosure (ABS) with Zinc Coating.	48
Figure 38: Component Lens Summary: ABS with Zinc Coating - Open Vent removed.	49
Figure 39: Enclosure Design: ABS with Zinc Coating and Fan - Open Vent removed... ..	49
Figure 40: Component Lens Summary: ABS with Zinc Coating, Fan and Open Vent.	50
Figure 41: DOME Optimization Interface: Enclosure Design Problem.....	51
Figure 42: Optimized Enclosure Design.....	52
Figure 43: Integrated Design Example including Production Module.	53
Figure 44: Product Life-cycle Network for Zinc-coated Plastic Enclosure.....	54
Figure 45: 3-D Process-material Interaction Matrix.	58
Figure 46: Transmission of EM Radiation through a Single Layer of Material.	67
Figure 47: Derivation of Multiple-layer Equations.	69
Figure 48: Comparison of Shielding Effectiveness values from Different Models.	72
Figure 49: Absorption and Reflection values from Different Models.	73

List of Tables

Table 1. Average Process Performance Parameters.....	21
Table 2: Parameter Categorization for the Generalized Process Module.....	28
Table 3: Performance Parameters for Hypothetical Plastic Molding Process.....	29
Table 4: Steady-state Response Values for the Resource Supply Chains.	35
Table 5: Modular Decomposition of the Enclosure Design Problem.....	39
Table 6. Definition of Variables for Embedded Equations.	62
Table 7: Variables for Shielding Effectiveness Calculations.	65
Table 8: Aperture Equations - The Effect of Apertures on Shielding Effectiveness.	68
Table 9: Material Constants for Assessment of Multiple-layer Models.....	71
Table 10: Variables for Heat Transfer Calculations.....	74
Table 11: Derived Geometric Variables for Heat Transfer Calculations.	75
Table 12: Equations for Thermal Resistance Calculations.....	75

1. Introduction

The integrated design of products requires that tradeoffs be made between many design requirements (including safety, performance, economic, environmental and social factors). Qualitative approaches for modeling various aspects have had a positive impact on product design. However, these approaches may neglect interactions with other design considerations that are important to making good decisions. It is therefore necessary to develop tools which allow designers to rapidly model, evaluate and optimize design problems subject to multiple criteria.

The environmental and health impacts resulting from the life-cycle of consumer products (production, use, recycling and disposal) are increasingly perceived as a product design issue to be integrated into traditional design procedures [1]. As a result, there has been a concerted research effort to develop procedures and tools to quantify environmental impact. This effort has focused on assessing the effects of static resource flows resulting from products and their predefined life-cycle networks. However, environmental impact is often affected by the time-dependent nature of resource flows. This is especially true in the area of toxicology where emission rates and material concentrations are critical factors [2, 3]. This concern is addressed in this thesis by presenting a method for quantifying the resource flows related to a product's life-cycle as a function of time. While existing environmental impact assessment tools are not able to take advantage of this level of information, we believe that it will become an important issue as research efforts in the related fields of study progress.

In order for environmental assessment tools to be useful for design purposes, it is necessary for designers to be able to change parts of a product's life-cycle network to consider production alternatives. The approach presented has a modular structure which is compatible with this type of manipulation, though addition work is required before this functionality can be achieved. A number of conceptual suggestions have been included in chapter 7 to assist in the future implementation of a fully modular system.

1.1 Research Scope

The research presented is part of an ongoing effort to develop an integrated product design framework for modeling and balancing tradeoffs between a diverse range of design requirements. The background for this effort is described in previous publications [4-9] and summarized in section 2.3 as part of the *Review of Related Work*. The framework is realized in the form of DOME software (Distributed Object-based Modeling Environment) which will be used in sections 4 and 5 for the implementation and visualization of the examples presented. However, the modeling concepts described are independent of the implementation framework used.

The approach presented is for modeling product life-cycle networks to create time-dependent inventories for use in environmental impact assessment. A network is constructed by combining modules which represent the processes involved in the product's complete life-cycle. The relationship between a process' input and output resource flows is defined in terms of a generalized process module and its embedded mathematical model. By adjusting the performance parameters which characterize the embedded model, the generalized process module can replicate the average performance of a large variety of processes. The user specifies the required output from the network as a function of time (product demand) and a numerical simulation calculates the necessary time-dependent flows throughout the network. The modular life-cycle definition facilitates the integration of environmental and traditional design considerations in the evaluation of alternative design scenarios.

Chapter 2 contains an overview of the work being done in related fields of research. The theoretical development of the product life-cycle model is presented in chapter 3 while the implementation and validation of the model are covered in chapter 4 by way of an example. A second example is provided in chapter 5 to illustrate the use of DOME for creating an integrated tool for designing enclosures for electronic components. Following the conclusion in chapter 6, a number of suggestions are presented for future work in chapter 7. The appendices contain the details of the mathematical models used in the implementation of the generalized process module and the modules contained in the enclosure design example.

2. Review of Related Work

The work presented in this thesis covers a wide range of inter-related fields of research. This section contains a summary of the related research being done in the following key areas:

1. The development of quantitative environmental impact assessment techniques.
2. The principles associated with process modeling and simulation.
3. An overview of the underlying principles behind the development of DOME software.

2.1 Recent Developments in Environmental Life-Cycle Assessment (LCA)

There have been many developments in methods and tools for environmentally-conscious design. Alting, Fiksel and Graedel *et al.* [10-12] provide good overviews of the relevant issues and existing techniques.

Methods for assessing environmental impact are being developed in the form of techniques for life-cycle assessment (LCA). The first component of an LCA, referred to as the *inventory analysis stage*, aims to define the overall flow of resources related to a product life-cycle [12]. This should include: extraction, manufacture, assembly, usage, recovery, recycling and disposal. In principle, the cascading of alternative re-use options should also be considered but this is generally not included in the scope of an LCA. In practice, the effects of cascading are accounted for using impact allocation techniques [2]. Life-cycle assessment also involves identifying impacts resulting from specific flows (*impact analysis*) and determining the action to be taken (*improvement analysis*) [13]. Both of these stages involve considerable uncertainty, making them very difficult to address.

As the principles of life-cycle assessment have matured, a large number of software tools have been developed to implement the resulting methodologies. A report compiled for the Hazardous Waste Branch of Environment Canada evaluates 37 environmental assessment tools currently under development [14]. Such tools include: Simapro (PRe Consultants), TEAMTM [15], Umberto [16] and IDEMAT [15]. These tools differ significantly in terms of: their ease of use, the scope of problems they can address, the quantity and quality of data provided and the impact valuation method incorporated.

Current inventory analysis tools generally view resource flows as being constant or static, implying that the rate of flow through a product's life-cycle network does not change with time. This approach is sufficient for many situations, such as mass-production processes whose demand remains unchanged over long periods of time. However, there are situations where product demand will display pronounced variability over time. This can be due to a product's seasonal nature, its marketable life-cycle [17] or its reliability characteristics [18]. Process degradation and improvement also produce time-dependent effects. These factors exhibit considerable levels of uncertainty in their prediction. Nevertheless, records of process history could be used to develop statistical process models which change as a function of time. Finally, much of the environmental impact from products manufactured today, will only be realized when the products are disposed of some time in the future. The prediction of these impacts is very difficult to quantify but almost certainly relies on the estimation of future material and waste flows and can potentially be modeled by means of uncertain time-dependent evaluation models. Thus, it is important to model time-dependent material flow dynamics.

Another issue pertinent to predicting material flows in product design is the ability to modify life-cycle networks and explore alternatives. While some of the existing approaches have the potential to consider the supply of the same resource from different vendors, they do not allow the user to change resources or processes without manually defining the effect of these changes on the rest of the network. Thus, a separate network must be created for each design configuration. As a result, it can be difficult to use these tools during the product development design phase. One way to address this issue is to modularize the definition of product life-cycle networks. This could allow designers to substitute sections of product life-cycle without needing to redefine the rest of the network. The model developed in chapter 3 is compatible with this type of modular network definition though it does not fully implement this flexibility. A number of suggestions are provided in chapter 7 which are considered to be essential to complete the required modular definition.

2.2 Process Modeling and Simulation

The modeling approach adopted in this research is suitable for providing a functional representation of manufacturing processes and networks. Its goal is the realization of a modular representation for product life-cycles and the calculation of the input and output resource flows needed to meet a specified product demand as a function of time.

In order to characterize and control a physical system it is necessary to observe, model and predict its performance. There are numerous well-defined mathematical techniques which have been developed for this purpose. Ogunnaike and Ray [19] provide an overview of techniques available for modeling and controlling process dynamics. While their focus is predominantly on chemical processes, the methods described can be generally applied to dynamic systems. They divide the techniques into four groups, based on the form of the resulting mathematical models, viz.: differential equations (state space), transfer functions, frequency response functions and impulse response functions. Systems are further characterized as continuous or discrete and as linear or non-linear. There are comparable techniques for analyzing both discrete and continuous systems and it is possible to switch between domains using Laplace and z-transformations. For non-linear systems, there are a limited number of techniques available, viz.: rigorous analytical solution, linearization (by variable transformation or approximation) or numerical solution (computer simulation).

The research presented here is concerned with modeling manufacturing networks for computer implementation. Although these systems are generally continuous and non-linear, it is possible to derive a linearized mathematical model to represent the behavior of an entire network. However, to facilitate the interchange of alternative network sections, it is desirable to modularize the system model. It is therefore appropriate to model each process in isolation, as a set of difference equations (in discrete time). While the equations for each of the system's modules are defined separately they can be solved concurrently using computer simulation, which is a widely used tool in the manufacturing industry [20].

Alternative approaches for modeling this type of system include: Petri-Nets and applications of Living Systems Theory. The method of Petri-Nets (and Time-based Petri-Nets) is a graphical technique for representing systems with sequential dependency, such as manufacturing networks [21, 22]. It provides a "front-end" for the numerical solution of a system of difference equations. The concepts behind the method presented are similar to those for Petri-Nets but with a focus on the modularization of the system model. Living Systems Theory (LST) was originally developed as a method for modeling the hierarchical structure of biological systems [23]. It has since been adapted for use in modeling of non-living systems [24]. LST characterizes the members of any system in terms of 20 predefined subsystems. However, the increased complexity associated with LST's flexibility is not required for describing manufacturing processes at the level adopted here.

2.3 DOME Software - Fundamental concepts and principles

DOME (Distributed, Object-based Modeling Environment) is a software design tool being developed in the MIT CADLab. The theory and principles behind this framework are summarized here to assist in understanding the software implementations presented throughout this thesis. The underlying concepts appear in previous publications which can be consulted for further information [4-9].

2.3.1 Problem decomposition into modules

One of the first steps in solving a complex problem is to subdivide it into manageable segments. Traditionally, procedural design sequences have been developed to manage complexity. When problems are tackled in this manner, tasks are performed in a prioritized sequence with one step being completed before proceeding to the next. The problem with this approach is that later steps are constrained by earlier decisions and the only way to alter a previous decision is to carry out iterations of the design sequence. This can result in time delays and local sub-optimal solutions. Specialized design tools are often created to mirror these design procedures. However, it is very difficult to reuse or generalize these tools for new, related design problems. This is problematic from the integrated life-cycle design perspective as it is probably not feasible to create new specialized models and tools for every design problem.

In DOME, the design problem is divided into a set of *modules* which each describe a conceptually separate part of the problem. This decomposition allows for specific sections of the problem to be modeled by people with the relevant expertise. Each module can be regarded as a “black box” representing a specific aspect of a design. Modules have embedded models, which may include data, relations (mathematical models) and even complete software programs. A module may also contain design requirements which characterize its own design viewpoint. Modules are visible to each other through a standardized *interface*, as illustrated in Figure 1.

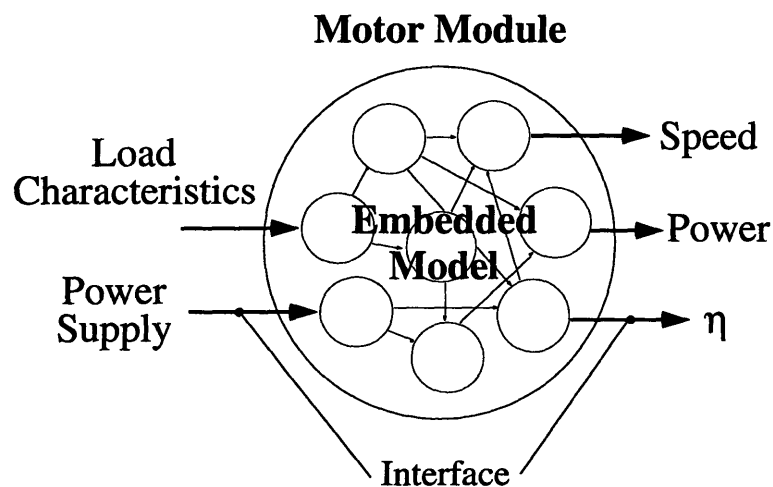


Figure 1: A Simplified Motor Module - Interface and Embedded Model.

2.3.2 Defining a module's embedded model

The modeling framework allows the definition of parameters and relations using a graph network. Both deterministic (exact) and probabilistic (uncertain) quantities may exist in a given problem. The framework provides the same capabilities as a programming language for defining mathematical relations and uses Monte-Carlo simulation to handle probabilistic data. Figure 2 shows an example. In addition to defining data and mathematical relations, specialized modules can contain existing software programs (e.g., LCA or CAD software).

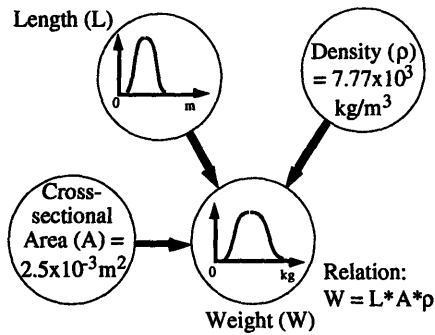


Figure 2: Embedded Relationships between Parameters.

2.3.3 Catalogs of modules: facilitating reuse

Once defined, modules can be reused to create new tools to describe other design problems. For example, a pre-defined life-cycle analysis (LCA) module could be connected into a new design problem to provide LCA capabilities. It is believed that such an approach will enable designers to more readily create integrated product life-cycle models. This approach is an extension of the vision for object-oriented software [32] and is analogous to the concept of creating “objects” in an object-orientated programming language and then storing them in libraries for reuse.

To facilitate the reuse of modules, they can be stored in a hierarchical *catalog* structure. Figure 3 shows a catalog hierarchy of materials. Each circle in the catalog corresponds to a module representing a different material. For example, the AISI 1020 module contains data representing this particular alloy while the wrought steel module contains probabilistic data spanning the whole wrought steel family. Catalogs can be used to help the designer explore alternatives by selecting different modules. Selecting the AISI 1020 module from the material catalog corresponds to choosing this material for use in the design.

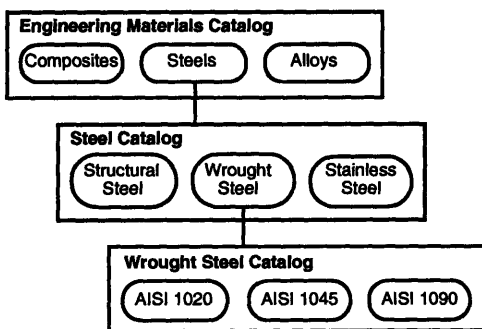


Figure 3: Partial Engineering Material Catalog.

2.3.4 Evaluating a design's performance

A module can also exert requirements on a problem. For example, an electronic component has a limited operating temperature range. Design performance is determined using embedded models. Decision models may then be used to determine how well requirements are satisfied. Many different decision models could be used (e.g., Utility Theory [33] or the Analytic Hierarchy Process [34]). In this work an acceptability-based approach has been selected [31].

Requirements (or *specifications*) are defined in terms of acceptability functions which indicate the subjective probability that the designer will judge values of a quantity as “acceptable”. The method draws inspiration from the evaluation principle in axiomatic design [35]. Figure 4 illustrates the concepts involved.

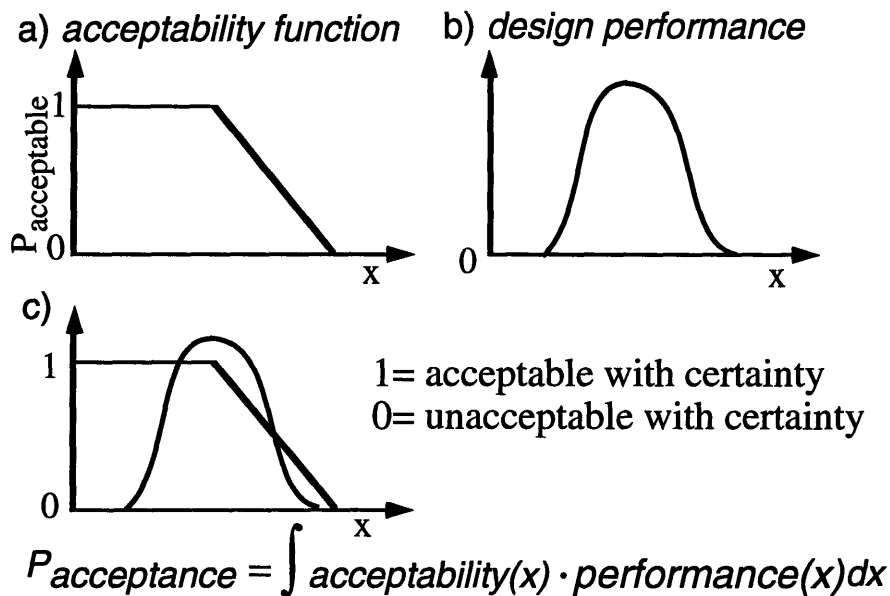


Figure 4: Acceptability-based Evaluation.

A module may have several different requirements. Together they describe the evaluation of the problem from the module's design viewpoint. This viewpoint is referred to as an *evaluation lens*.

2.3.5 Problem integration: connecting modules

The integrated design tool is constructed by linking together a collection of completed modules. This is accomplished using the input and output interfaces, which allow the transfer of information between modules. In this way, modules provide services to one another through their interfaces and the completed model behaves as an integrated system. A module sees other modules only in terms of their interfaces. Thus, two different modules capable of providing the same services are indistinguishable from the viewpoint of other modules. Figure 5 illustrates this idea. In this figure, any battery module capable of providing the motor module with the services requested can be used. These modules can have very different embedded models and can be stored in catalogs for convenient reuse.

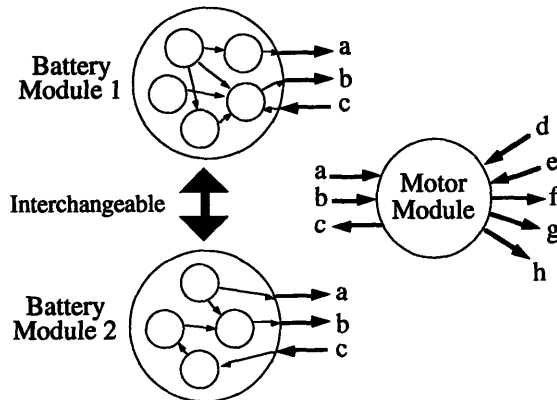


Figure 5: Battery Modules (Interchangeable with respect to the motor module).

2.3.6 Overall design evaluation and optimization

The overall acceptability of a design is assessed by aggregating the probabilities of acceptance for all the individual requirements. The user can alter the design by changing the values of individual data parameters or by substituting interchangeable modules and observe the resulting effect on the overall design evaluation.

However, it is not efficient to use a trial-and-error approach to balance the tradeoffs evident in most problems. For this reason, DOME has been equipped with an optimization engine. The engine uses a new form of genetic algorithm, developed in the CADLab, which is capable of finding the global optimum as well as multiple local optima [36, 37]. The optimization tool allows the designer to set search limits and to activate or deactivate the optimization of parameters as desired. A design can be continually improved by identifying its critical aspects and tightening the related specifications or by increasing the accuracy of the appropriate embedded models.

2.3.7 Model Definition Language: facilitating the rapid construction of DOME models

A recent research effort has seen the development of a high-level Model Definition Language (MDL) which facilitates the creation of DOME models [4]. The components of a model are entered in a text format and the dependencies between parameters can be established through a graphical user interface. This achievement greatly enhances the usability of the software and the speed with which models can be constructed. MDL is an intermediate step in an effort to develop a fully graphical user interface for building design models.

3. Modeling Concepts

In this chapter, a modular approach for quantifying the time-dependent resource flows related to product life-cycles is developed. The first step is to define a generic process module and to identify the distinction between its various input and output flows. Next, a mathematical model is presented to describe the “average” performance of the process being modeled. This model calculates the outputs from the process as a function of the resources received at the process inputs (“push system”). The generalized module can represent a wide variety of processes which can be connected to form complete product life-cycle networks. However, it is desirable for a life-cycle network to operate as a “pull system”. To facilitate this, the concept of *process demand* is incorporated into the basic process module. The resulting model is implemented using a numerical (time-based) simulation which calculates the magnitude of all the resource flows based on the overall product demand.

3.1 Terminology

A *product life-cycle* refers to the stages through which materials pass during the production, use, recycling and disposal of a product. This is represented in the form of a *network* of modules representing the processes involved at each stage.

Resources flows refer to the material, energy and component transfers between modules (measured in kg, Joules or number of units). In most cases, a single resource flow will represent multiple material and energy transfers.

The *form* of a resource flow refers to its properties resulting from the processes it has undergone. For example, in the life-cycle of an automobile, steel can be found in the *form* of ore, raw steel, steel sheet, body panels and as an assembled vehicle.

The *quality* of a resource flow refers to its usefulness from the user’s point of view, viz.: *ready for use*, *recyclable*, or *waste*. Thus, two resource flows may be of the same form (e.g., steel sheet) but may be vastly different by virtue of their usefulness. For example, steel sheet and off-cuts are of the same *form* but the steel sheet is *useful* to a stamping process while the off-cuts can be either *recyclable* or *waste*, depending on the user’s perspective.

Waste refers to resources that are considered *useless* from the point-of-view of the designer. In other words, *waste* is material which the user cannot recover in a feasible manner. Graedel uses the term *residues*, rather than waste, to describe materials and products that are obsolete. He argues that all material is recoverable and hence reusable - even if the technology is as yet not available to do so [12, p10]. For simplicity, this distinction will not be made.

The term *recycling* refers to the processes involved in improving the quality of the materials in a resource flow. These processes generally also convert the material into a less processed form, but this is not always the case.

3.2 Defining a Generic Process Module

This section defines a generic process module that can be used to represent a wide variety of manufacturing processes. To the rest of the life-cycle, a process module can be viewed as a “black box” which takes in resources and produces certain specified outputs (which are dependent on the inputs received). From the designer’s point of view, its function is to change the *form* of the resources received. Consequently, a module must define its feasible input and output flows and dictate the interactions between them. Figure 6 presents an external view of the generic process module and summarizes the related resource flow types. The module shown resembles the “Life-cycle inventory template” adopted by the US EPA [13]. However, its dynamic behavior and the interactions between its flows are defined by an embedded mathematical process model. The characterization of the specified flows is described in the following paragraphs.

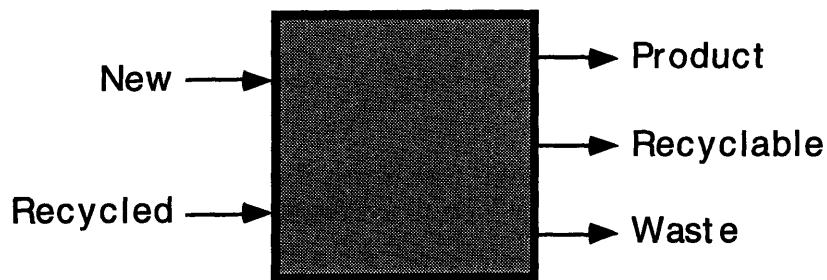


Figure 6. External View of the Generic Process Module.

There is an implicit assumption in the definition of the generic process module in Figure 6. The flows shown do not represent individual resources but resource vectors whose contents are grouped together because they have similar characteristics from the designer’s perspective.

- The output flow types (product, recyclable and waste) are distinguished by virtue of the *quality* of the resources contained. All three flows can contain resources of the same *form* (e.g., steel sheet) but the usefulness of each flow will be different. The *product* flow contains ready-for-use material, the *recyclable* flow contains recyclable material and the *waste* flow contains material which is of no use to the product life-cycle.
- Input flows (new and recycled) are grouped according to the source of the resources contained. In order for new and recycled input flows to be combined, it is essential that the resources in the two flows be compatible in both *form* and *quality* (e.g., raw steel & useful). Virgin resources are viewed as “new” while resources which are restored through reprocessing are considered as “recycled”. In other words, recycled material is obtained from the outputs of processes downstream in the product life-cycle. It is important to note that this characterization is specific to the network under consideration. If resources are derived from a process which is not part of the current network, then they are considered to be “new”.

The relationship between input and output flows must be defined by a mathematical model embedded within the process module. However, the module representation presented thus far is independent of this internal model. This characteristic allows one to define multiple processes with the same inputs and outputs but different embedded models. Such modules could be interchanged within a life-cycle network without needing to redefine the overall system structure or the related interactions. This functionality facilitates the substitution of approximate process models with more accurate ones or the substitution of different processing alternatives within a given life-cycle network.

3.3 Defining the Interactions between Input and Output Flows

The process module defined in the previous section is completely general. As a result, it might be used to represent anything from a single milling process to a complete automobile manufacturing facility. To represent a specific process, it is necessary to define an embedded model to specify the relationships between the relevant resource flows. The form of this model can range from an approximate, steady-state description of the process to a detailed state-space representation.

This section presents a specific mathematical model which can be embedded within a process module to define the average performance of the process as a function of time. The aim of this model is not to create detailed individual process models but rather to evaluate the time-dependent nature of the resource flows for a product life-cycle as a whole.

Underlying Assumption - based on mass conservation.

The mass of material exiting a process at any point in time can be considered as a mathematical function of the material entering the process at earlier points in time. Therefore, in principle, the output flows from a process can be represented as a time-delayed linear combination of its input flows.

However, for most physical systems, the relationships between input and output flows are highly-correlated functions of time and are non-linear. This makes them very difficult to model. Nevertheless, it is possible to model the approximate performance characteristics for existing processes. This is done by defining parameters which describe the “average” performance of a process as a function of time. The key parameters chosen for this specific model are described in Table 1.

Table 1. Average Process Performance Parameters.

Performance Parameter	Description
Cycle Time	Controls time delay from resource input to product output
Capacity	Maximum quantity of product output from the process for each time step.
Max%	Limit on percentage of recycled resource in input
Ratio of Inputs (e.g., Input/Ref)	Describes the ratio between the process inputs (for processes with multiple inputs).
Ratio of Outputs (e.g., Product/Ref)	Defines the fraction of input which exits as Product / Recyclable / Waste

The mathematical relationships between the input and output flows are an elaboration of the laws of mass and energy conservation and are represented using a set of difference equations. Resource flows are represented as discrete functions of time that are dependent on the process’ performance parameters. The embedded model functions as a “push system”, calculating the magnitude of the output flows based on the quantities of resources supplied to the process inputs. In the basic model, the ratio between the new and recycled resource inputs is set so as to maximize the amount of recycled material used. However, by changing the embedded model, this ratio could be governed by different objectives, such as minimizing cost (addressed in section 4.2.4). Figure 7 shows the elements which define the operation of the basic process module. The arrows show the flow of resources through the process.

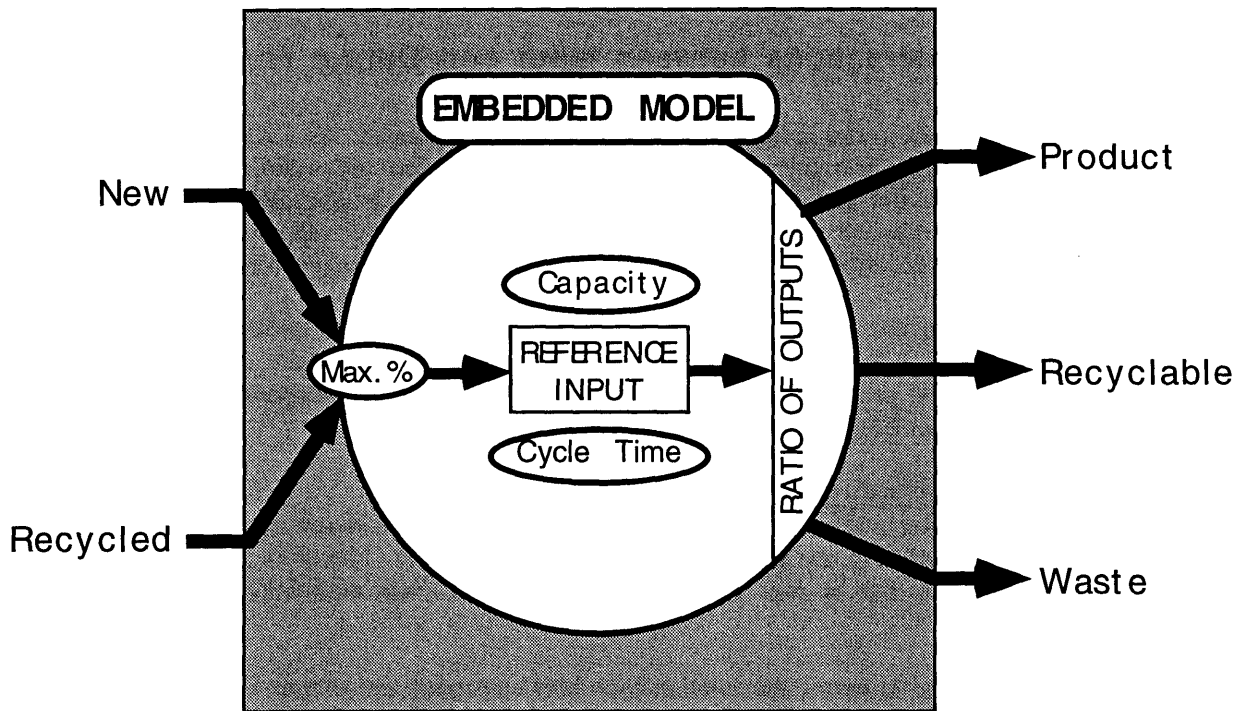


Figure 7. Schematic Representation of the Basic Process Module.

The generic process module represents a high-level “average” process whose characteristic variables are determined from observation of the real process. The simplicity of this embedded model makes it straightforward to implement for a variety of processes. For example, by adjusting performance parameters the basic module can be used to represent the processes involved in the manufacturing, recycling, transportation, storage and use phases of a product life-cycle. If increased accuracy or functionality are required, these can be included at the expense of increased complexity. For example, time-dependent process parameters can be used to model the effects of startup, shutdown and process aging (e.g., tool wear). Material-dependent parameters would allow the substitution of resources without the redefinition of the life-cycle network (described further in chapter 7).

Numerous models have been developed for simulating the performance of specific processes. For example, Sheng *et al.* [25] describe theoretical models for machining processes while Amon *et al.* [26] illustrate the use of statistics for creating an injection molding model. Models like these could be embedded within the generic process module and the resulting modules used to create product life-cycle networks.

3.4 Representing Product Life-cycle Networks

By considering the output of one process module as the input to another, they can be used to construct networks of manufacturing processes which represent realistic product life-cycles. Figure 8 shows a sample product life-cycle network created by specifying the flow of resources between the inputs and outputs of the adjacent processes.

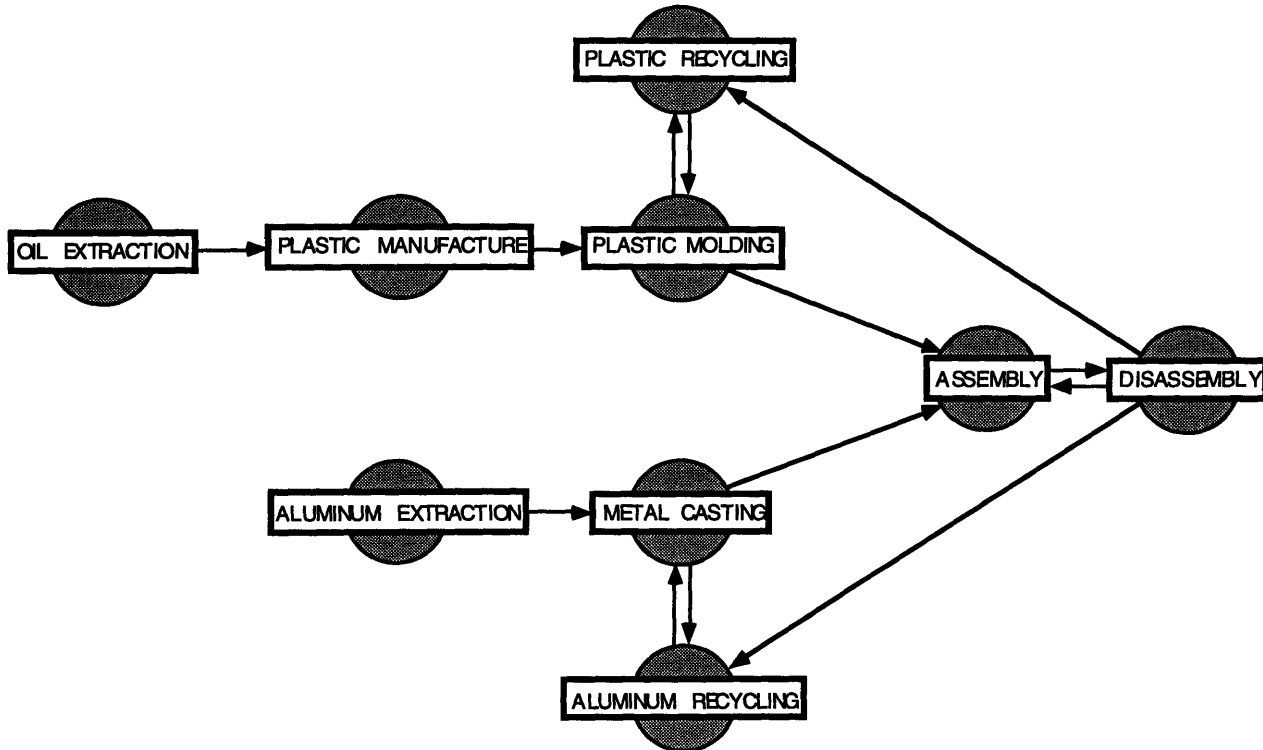


Figure 8. Modular Representation of a Generic Product Life-cycle Network.

The propagation of resources through the resulting network is carried out by using numerical (time-based) simulation in conjunction with the set of difference equations defined by the embedded models. By defining the available resources to the system, the magnitude of all resource flows in a life-cycle network can be calculated at all points in time.

3.5 Developing a “Pull-System”

The process model defined thus far operates as a “push system”. The output flows from each process are calculated based on the quantity of process inputs and internal capacity. However, in most design circumstances it is the desired quantity of product produced, not the resource intake, which is stipulated. It is therefore preferable to model the product life-cycle as a “pull system”. This would allow the designer to place a demand on a specific process output and have the system adjust the process inputs accordingly. Unfortunately, the dynamic effect of recycling makes it difficult to predict the amount of material required to produce a specified amount of product. As a result, the amount of new resources required is usually over-estimated which results in excessive quantities of resources remaining in process buffers. However, in order to minimize the potential environmental impact of a product’s life-cycle, it is usually desirable to minimize the amount of new material used.

In order to achieve this, the concept of *process demand* is added to the embedded model for each process module. This is the quantity of *useful* product required by processes downstream. Each process’ requirement for new resources (*new demand*) can subsequently be calculated by accounting for its recycled resources available and its limitations for incorporating recycled material. Just as the product output from one process becomes the new input for the process which follows it, so the *new demand* of each process defines the required output of the process or processes upstream. In this way, the overall demand of the system propagates backward, up the supply chain, at every point in time (referred to as the *demand pulse*).

Once the demand pulse is complete, the available resources propagate forward, through the network, to determine the magnitude of all the flows in the product life-cycle (referred to as the *supply pulse*). The flows which occur downstream from the specified flow are calculated by means of the “push system” approach described before. This sequence is summarized by the flow chart presented in Figure 9. The indices “i” and “t” represent the process number and the time index respectively. “N” represents the process that specifies the overall product demand. It may be thought of as the last process in the network.

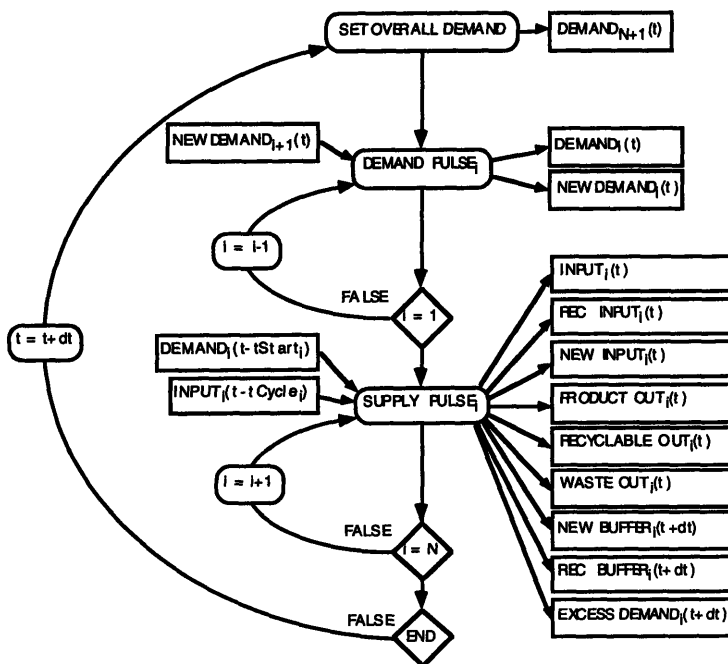


Figure 9. Flow Chart Representing the Information Flow for a “Pull System”.

The time taken for resources to reach a given process is dependent on the accumulative effect of the cycle times of all preceding processes. As a result, the resource supply will lag behind the demand of most processes. To overcome this problem, a *start time* is defined for each process. This parameter delays the way in which the process reads the network's demand pulse, thus bringing the demand into phase with the material supply. When a process relies on multiple process chains for its inputs, its start time is set equal to the supply time for its longest supply chain. The initial start times of the shorter supply chains are also altered so that the material supplied by all process chains are in phase.

In addition, there are times when a process is unable to meet the demand placed on it (due to capacity or supply limitations). It is necessary for each process to keep a record of its accumulated *excess demand* and to make up the shortfall as soon as possible.

The inclusion of these additional parameters results in the creation of a revised process module which contains both the basic process parameters and the demand-related parameters defined above. Figure 10 shows a graphical representation of this *generalized process module*. The resulting mathematical model is represented by a set of differential equations which are summarized in Appendix A.

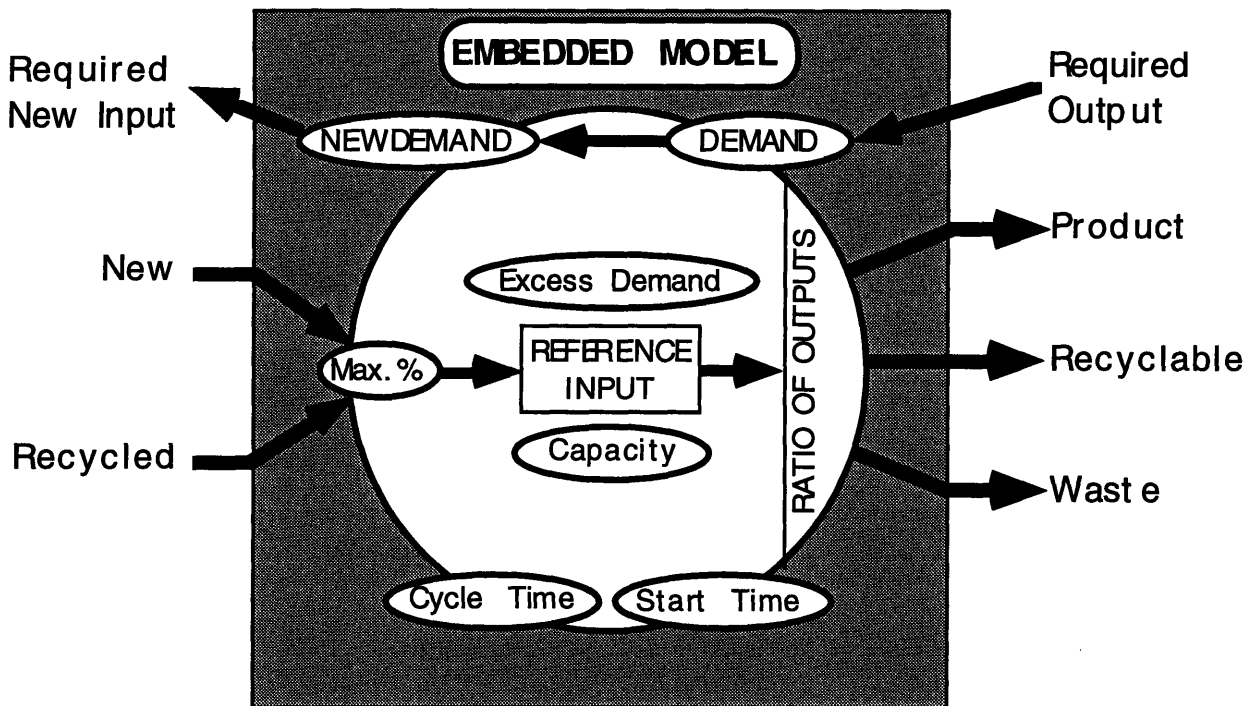


Figure 10. Schematic Representation of the Generalized Process Module.

It is worth noting that the input and output flows of any section of a product life-cycle can be grouped in the same way as the flows for the generic process module. Consequently, multiple processes can conceivably be embedded into a single "process" module. By doing this, the designer is able to group modules into functional groups thus improving the portability of network segments and simplifying the visualization of the product life-cycle.

4. Model Implementation and Validation

In this chapter, the generalized process module, which was developed in chapter 3, is implemented using DOME software. A summary of the underpinnings of this tool is provided in section 2.3. The implementation of the model is described through the development of a generic product life-cycle which is simple enough to facilitate ease of understanding while displaying all the complexity of a larger network.

4.1 General Problem Description

The example represents the manufacture of a product involving the assembly of a molded plastic and an aluminum part as shown in Figure 11. The network comprises two independent process chains (viz., for plastic and aluminum components) which converge at an assembly stage. In addition to the recycling which occurs within each chain, some of the assembled product is dismantled and some of the parts can be reused or recycled.

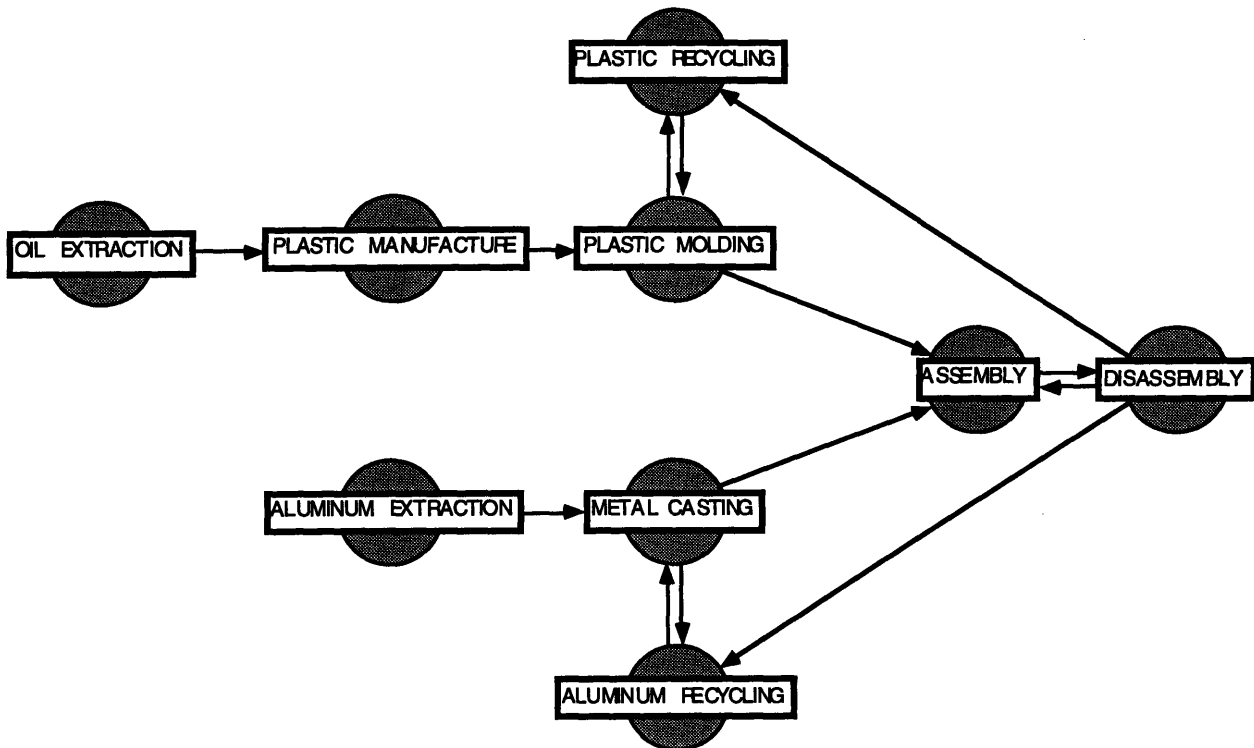


Figure 11. Modular Representation of a Generic Product Life-cycle Network.

Each of the production processes is implemented by using the generalized process module with the performance parameters set appropriately. The input and output flows from the adjacent process modules are linked to form a complete product life-cycle network. However, it is necessary to include certain other modules to facilitate the functional performance of the system. A *User* module is required to specify the demand for the finished product as a function of time and a *Clock* module is included to control the numerical simulation and system timing. Modules to keep track of the *New Resources* used and *Waste* produced are also required. The resulting software implementation is shown in Figure 12.

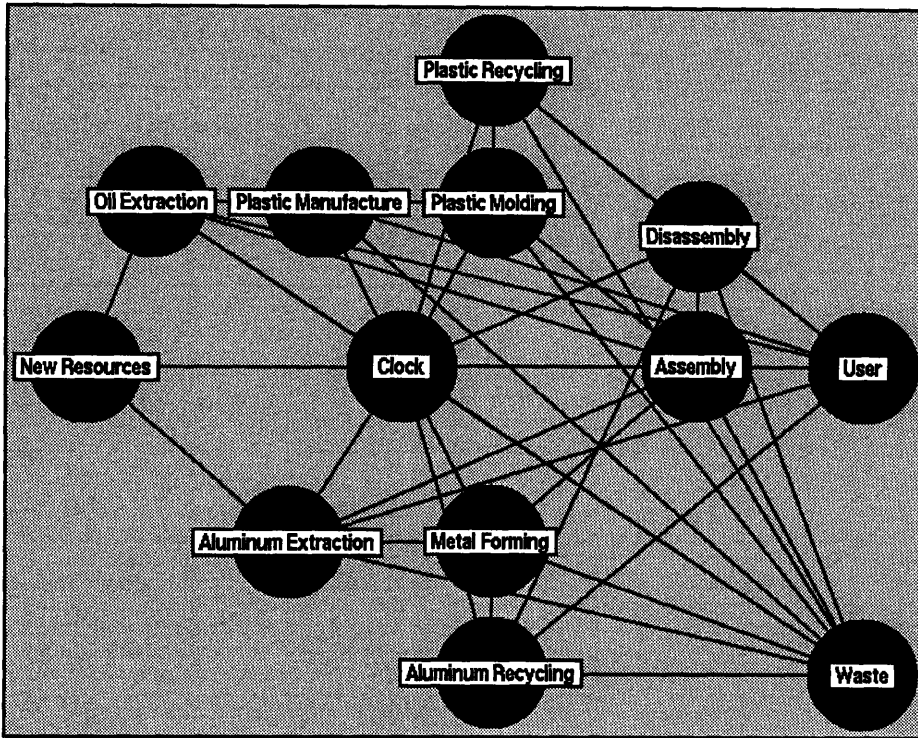


Figure 12. Implementation of the Product Life-cycle Network.

There is a noticeable difference between the physical system and the visualization of the network shown in Figure 12. This is a function of the model structure inherent in the software used for the implementation. As a result, the connecting lines shown in the implementation do not represent resource flows; they show the dependencies which exist between the various modules involved in the problem. The implementation of each of these modules will be defined in detail in the sections which follow.

4.2 Implementing the Generalized Process Module

Current system identification techniques make it possible to derive a single mathematical representation to define the functioning of a complete life-cycle network. However, for design purposes, it is desirable to facilitate the replacement and reuse of parts of a life-cycle network. As a result, it is necessary to define process modules as self-contained “objects”, containing their own functional definitions. In the sections which follow a modular implementation of the generalized process module using DOME will be developed. In addition to the standard process module, various additional features will be included to illustrate the flexibility of the model definition.

4.2.1 Definition of the standard process module

The internal workings of the generalized process module are defined by means of a discrete-time embedded model. In addition to the *performance parameters*, which define the average performance of the module, there are a large number of parameters required to reflect the status of the process. The values for these parameters are recorded at each time step for calculation purposes and to assist in visualizing the behavior of the life-cycle network. The parameters can be grouped into four categories, as shown in Table 2.

Table 2: Parameter Categorization for the Generalized Process Module.

Category	Member parameters
Performance Parameters (Independent of time)	Cycle Time Capacity Max % Recycled Ratio of Inputs (for processes with multiple inputs) Ratio of Outputs (Product/Input, Recyclable/Input, Waste/Input) Start Time
Demand-related parameters	Demand New Demand Excess Demand
Resource Buffers at Inputs	New Buffer (and New Buffer (t)) Recycled Buffer (and Recycled Buffer (t))
Resource Flows	New Input Recycled Input Total Input (Reference Input - for processes with multiple inputs) Product Out Recyclable Out Waste Out

Figure 13 shows the DOME implementation of the generalized process module as it is applied to the *Plastic Molding* process. The process' parameters are represented by the smaller circles contained within the module and the performance parameters are set to describe the "average" performance of the process. The arrows in this figure do not represent the flow of resources through the model but show the dependency relationships between the parameters. The connections to parameters outside the module show the interdependencies between this process and other process modules within the life-cycle network. The details of the embedded model used are given in Appendix A.

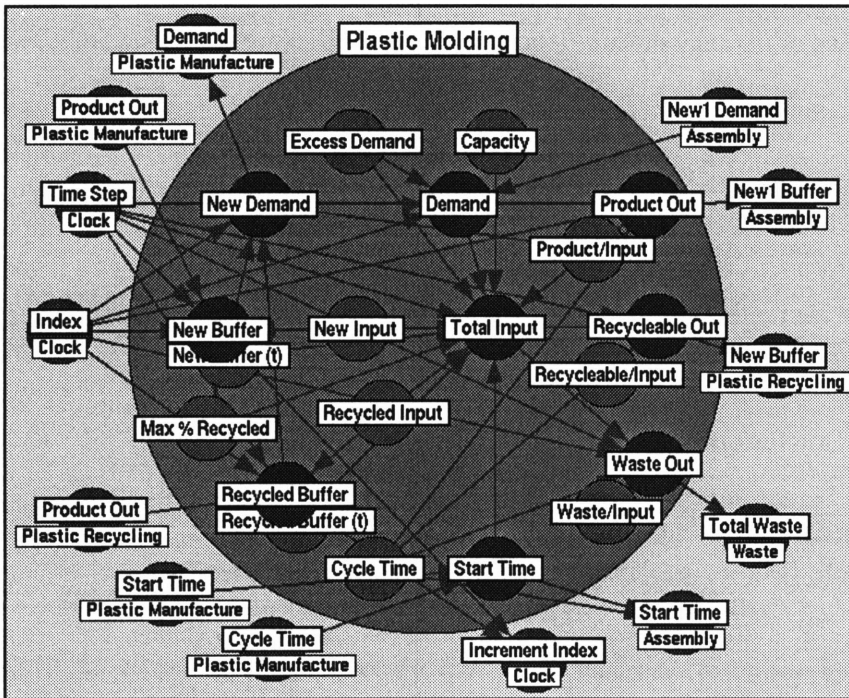


Figure 13: Visualization of the Generalized Process Module in DOME.

The functioning of the process' embedded model occurs in two distinct stages for each time increment.

- During the demand pulse, the module takes the value of *New Demand* from downstream and uses it to calculate the value of its *Demand* parameter. The *New Demand* is subsequently calculated by taking account of the amount of recycled resources available.
- The supply pulse works in the direction of resource flow. The input buffers perform a mass balance (using past outputs from upstream processes along with internal input information) to calculate the quantity of resources available to the process. The “brain” of the supply pulse is the mathematical model for the *Total Input* (or *Reference Input*). Here the process' demand is compared to its capacity and the available material (new and recycled buffers) and the resources to be used by the process are determined (new and recycled inputs). The output flows are computed separately - proportional to past values of the reference input.

The pulse sequences described above form a complex web of infinite circular dependencies. However, wherever parameters depend on past information, these cyclic dependencies are interrupted. In the implementation, this is achieved by using “dummy variables”, viz.: *New Buffer (t)* and *Recycled Buffer (t)*. These parameters contain the same information as their parents but are only updated when their parent's values change. This prevents the design tool from entering an infinite loop.

4.2.2 Customizing the standard process module

The standard process module implementation described in the previous section can be used to represent a large range of processes. The same module which was used to describe the *Plastic Molding* process above can be used to describe transportation, recycling and usage processes. In addition, the module could represent anything from a single machine to a complete production facility. In the near future, it will also be possible to embed multiple process modules within a single DOME module. This flexibility lends itself to the development of reusable process modules and network segments which facilitates the portability of modules and the ease of construction and visualization of life-cycle networks.

In order to differentiate between modules it is necessary to suitably assign each process' *performance parameters*. Let us consider a set of hypothetical values for the *Plastic Molding* process. Assume that the process requires 10kg of plastic to produce: 7 good parts (1kg each), 1 recyclable part (1kg) and 2kg of waste. It has a cycle time of 2 hours and a maximum allowance for recycled material of 70%. The equivalent *performance parameters* are summarized in Table 3.

Table 3: Performance Parameters for Hypothetical Plastic Molding Process.

Performance Parameter	Values for the hypothetical situation described.
Max % Recycled	0.7
Cycle Time	2 (hrs)
Product/Input	0.7 (parts per kg plastic)
Recyclable/Input	0.1 (parts per kg plastic)
Waste/Input	0.2 (kg waste plastic per kg plastic)

The only other thing required is to specify the source for the inputs to the process and the destination of the outputs produced. In DOME, this is done by connecting the dependencies of each process' new and recycled buffers to the relevant output parameters upstream.

An interesting situation arises in the definition of recycling processes. For example, in the *Plastic Recycling* process, *recycled* plastic is received from both the molding and disassembly processes. However, these flows are the primary inputs for the recycling process and could thus be considered as being “new”. In other words it is unclear whether these flows should be incorporated as “new” or

“recycled”. In the current implementation, plastic from the molding process is considered as a *new* input while plastic from the disassembly process is taken as *recycled*. While this type of dependency allocation is arbitrary, consistency is important in order to enhance the manageability of the resulting network. As another example, some of the outputs from the disassembly process are still *recyclable*. Nevertheless, it makes sense to identify those resources which are ready for reuse by the assembly process as *product* outputs and those which require further recycling as *recyclable* outputs.

While the concepts described here are general, the current implementation is only directly applicable for processes with single resource inputs and outputs. This is a limitation of DOME, the software modeling framework being used. A temporary but rather awkward solution to this problem is presented in the next section. The topic is further discussed under future work in chapter 7 where a more satisfactory solution is suggested.

4.2.3 Representing processes with multiple resource inputs

When a process requires more than one resource as an input it is necessary to account for the interactions between the inputs. In particular, the ratio between the inputs must be specified and the *Reference Input* computations must consider all of the inputs and any interactions which may exist. The start time for such processes must be set to the supply time for the process’ longest resource supply chain and the initial start time for each process chain must be altered to ensure that all the resources arrive in phase.

In the example being considered, the *Assembly* module requires both plastic and aluminum parts for its operation. The ratio between the inputs is set by specifying the ratio of each input to a reference input (e.g., *RefInput/Input1*). The mathematical model for the parameter, *Start Time*, performs the necessary start time manipulations. The resulting implementation is shown in Figure 14.

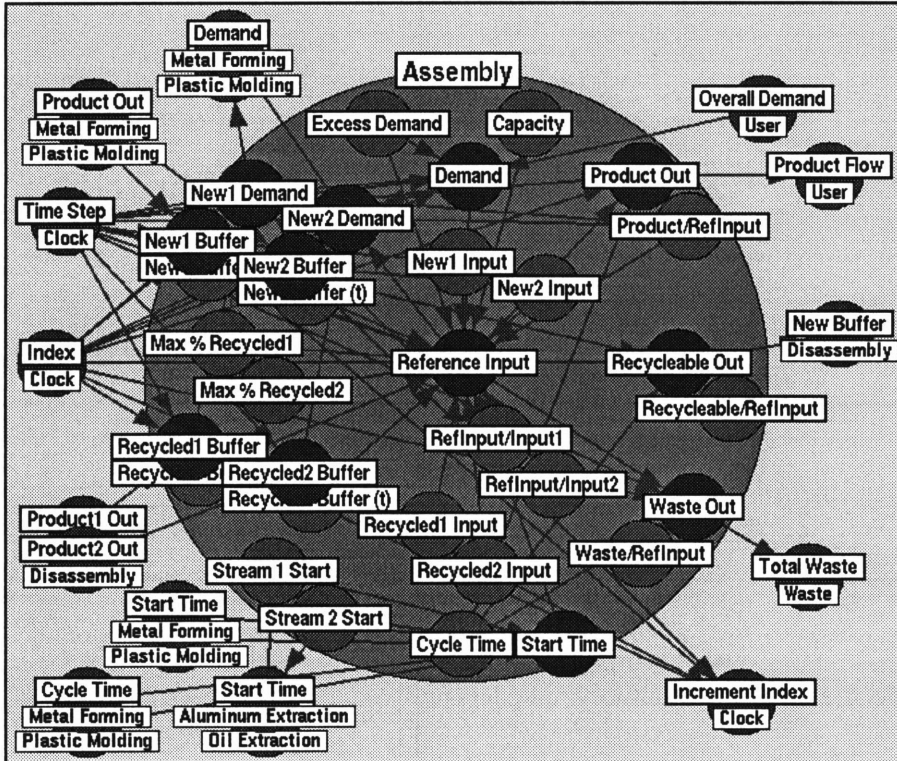


Figure 14: Visualization of the Assembly Module (Multiple Resource Inputs).

The most obvious result of the increased complexity of this module is the duplication of parameters (and this is with only two inputs). For practical purposes, the handling of multiple inputs should be implemented by using input vectors and by defining *performance parameter matrices* to streamline the module visualization and mathematical manipulation. This extension will be discussed further in the section on future work (chapter 7).

4.2.4 Including additional functionality - Balancing inputs to minimize cost

The process module defined thus far operates to minimize the quantity of new resources used to meet the overall product demand. However, in certain situations it is desirable to determine the ratio between new and recycled resource inputs based on other criteria. For example, it may be desirable to minimize the energy consumption or the cost related to an individual process or for the network as a whole. If this is the case, the mathematical model for the *Reference Input* must be able to automatically change to satisfy the alternative objective. In the example considered, the option of controlling the input ratio according to resource cost has been included. This flexibility has been achieved by introducing parameters to define the costs related to the use of new and recycled resources as well as a “toggle switch”, $MaxRec(0) \rightarrow MinCost(1)$, which allows the user to specify which objective is to be used. Figure 15 shows the *Plastic Molding* process module with the cost-related parameters included.

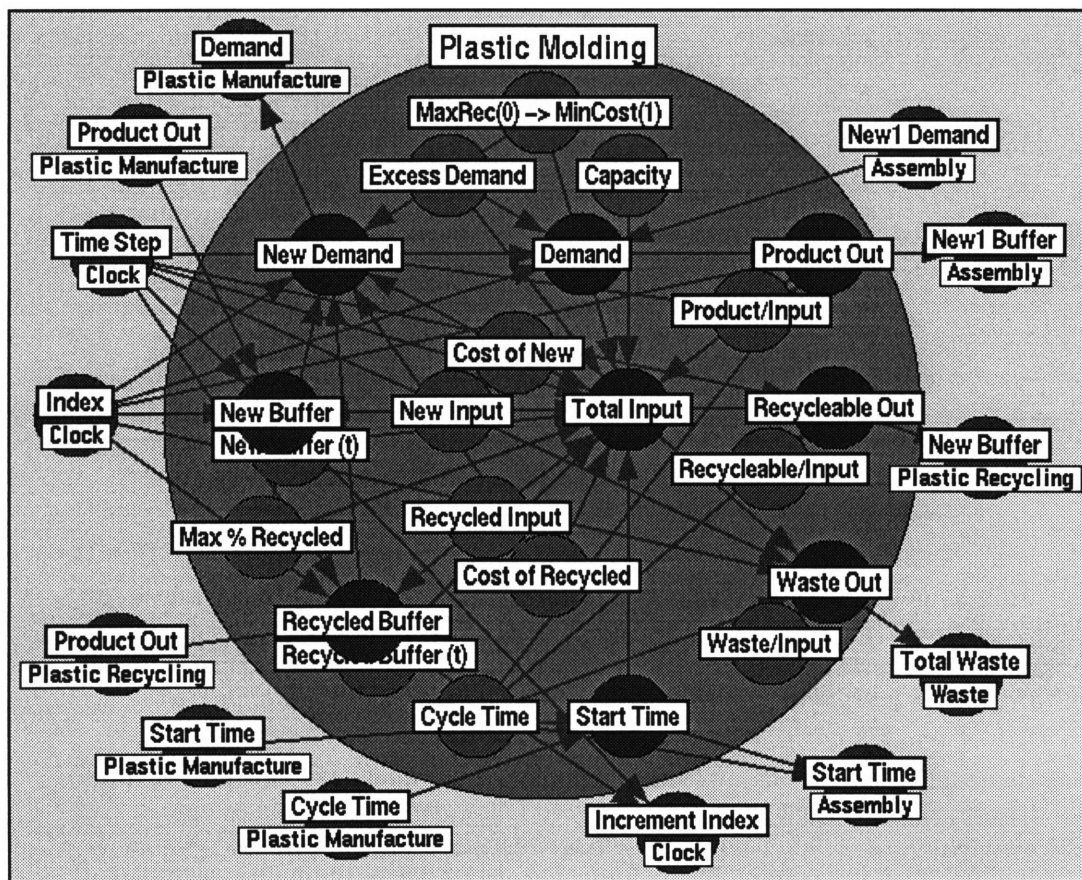


Figure 15: Generalized Process Module with Cost-related Parameters.

Further functionality can be included into the model by the addition of parameters with the relevant information and necessary mathematical relationships.

4.3 Implementing Supporting Modules

In addition to the process modules, which are implemented using the generalized process module, there are a number of other modules which are required for the functioning of the complete life-cycle network.

The *Clock* module, shown in Figure 16, controls the time-based simulation which is used for calculating the resource flows throughout the network. Its essential component is the parameter *Increment* which checks to see that the rest of the system is up to date before it increments the simulation *Index*. The other parameters contained in this module provide additional information and increased flexibility to the user. Their functions should be self-explanatory.

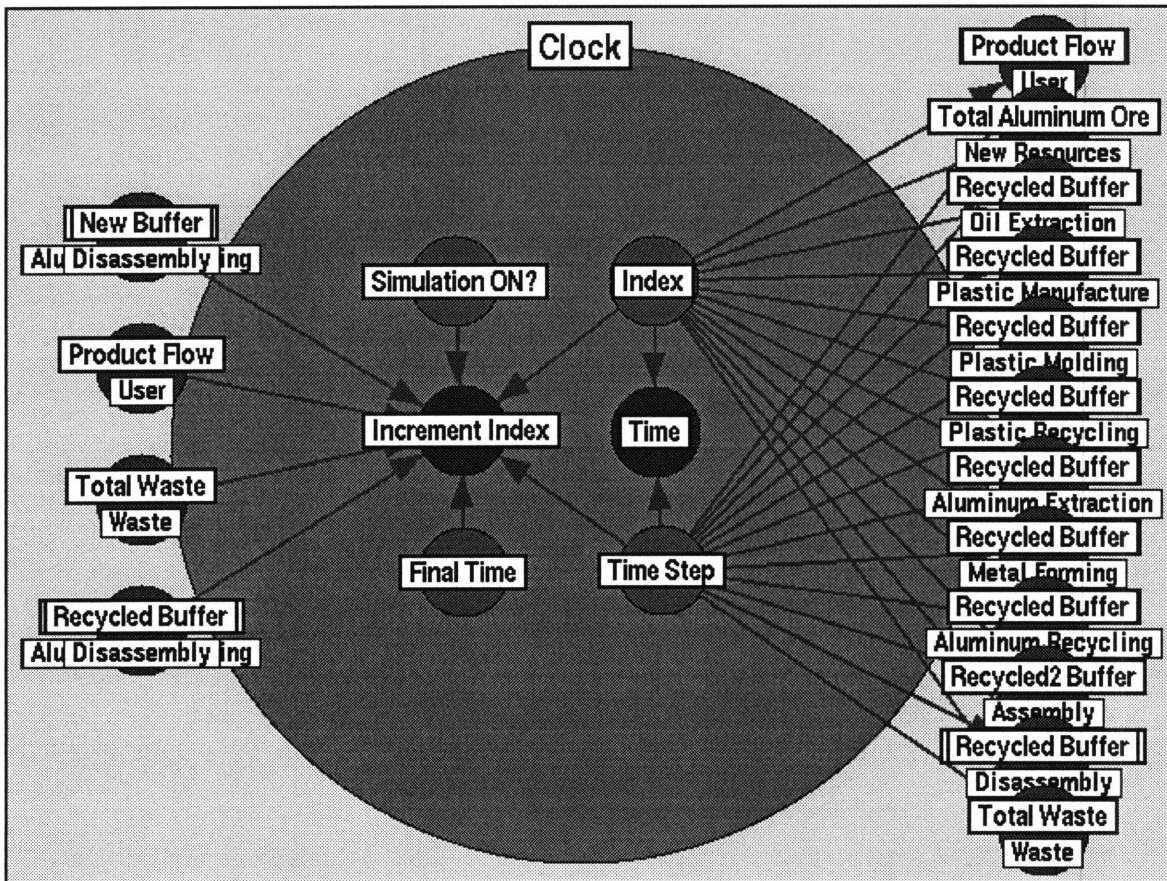


Figure 16: Clock Module Visualization (Controls the time-based numerical simulation).

The graphical representation of the current implementation of the *User* module is shown in Figure 17. The function of this module is to specify the user's *Overall Demand* as a function of time. In addition, it can be used to provide additional information to the user, such as the *Total Demand* and *Total Flow* of product for the network. Additional information can be derived from the network and displayed in this or other modules if desired. There are also various "dummy variables" which have been placed in this module which contain redundant information but which are necessary for the proper functioning of the network (e.g., *No Flow* where buffers are not connected to a flow source). It is worth noting that the information supplied by this module could come from a remote (distributed) module and the information displayed could be used by other parts of a larger problem.

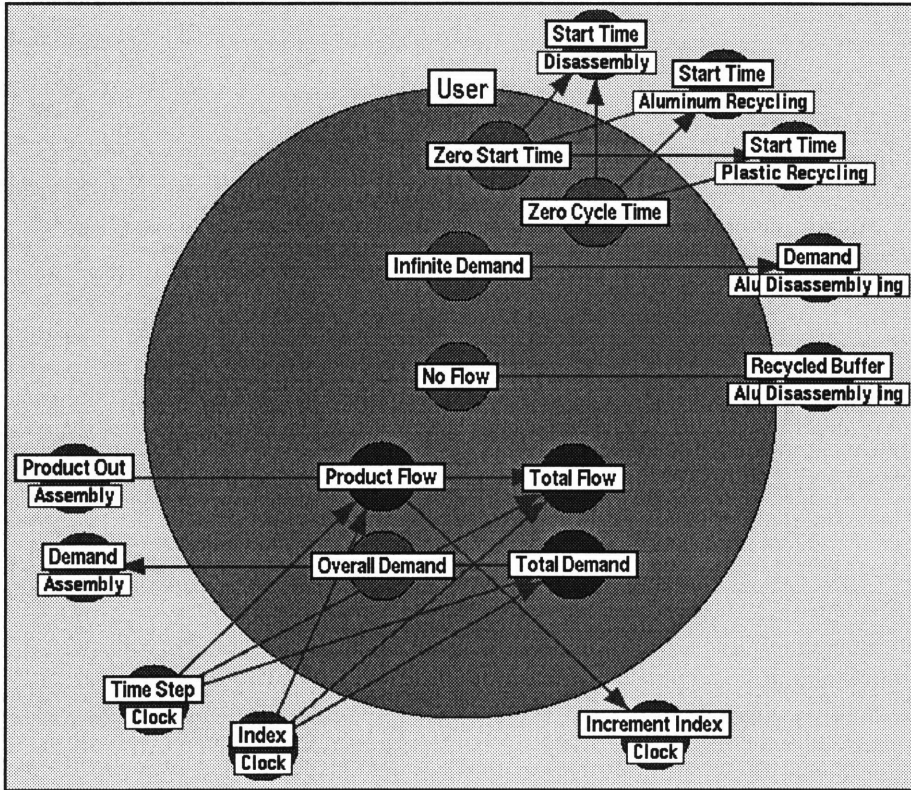


Figure 17: Graphical Representation of the User Module.

The *New Resources* and *Waste* modules are essentially included for accounting purposes, to keep track of the quantity of new resources used and waste produced by the network. In addition, the *New Resources* module provides the resource availability and timing information required by the first process in each process chain. As such, it could be used to model non-renewable resources by limiting the quantity of new resources available. Figure 18 a) and b) show the visualization of the *New Resources* and *Waste* modules respectively.

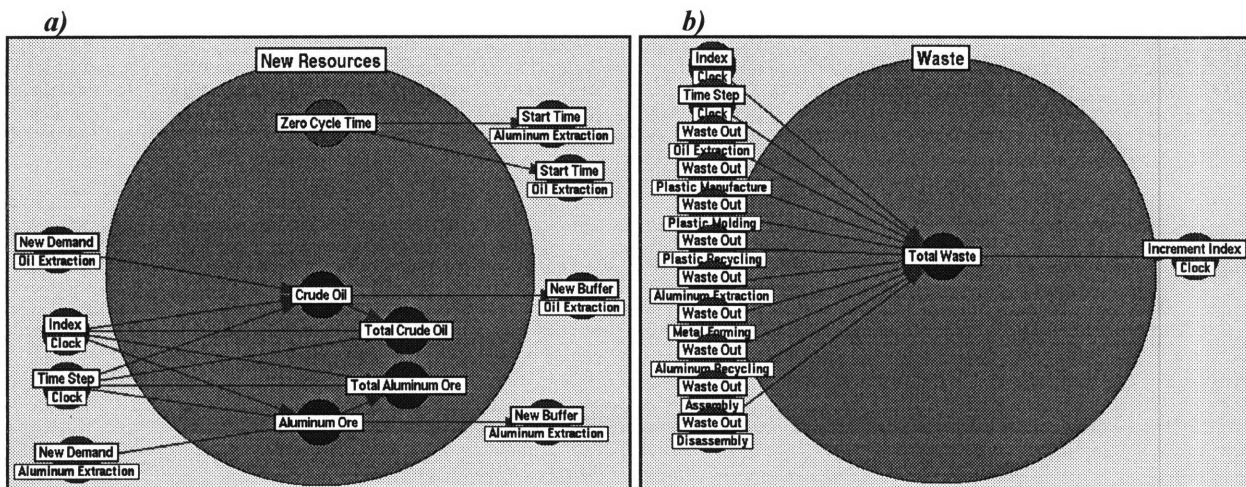


Figure 18: Visualization of Support Modules for Product Life-cycle Network.

a: *New Resources* Module.

b: *Waste* Module.

4.4 Interpreting Results

In this section we will use the generic network to examine the functioning of the life-cycle model developed. The program performs a numerical simulation to determine the values of the resource flows required to satisfy a specified product demand. In particular, we will consider the response of the network to three different demand functions:

1. Step Response (Steady-state)
2. Periodic Demand Curve (Saw Tooth Function)
3. Mixed Demand Curve

In all cases, each process' toggle switch, $MaxRec(0) \rightarrow MinCost(1)$, is set to maximize the quantity of recycled material used by the network. One of the most significant results of these simulations is the dynamic effect of recycling on the response of the system. This is best observed by comparing the flow patterns in the plastic process chain (low recycling potential) to those in the aluminum process chain (high recycling potential).

4.4.1 Step response (Steady-state)

The response of a system to a unit step input is a common tool in system identification. It is used here to provide certain information about the response of the product life-cycle network defined in the previous section. It is important to note that in the life-cycle model, the “input” to the system is in fact the *Overall Demand* specified by the user. The “response” of the life-cycle network is defined by the resource flows throughout the network required to meet this demand. The specified *Overall Demand* curve and resulting *Product Flow* are shown as functions of time in Figure 19. The shape of the network's output matches the specified demand curve but it displays a pure time delay brought about by the accumulative effect of the cycle times of all the processes involved.

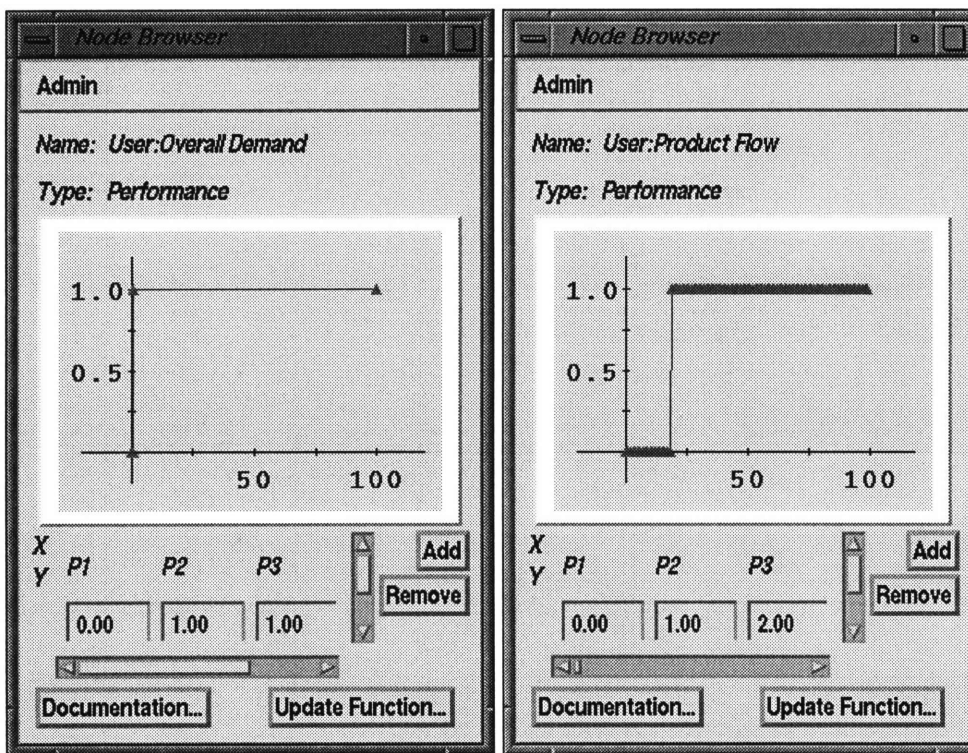


Figure 19: Response of the Network to a Unit Step in the Overall Demand.

For environmental impact assessment we are interested in assessing the variation in the *New Inputs* required to meet the *Overall Demand*. Figure 20 provides a comparison between the amount of new resources required for three different scenarios - differentiated by recycling potential. This figure clearly shows the reduction in required resources and the dynamics introduced by recycling. A similar result occurs for the waste and emissions from the network.

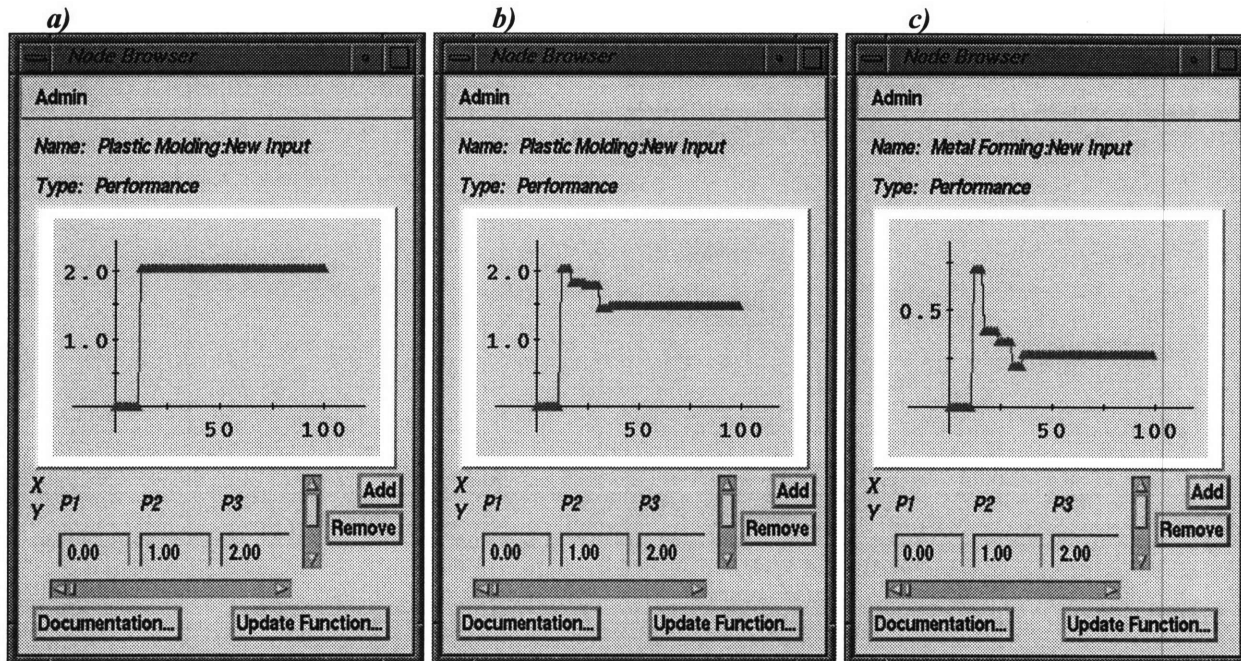


Figure 20: Comparison of New Input Required for different Recycling Potentials.
a: Plastic Molding Process (No recycling).
b: Plastic Molding Process (Low recycling potential).
c: Metal Forming Process (High recycling potential).

The network's step response also provides information about the quantity of new resources required for operation at steady-state (final values in Figure 20). The steady state values for the network defined are given in Table 4 along with the percentage reduction in new resources required due to recycling.

Table 4: Steady-state Response Values for the Resource Supply Chains.

Response Ratio (New Input Required / Product Output)	No Recycling	Recycling	% Reduction
Plastic - New Input (low recycling potential)	2.040	1.481	27 %
Aluminum - New Input (high recycling potential)	0.714	0.270	62 %

4.4.2 Periodic demand curve (Saw tooth function)

This section considers the response of the life-cycle network to a periodic demand curve. The *Overall Demand* and resulting *Product Flow* curves, shown in Figure 21, have a period of 100 hours and are scaled to produce a unit peak demand. The *Product Flow* again exhibits a pure time delay due to the cycle times of the processes in the network's process chains. A 20 hour time-delay is included between the "cycles" of the demand curve to allow sufficient time for the network to finish responding to the first demand cycle before the second cycle commences.

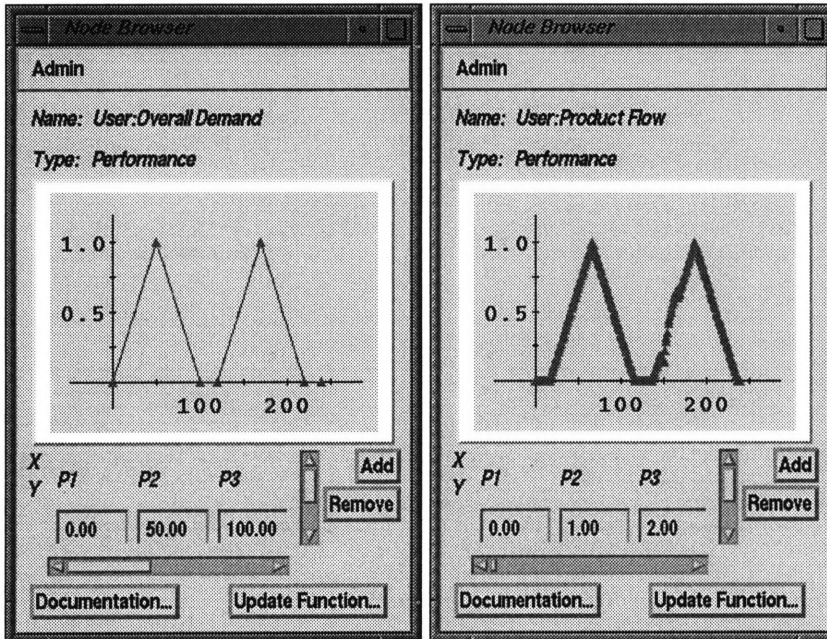


Figure 21: Response of the Network to a Periodic Demand Curve (Saw Tooth).

Let us compare the quantity of new resources required for process chains with no recycling, low recycling potential and high recycling potentials. The effect of recycling on the quantity of new resources required for the three scenarios is clearly illustrated by the plots shown in Figure 22. The time delays apparent in each of these curves result from the time delays of the preceding processes in the respective process chains.

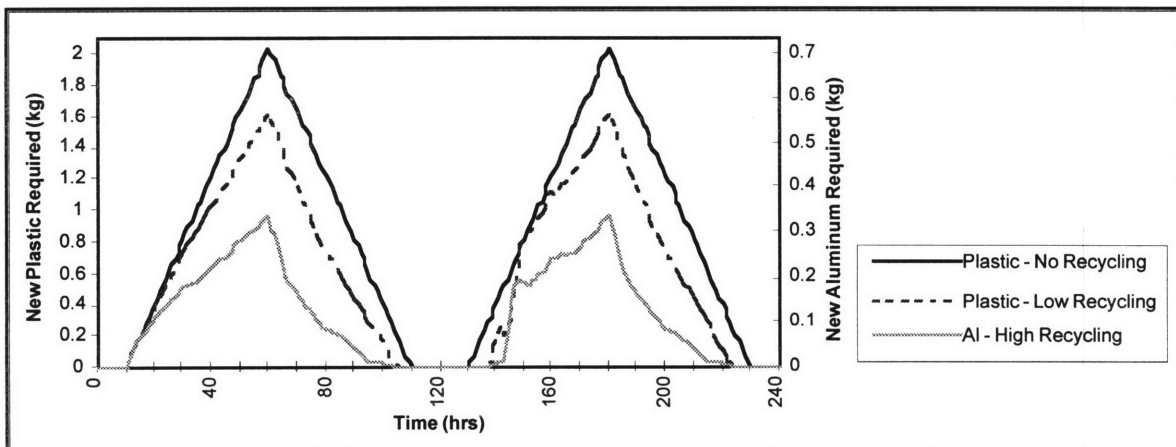


Figure 22: Effect of Recycling on the New Inputs Required (Periodic Demand Curve).

In addition to the qualitative effects displayed above, it is necessary to ensure that the production of final products meets the overall demand specified. To confirm this, parameters have been included in the *User* module to perform a numerical integration of the demand and product flow curves over time. The resulting values are visualized by means of the browsers shown in Figure 23.

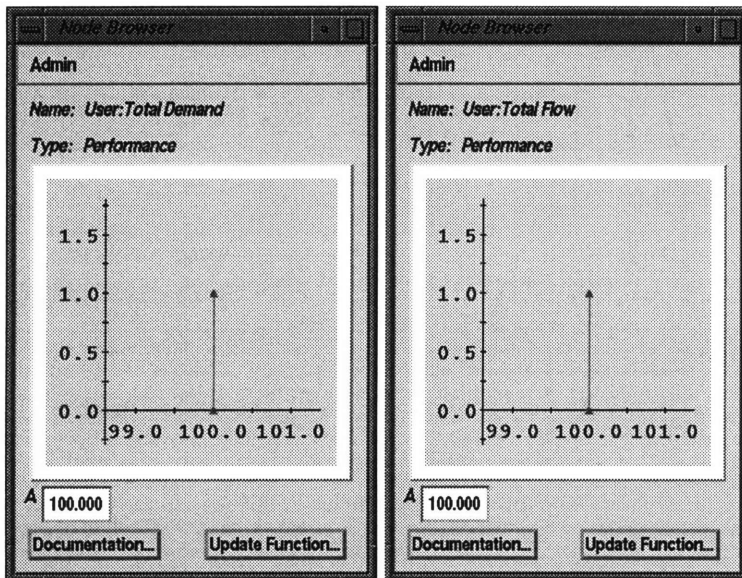


Figure 23: Comparison of the Network's Total Demand and Total Product Flow.

4.4.3 Mixed demand curve

Finally, let us consider the response of the network to the mixed demand curve as shown in Figure 24. This type of variation in demand could result from a product's seasonal nature, its limited useful life (due to the effects of fashion or technical advancement) or its reliability/failure characteristics. The network's response is also provided and as expected it lags behind the demand curve due to the time delays inherent in the system.

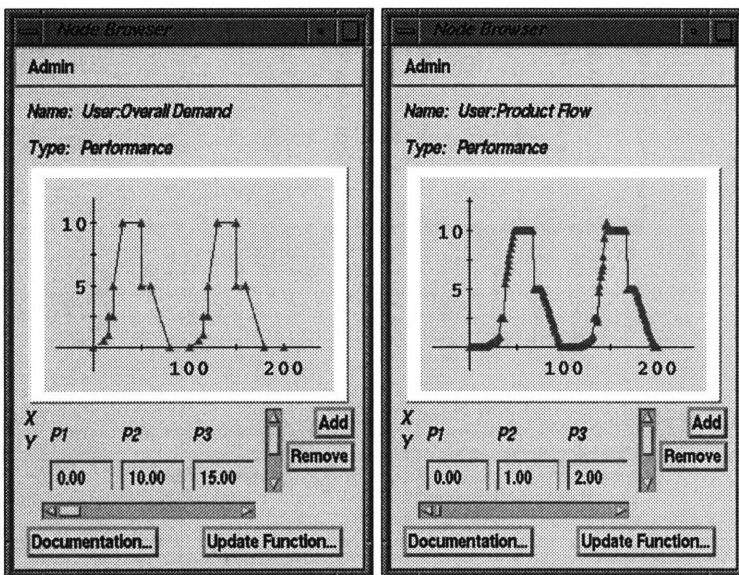


Figure 24: Response of the Network to a Mixed Demand Curve.

Once again, let us consider the effect of recycling on the network's performance by observing the response of the three recycling scenarios. Figure 25 provides the plots of new resources required as a function of time.

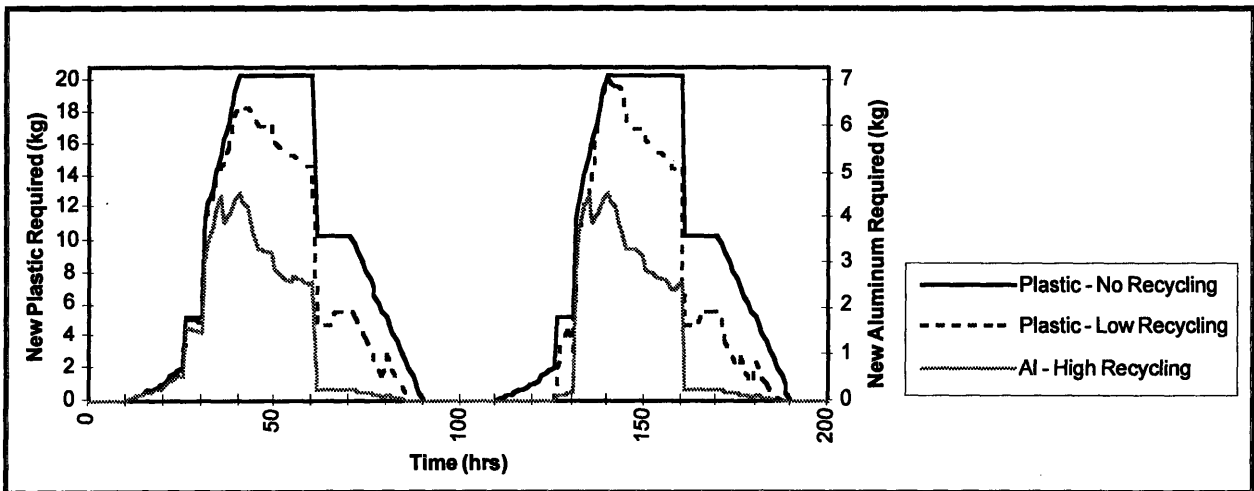


Figure 25: Effect of Recycling on the New Inputs Required (Mixed Demand Curve).

Despite the marked dynamic behavior of the new resource inputs, the total demand placed on the system is matched by the quantity of the product flow produced.
(Total Demand = Total Flow = 789 units)

These examples illustrate the use of the model presented to quantify the time-dependent resource flows for a product's complete life-cycle network. The resource flows required to meet a specified demand curve are calculated by means of numerical (time-based) simulation. These simulations demonstrate the significant effects of recycling on the a network's resource flows. Of particular interest is the reduction in new resources required and the system dynamics introduced. The inventory information provided by the product life-cycle simulations is intended to be used in conjunction with time-dependent LCA tools to improve the accuracy of existing environmental impact assessment techniques. While this level of information is not currently required, it is expected that it will become useful as LCA techniques continue to develop.

5. Integrated Design Example

This section provides another example modeled using DOME software (described in section 2.3). The example describes the creation of an integrated tool for designing rectangular enclosures for housing electronic components, like the one shown in Figure 26. The objective is to illustrate the use of the DOME framework to simultaneously consider multiple objectives in the evaluation and optimization of a design's performance. The criteria considered in the evaluation of the enclosure design tool include: electromagnetic radiation (EM), temperature, environmental impact, cost, and geometric fit (for internal components). Although this example does not fully utilize the life-cycle model described in chapters 3 and 4, it does illustrate how this model could be combined with specialized LCA techniques to provide improved environmental impact assessment capabilities using DOME (section 5.6).

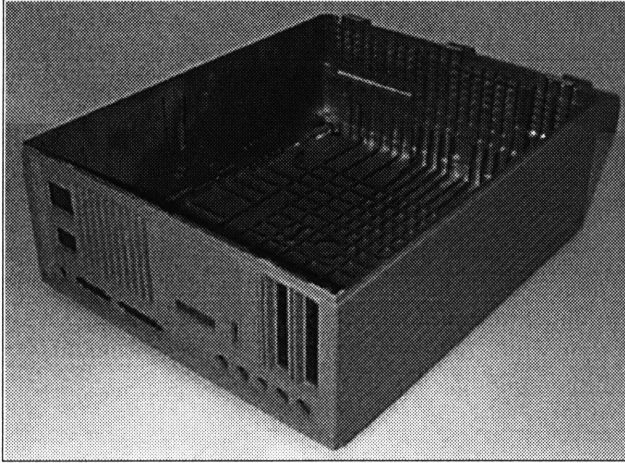


Figure 26: Enclosure for Computer Components.

5.1 Breaking Problem into Modules

The enclosure problem was decomposed into modules representing key aspects of the design problem. The problem was subdivided so that modules could be constructed for maximum reusability. A conceptual decomposition of the enclosure design problem is given in Table 5. It shows modules which represent data (e.g., materials), physical components (e.g., cooling fan) and analysis capabilities (e.g., EM calculations).

Table 5: Modular Decomposition of the Enclosure Design Problem.

Module	Description
Electronic Component (e.g., PC Board)	Represents the electronic component to be shielded. Includes electromagnetic, temperature and geometric requirements.
Fan	Contains characteristics for a cooling fan and its temperature requirement.
Materials modules	Describes material properties for the enclosure material and coatings.
Enclosure Geometry	Specifies the housing geometry parameters.
Aperture modules	Geometric description of seams and apertures in the housing.
Surrounding Conditions.	Defines the ambient conditions in which the component must operate.
External Source	Specifies spectrum of incident EM radiation outside of the enclosure.
EM Calculations	Performs multiple-layer SE calculations for box housings with apertures.
Heat transfer	Calculates the internal temperature of the enclosure based on necessary heat transfer parameters for either natural or forced convection.
Cost	Assesses the cost of an enclosure.
Environment	Estimates environmental impact from recycled material and energy usage.
Interference Check	Determines whether the components can fit within the enclosure.

5.2 Definition of Individual Processes

After decomposing the problem, each module's embedded model and external interfaces must be specified. This is most easily done using the Model Definition Language (MDL) which was developed in the CADLab to enable users to rapidly construct DOME models [4]. This section describes the structure of the more important modules in the enclosure design problem, viz.:

1. Electronic Component
2. Electromagnetic (EM) Shielding Calculations
3. Heat Transfer
4. Environmental Impact Assessment

5.2.1 Electronic component

The reason for performing this enclosure design is to protect the electronic equipment being housed (in this case a PC Board). As a result, the *Component* module must contain all the data necessary to specify its characteristics and requirements. Figure 27 shows the contents of a module representing an electronic component with electromagnetic shielding and temperature requirements.

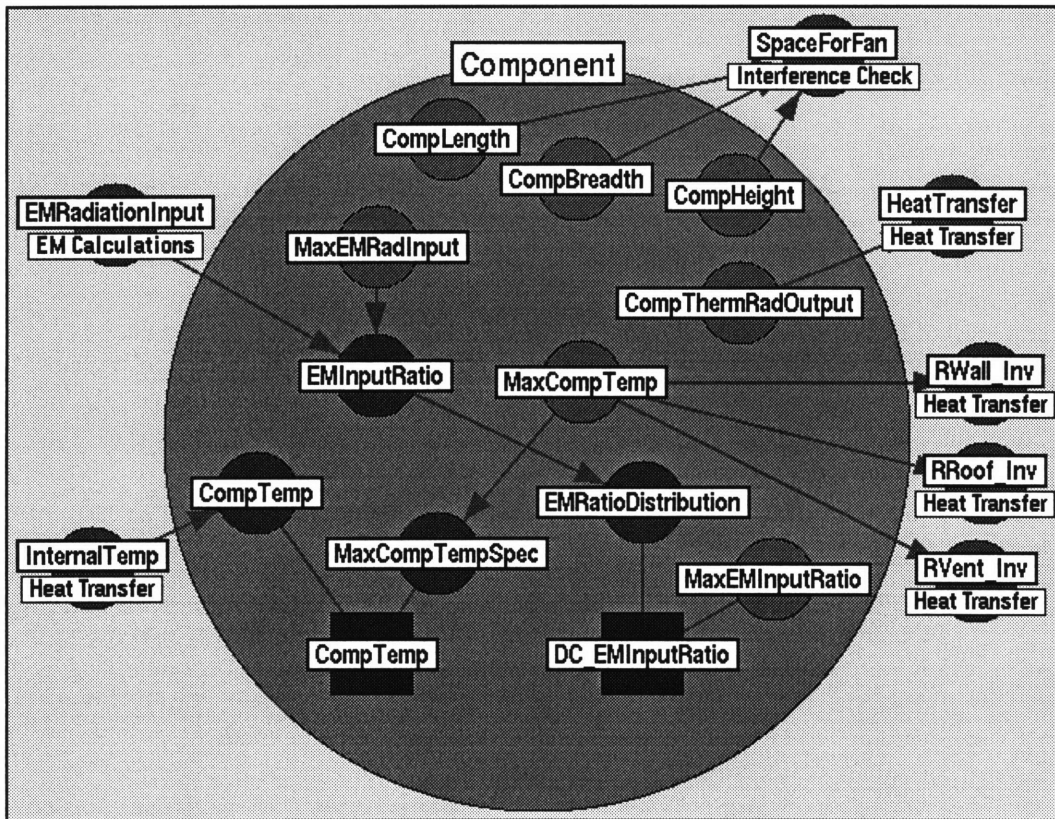


Figure 27: Contents of a Module Representing an Electronic Component.

The module contains independent quantities (such as component dimensions) as well as derived quantities calculated using embedded mathematical models. For example, the operating temperature inside the enclosure is obtained from models in a heat transfer module. The variables outside the large circle represent the interface to parameters in other modules in the problem (inputs on left, outputs on right).

Variables can either be represented deterministically or by a probability density function. Figure 28 shows the component's expected operating temperature.

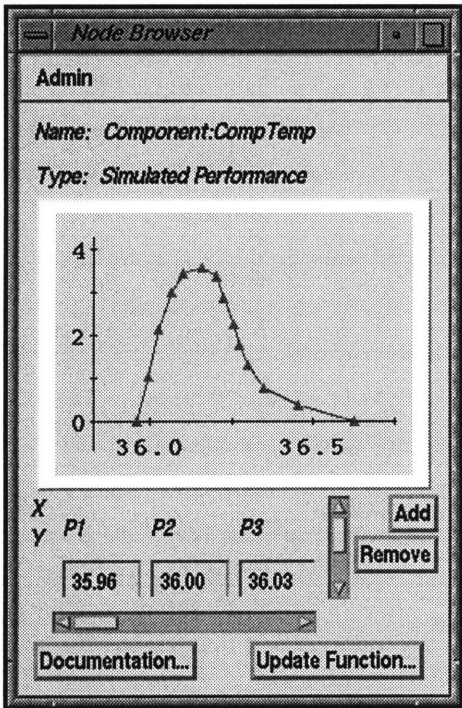


Figure 28: Probabilistic Data for the Component's Operating Temperature.

In addition to data, the module has EM radiation and operating temperature requirements (drawn as squares in Figure 27) which form its evaluation lens. A summary of this lens and the current design's probabilities of acceptance are shown in Figure 29.

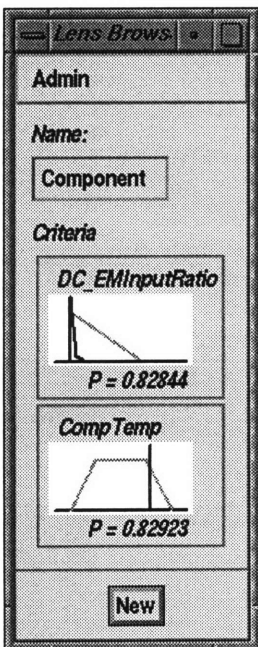


Figure 29: Component's Evaluation Lens.

5.2.2 Electromagnetic (EM) shielding calculations

The *EM calculations* module contains mathematical models which estimate the *shielding effectiveness* (SE) of multiple-layer enclosures accounting for the effect of apertures. The models developed represent a significant extension to the currently available single-layer equations [27-30]. A summary of the models developed have been included in Appendix B. All of the data required to perform the SE calculations are contained in other modules and are accessed through the module's input interface. The resulting value of *EMRadiationInput* is compared to an EM radiation specification by the *Component* module. The graphical DOME representation of this module is shown in Figure 30.

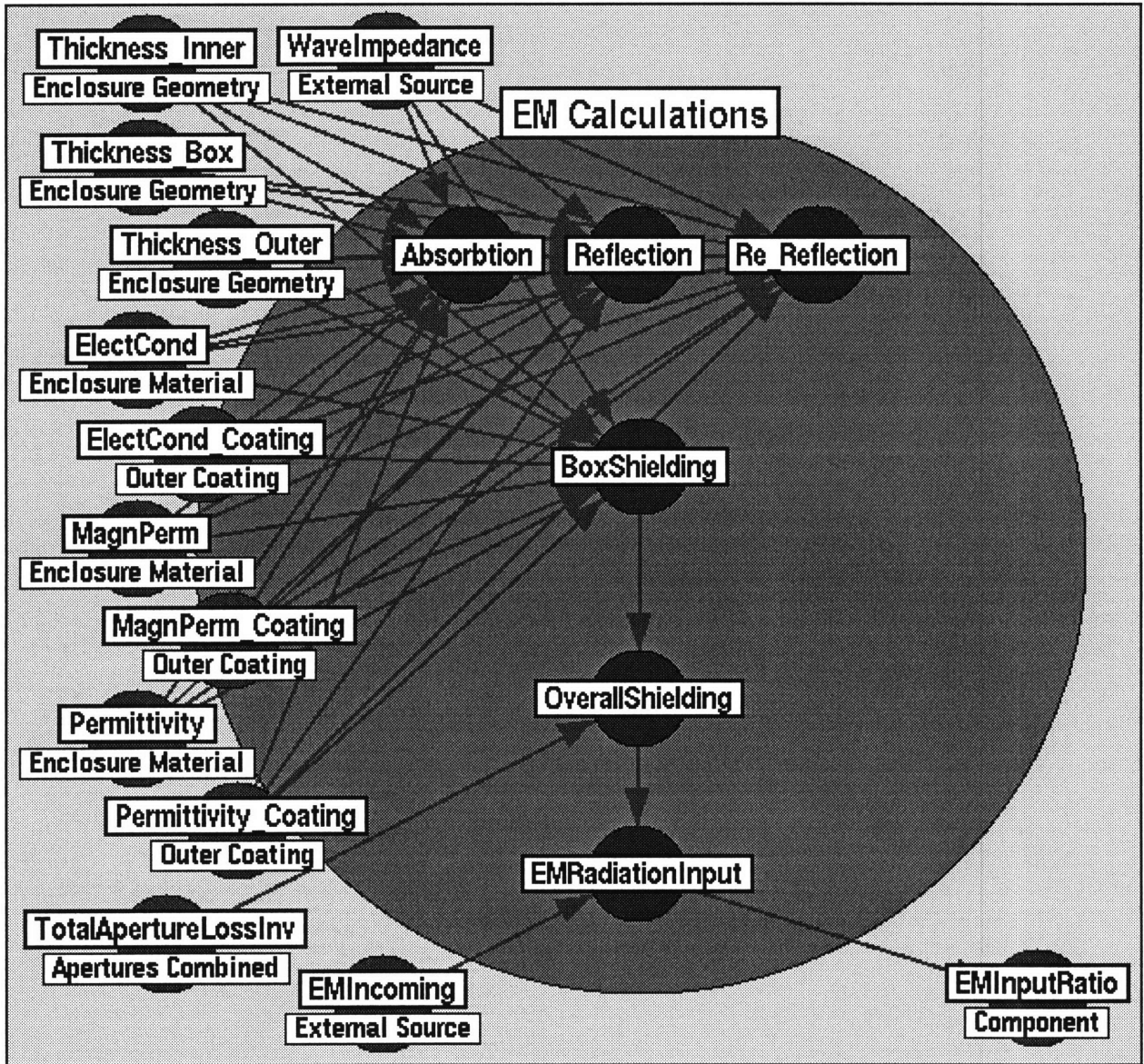


Figure 30: DOME Representation of the Module for EM Shielding Calculations.

5.2.3 Heat transfer

The heat transfer calculations in the integrated design example are used to calculate the enclosure's internal temperature and are embedded within a *Heat Transfer* module. The enclosure is modeled as a hollow rectangular prism with uniform internal temperature. A resistance analogy is used to combine the effects of conduction and convection from the enclosure's walls, roof and vents. If a fan is included in the design, forced convection is also incorporated. The details of the equations used are presented in Appendix C.

Figure 31 shows the DOME visualization of the heat transfer module. The heat transfer equations make use of information supplied by other modules through the module's interface. The calculated values are used outside this module in the form of the component and fan operating temperatures.

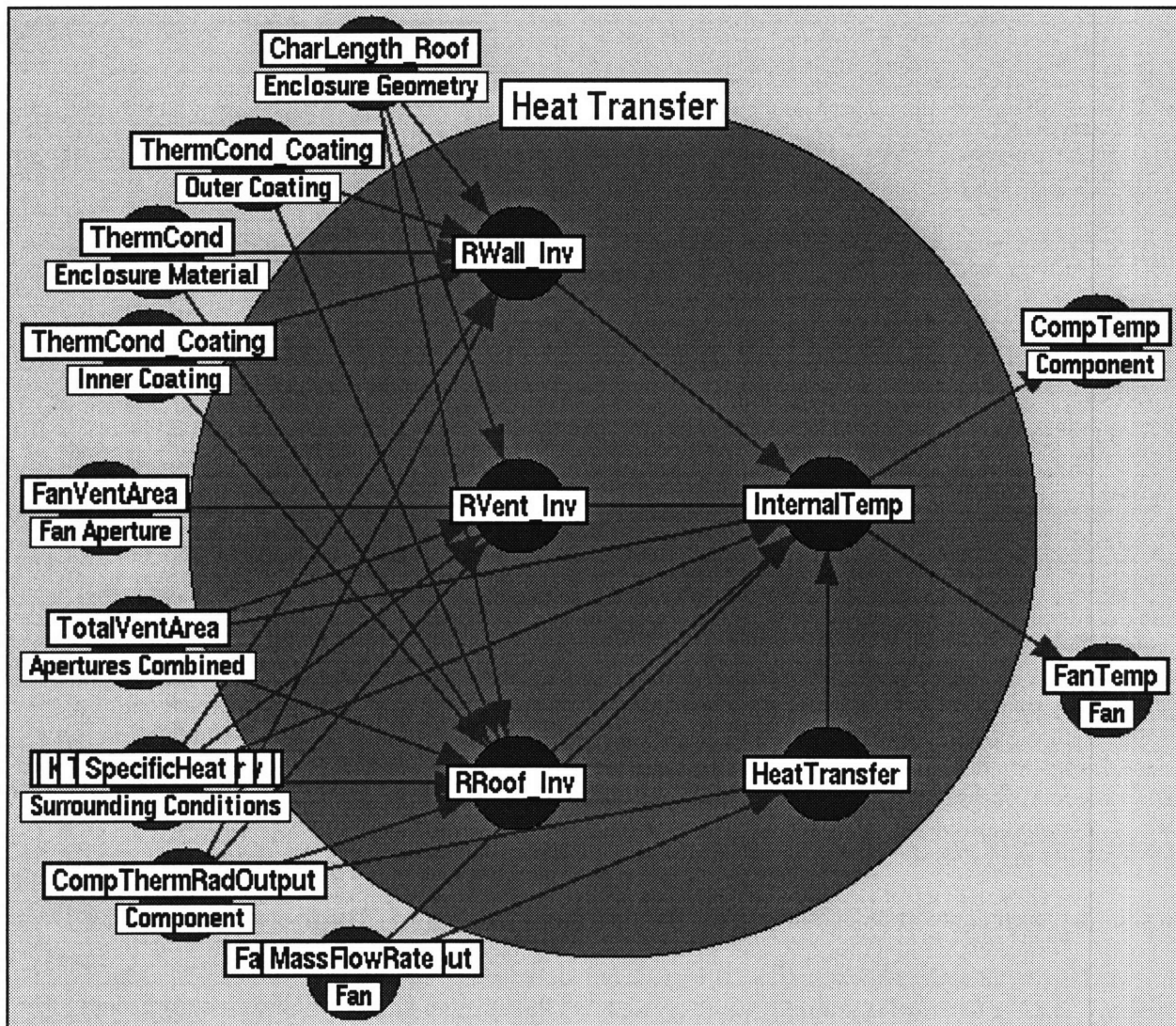


Figure 31: DOME Representation of the Heat Transfer Module

5.2.4 Environmental impact assessment

The *Environment* module, shown in Figure 32, provides an estimate of the environmental impact associated with the enclosure design. It evaluates the design according to the percentage of recycled material and energy used for its manufacture. The environmental evaluation lens summary is included alongside the module visualization.

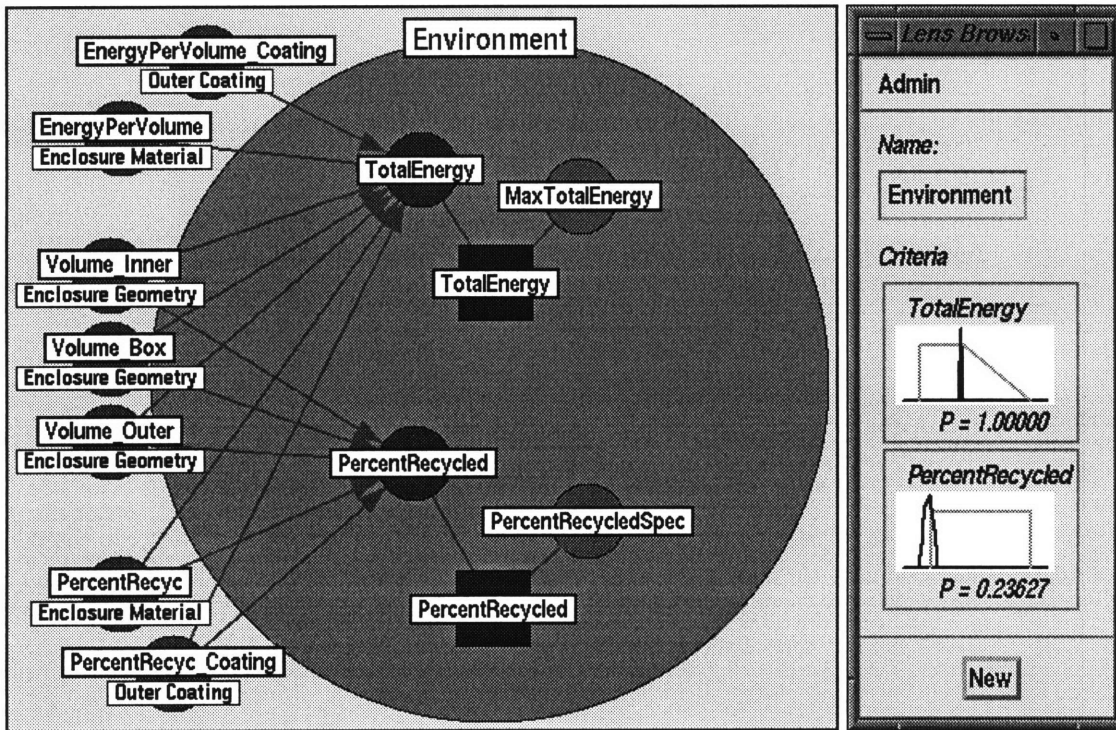


Figure 32: Environment Module and Evaluation Lens.

The mathematical models in this module were developed prior to the work on product life-cycles. As a result, their evaluation is based on the types and quantities of materials used and do not consider the enclosure's complete life-cycle. Work is currently underway in the CADLab to embed a specialized LCA tool within an environmental assessment module to provide detailed life-cycle assessment of a design's environmental impact. Once completed, it will be possible to integrate environmental analysis into any design problem that can provide the necessary input parameters. At present an environmental assessment package, TEAMTM, has been integrated in this way and has been applied to various example problems. However, it has not been applied to the enclosure design problem because the available materials database is incapable of evaluating many of the materials used in this example.

In addition, current environmental impact assessment tools, like TEAMTM, are not designed to take account of time-related inventory effects. It is therefore not possible to exploit all the information provided by the time-dependent product life-cycle model presented in this thesis. However, as the accuracy of LCA techniques improve, it is expected that this level of analysis will be required and that the model can then be fully utilized. In the interim, even the steady-state information provided by accurately considering recycling in product life-cycles can have a marked effect on the accuracy of environmental impact assessments currently being performed. For example, in section 4.4.1 the inclusion of recycling resulted in a substantial reduction in the network's steady-state requirement for new resources. A possible implementation of this application of the time-based inventory information is presented in section 5.6 which integrates the product life-cycle models into the enclosure design example.

5.3 Assembling the Integrated Model

The integrated enclosure design tool is shown in Figure 33. The evaluation summaries for the *Component* (PC Board) and *Environment* lenses are displayed on the right of the figure.

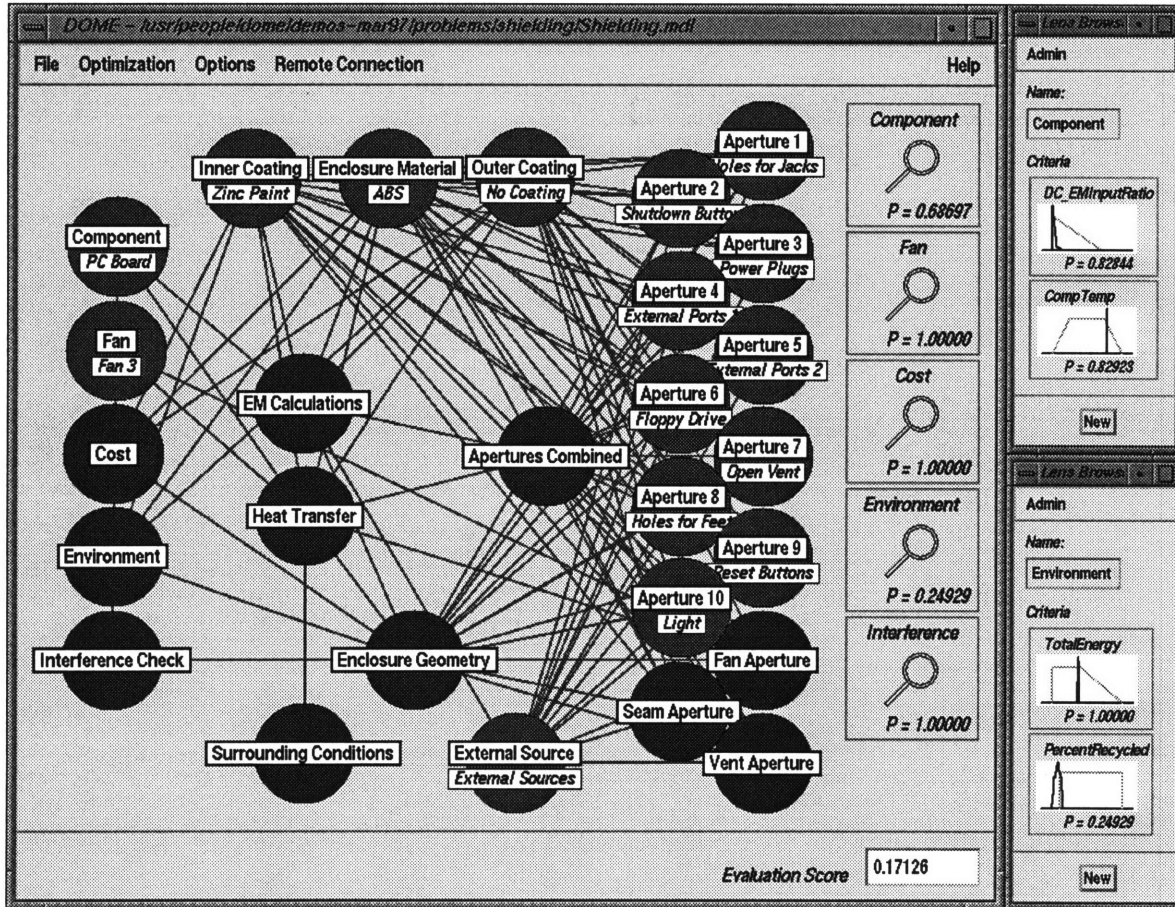


Figure 33: Integrated Enclosure Design Tool.

5.4 Exploring the Enclosure Design Problem

The previous sections used DOME to build a parametric design tool for the enclosure design example. In this section the tool is used to investigate the interactions inherent in the enclosure design problem and to identify good tradeoffs subject to the multiple requirements included. Design modifications are made by altering independent continuous design parameters or by replacing interchangeable modules through catalog selections. All changes propagate through the design providing interactive feedback on the effect of the changes relative to design goals. The geometric features are set to correspond to the enclosure shown in Figure 26.

Figure 34 shows the visualization and evaluation of a steel enclosure. The design requirements for the electronic component, cost, environment and geometric interference are grouped into lenses and the probability of each lens accepting the current design, P , is displayed. We can see that the steel enclosure is partially acceptable from the component's viewpoint ($P = 0.846$) but is completely unacceptable from the environment's perspective ($P = 0.000$). The design is partially acceptable based on cost ($P = 0.897$) and is acceptable with certainty from the geometric interference perspective ($P = 1.000$). The overall evaluation of the design, which aggregates the probabilities of acceptance, is unacceptable (Evaluation Score = 0.000).

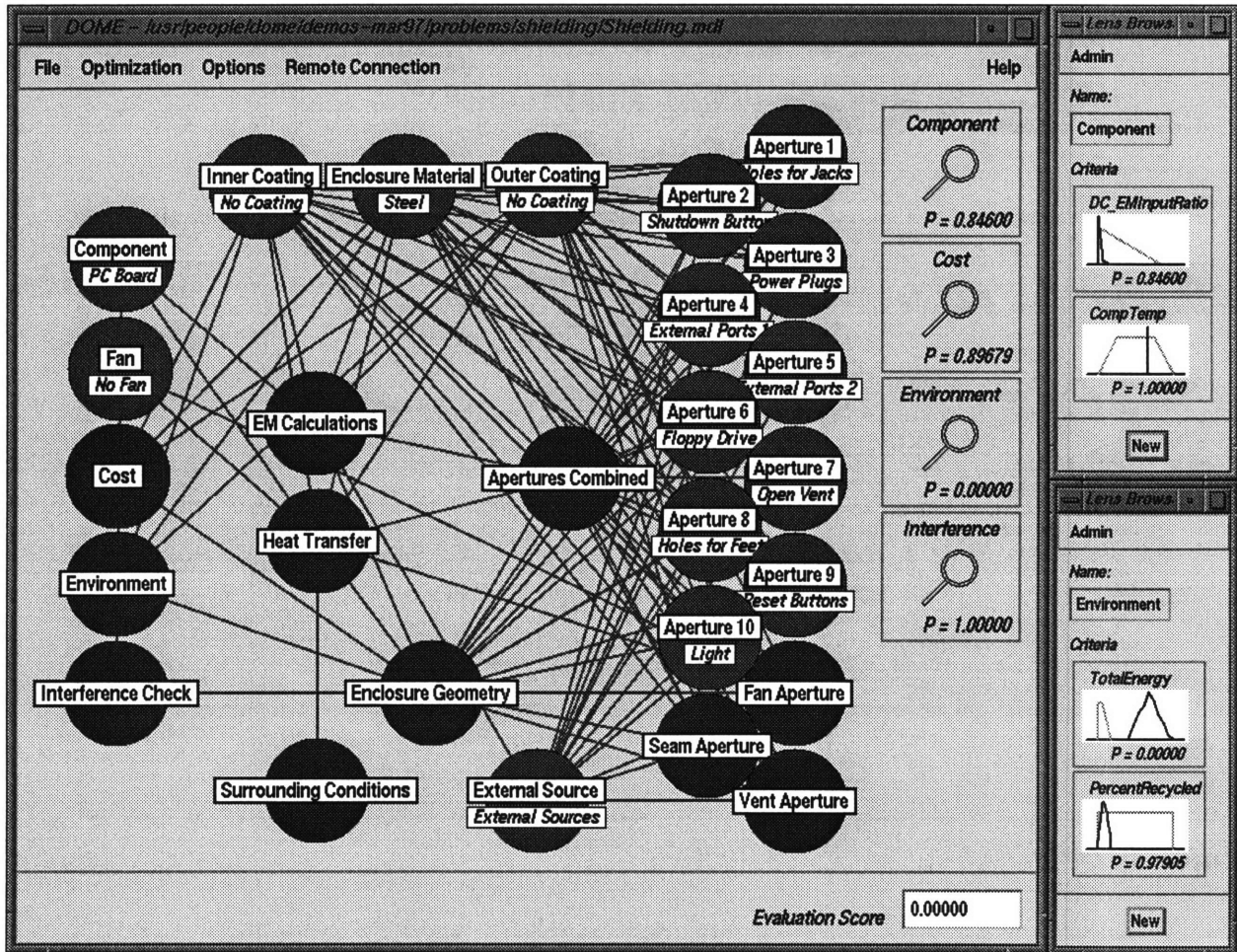
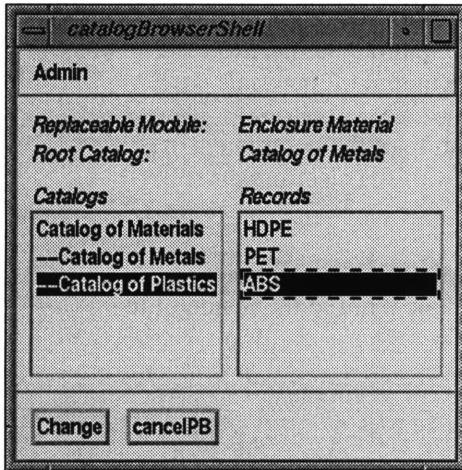


Figure 34: Design Visualization: Steel Enclosure.

The evaluation summaries for the *Component* and *Environment* lenses have been included to provide additional information about the design's performance relative to specific criteria. The component places requirements on the level of electromagnetic (EM) radiation entering the enclosure and internal temperature. The environmental lens evaluates the design based on the amount of energy and recycled material used to manufacture the enclosure. In the lens summaries, the light lines represent the required operating range for the design variables while the darker distributions represent the expected value resulting from the current design configuration. Section 2.3 provides further details about the evaluation scheme used.



It is clear from the lens summaries in Figure 34 that the overriding problem with the steel enclosure is the amount of energy used for its manufacture. To address this, let us change the enclosure material from steel to ABS (plastic). This substitution is done by selecting ABS from the catalog of enclosure materials, as shown in Figure 35.

Figure 35: Catalog Browser for Enclosure Materials.

In Figure 36, the evaluation of the ABS enclosure is shown along with the lens summaries for the component and environment lenses.

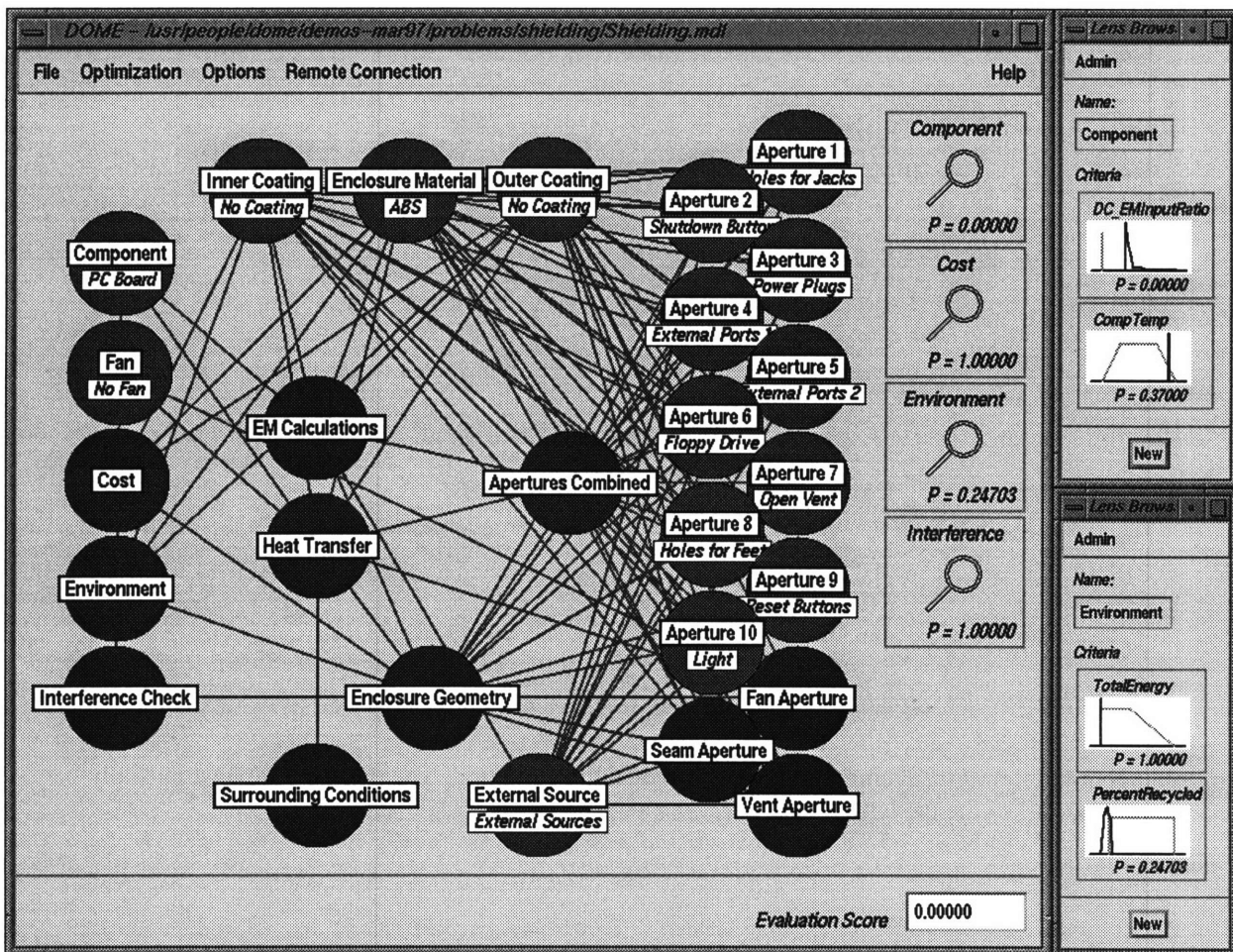


Figure 36: Enclosure Design: Plastic Enclosure (ABS).

As can be seen from the lens summaries included in Figure 36, the design scenario considered is:

- acceptable with regard to the design goal for the energy used in manufacture (*TotalEnergy*), but has a low probability of acceptance with respect to the recycled content of materials used (*PercentRecycled*).
- acceptable with regard to the design goals for operating temperature of the component (*CompTemp*) but completely unacceptable from the point of view of the electromagnetic shielding capacity (*DC_EMInputRatio*).

In this case, the unacceptable level of EM radiation causes the overall design evaluation to be unacceptable. This problem might be addressed by adding a coat of zinc paint to the inside of the enclosure as shown in Figure 37.

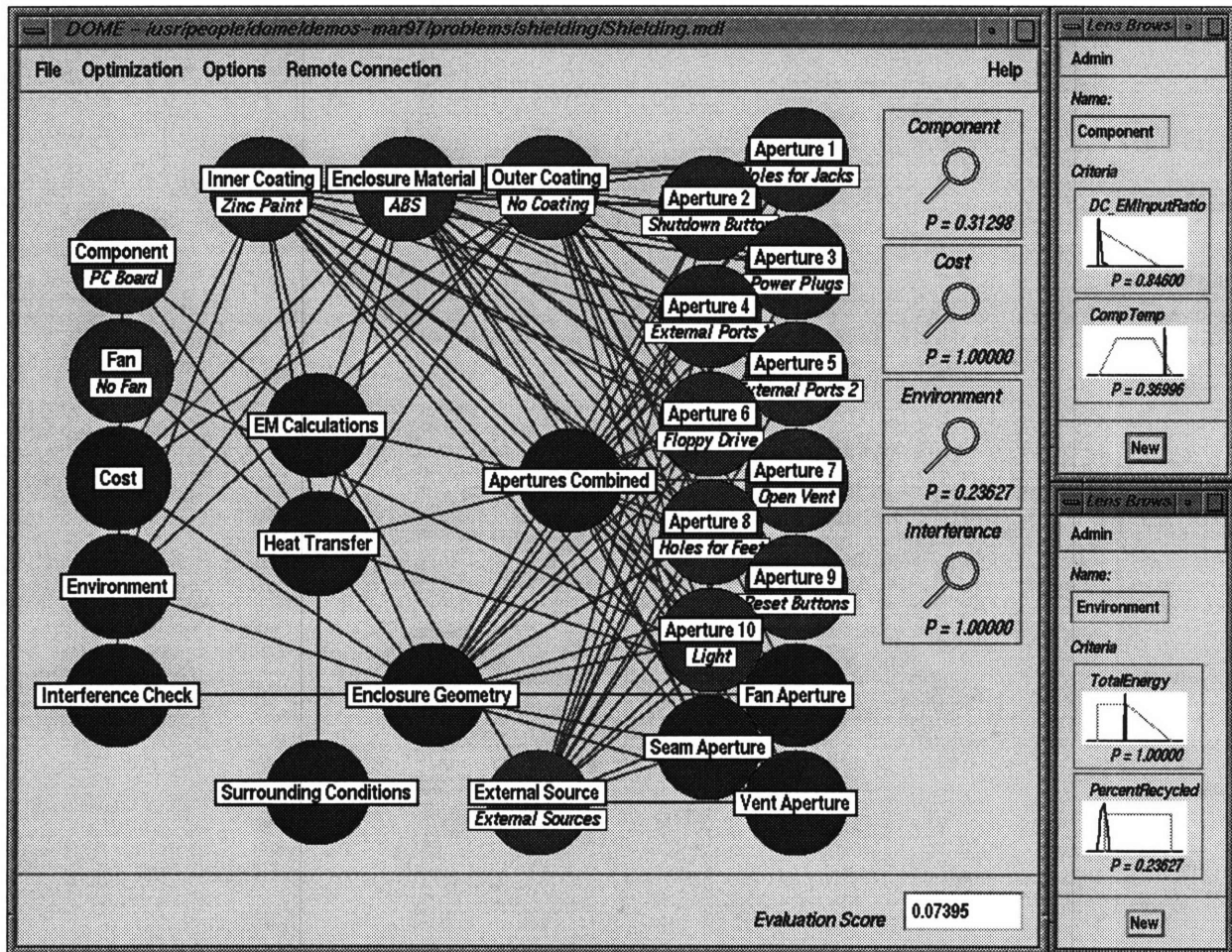
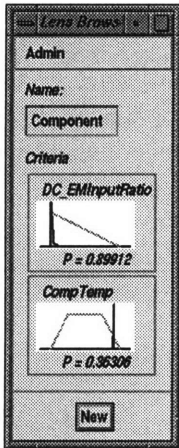


Figure 37: Enclosure Design: Plastic Enclosure (ABS) with Zinc Coating.

This change makes an improvement to the overall design evaluation. The design is at least partially acceptable from all of the design viewpoints.



It is interesting to note that the EM shielding performance of the zinc coated ABS enclosure shown in Figure 37 and steel enclosure shown in Figure 34 are practically equal ($P = 0.846$). This might seem counter-intuitive but further investigation into the model reveals that the amount of transmitted EM radiation is not particularly sensitive to the thickness of the metal layer (provided that there is a metal layer). The predominant factor determining the EM radiation is the existence of apertures in the enclosure. Evidence for this is given in Figure 38 which shows the component's lens summary for the design with the open vent removed (aperture 7 in Figure 37). The acceptability of the *EMInputRatio* has improved accordingly.

Figure 38: Component Lens Summary: ABS with Zinc Coating - Open Vent removed.

Next, let us see if we can improve the heat transfer characteristics of the enclosure by including a fan into the design. The evaluation of the enclosure design resulting from the inclusion of *Fan 3* is shown in Figure 39. Note that the *Fan* lens has been automatically included into the design evaluation.

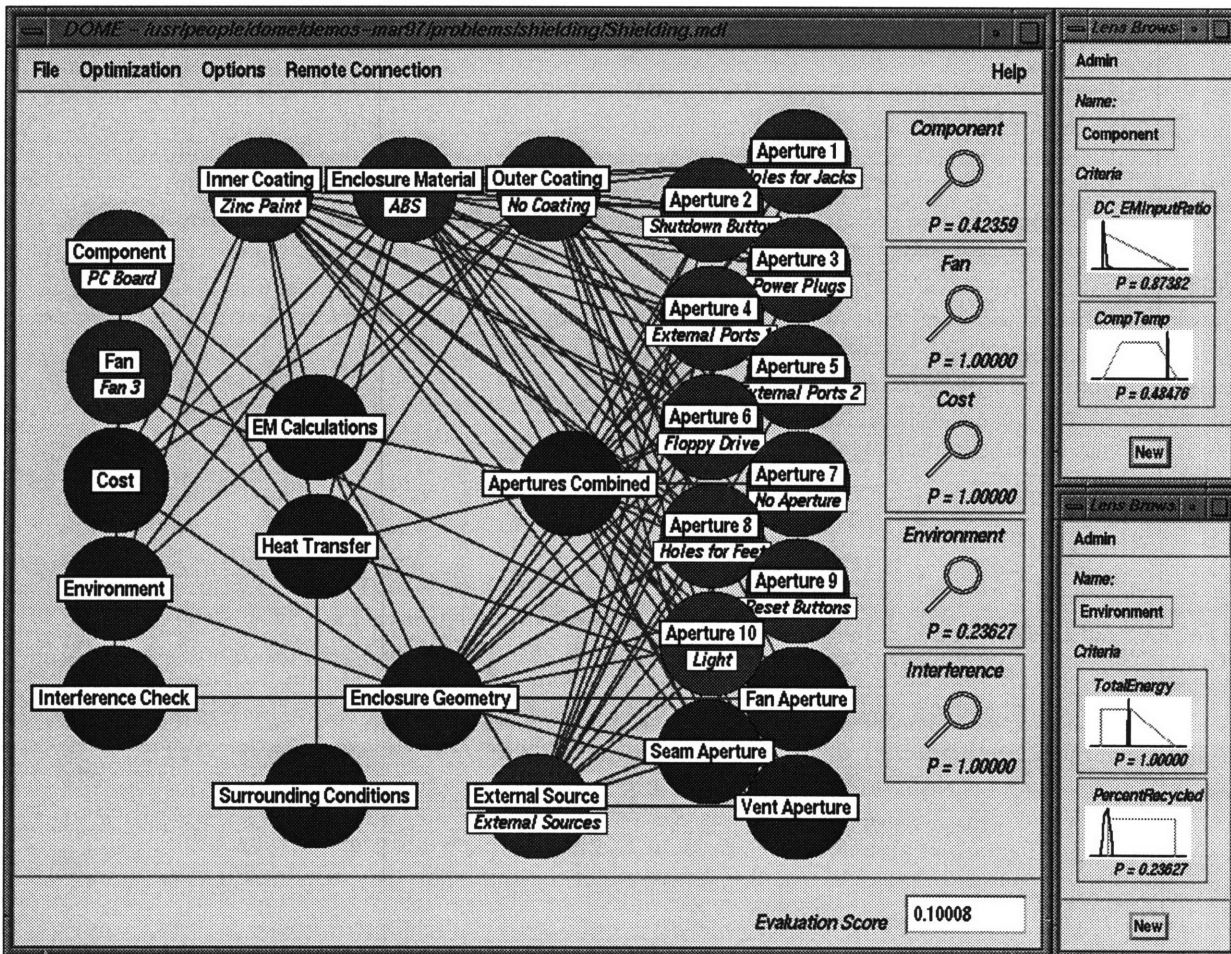
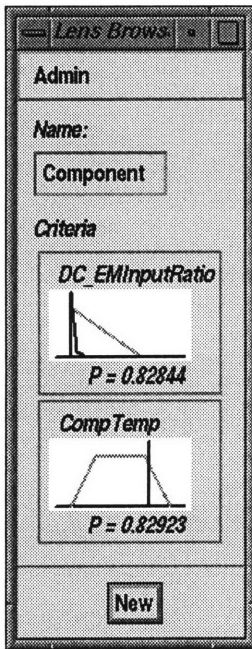


Figure 39: Enclosure Design: ABS with Zinc Coating and Fan - Open Vent removed.



However, this change has a negligible effect on the internal temperature (as shown by the component lens summary in Figure 39). This makes sense when we consider that the open vent was removed from the enclosure. Figure 40 shows the component's lens summary which results when the open vent is re-introduced. The overall design evaluation improves too (Evaluation Score = 0.16231).

Figure 40: Component Lens Summary: ABS with Zinc Coating, Fan and Open Vent.

All of the examples given have involved making design changes by selecting modules from catalogs. These changes bring sets of new variables and models into the design and thus result in the largest changes in the design. In addition to module substitutions, the designer can also interactively modify independent variables within modules. For example, the atmospheric temperature or geometric characteristics of the enclosure, which were described previously, can be changed to determine their effect on the design evaluation.

This example shows how the integrated design tool can help the designer to investigate and understand the relationships between various design characteristics. This can be useful for improving the overall quality of a design. However, the example also clearly illustrates the need for an optimization tool in order to find the best set of design tradeoffs. The optimization of the enclosure design problem is presented in the next section.

5.5 Optimization

As can be seen from the preceding section, there are complex interactions which exist between the various parts of the integrated model defined. By substituting interchangeable modules and manipulating individual parameters the user can obtain useful information about these interactions which provide a deeper understanding of the problem being modeled. However, with over 100 design variables that can be interactively manipulated in this complex design space it is not feasible to attempt to optimize the design through trial-and-error.

By using the optimization engine contained in DOME it is possible to stream-line this optimization procedure. Figure 41 shows the Optimization Browser for the enclosure design problem after having completed 150 generations of optimization.

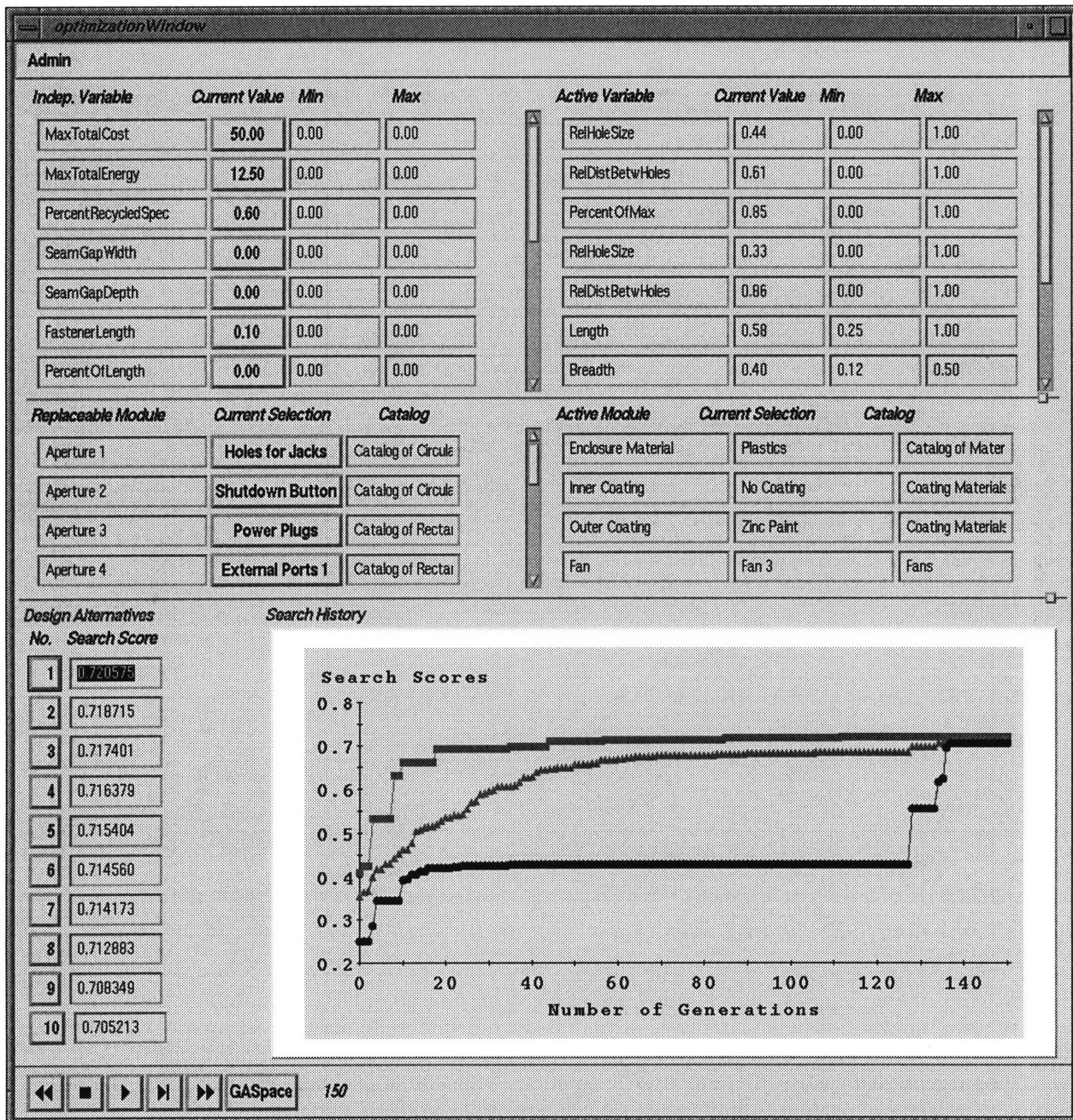


Figure 41: DOME Optimization Interface: Enclosure Design Problem.

The browser is divided into three main sections. The top section shows continuous variables, the central section shows modules which can be interchanged, and the bottom section provides a summary of the search history as it is carried out. In addition, the top two sections are subdivided with static variables on the left (excluded from optimization) and active variables on the right. Parameters can be activated or deactivated by dragging the relevant parameters from one side to the other. The user can define search limits for the active variables or use the default values determined by the program. The bottom section displays the evaluation scores for the design alternatives being considered by the genetic algorithm at each generation. The search history shows the progression of the best, average and worst evaluation scores during the search procedure.

The optimum solution for the enclosure problem as it is derived here is shown in Figure 42 along with the relevant evaluation lenses.

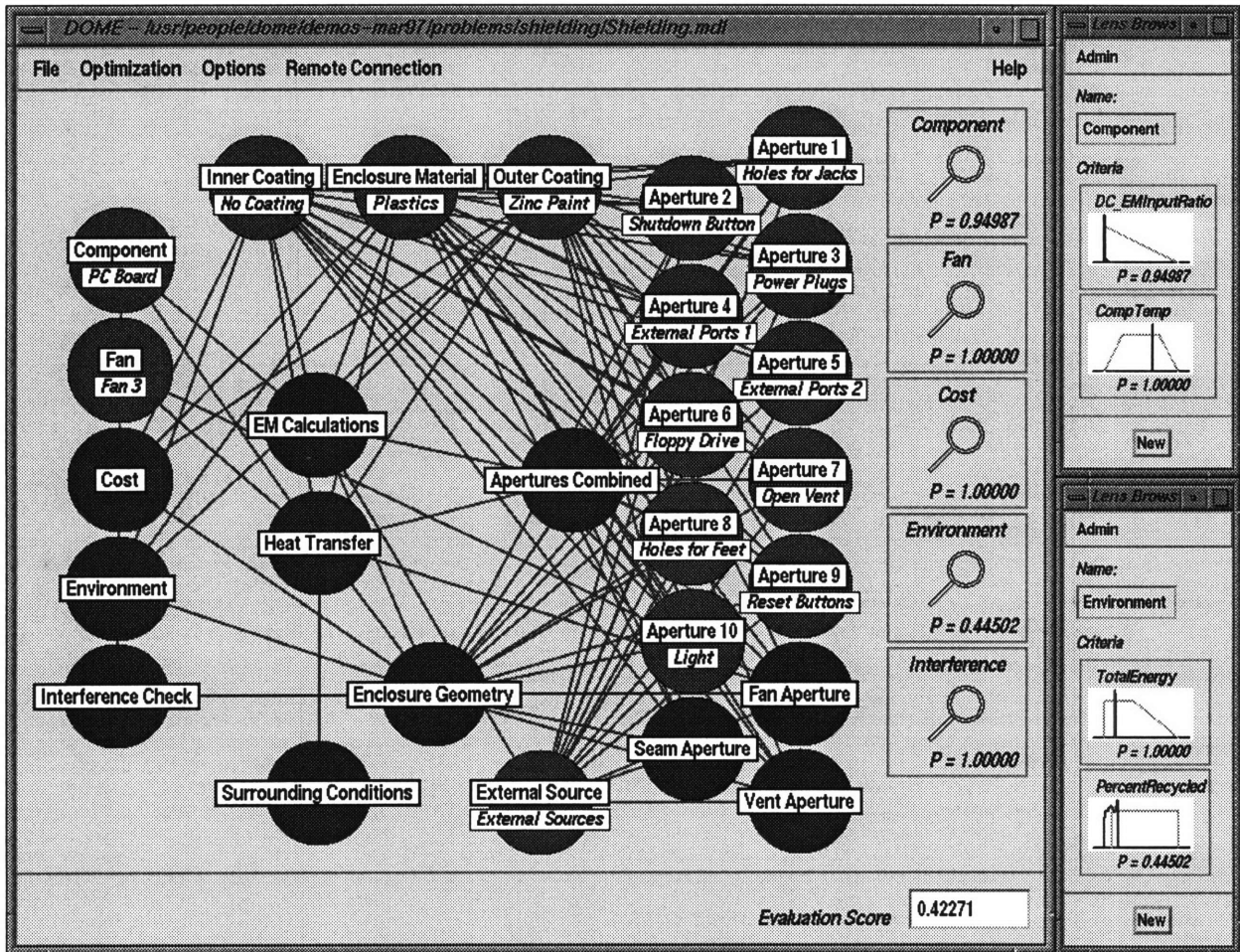


Figure 42: Optimized Enclosure Design.

In many cases the optimum solution is only one of many feasible solutions. The current algorithm used by the optimization engine is capable of finding the global optimum as well as multiple local optima within the problem's search space. This provides the designer with numerous alternatives which could represent vastly different physical solutions with similar evaluation scores. The usefulness of an optimization is limited by the accuracy of the problem model and by the specifications used for the optimization. If a specific area of a problem is determined to be critical to the design's evaluation, a more accurate model could be used to represent that area or the stringency of its related specifications could be increased. In this way the resulting design could be continuously optimized and improved.

5.6 Incorporating Time-based Inventory Information

While the existing environmental assessment module is not capable of directly exploiting the time-based life-cycle model presented, it can still make use of the increased accuracy obtained by considering the effect of recycling on the amount of new material required. This can be achieved by using the average quantity of new material used per product produced.

To implement this in DOME it is necessary to provide a link between the product life-cycle and the integrated enclosure design models. This can be done by introducing a *Production* module into the enclosure design example. In this way, the integrated problem (now the user) specifies the overall demand as a function of time and the appropriate product life-cycle network calculates the total amount of new material required to meet the demand. The updated enclosure design model is shown in Figure 43.

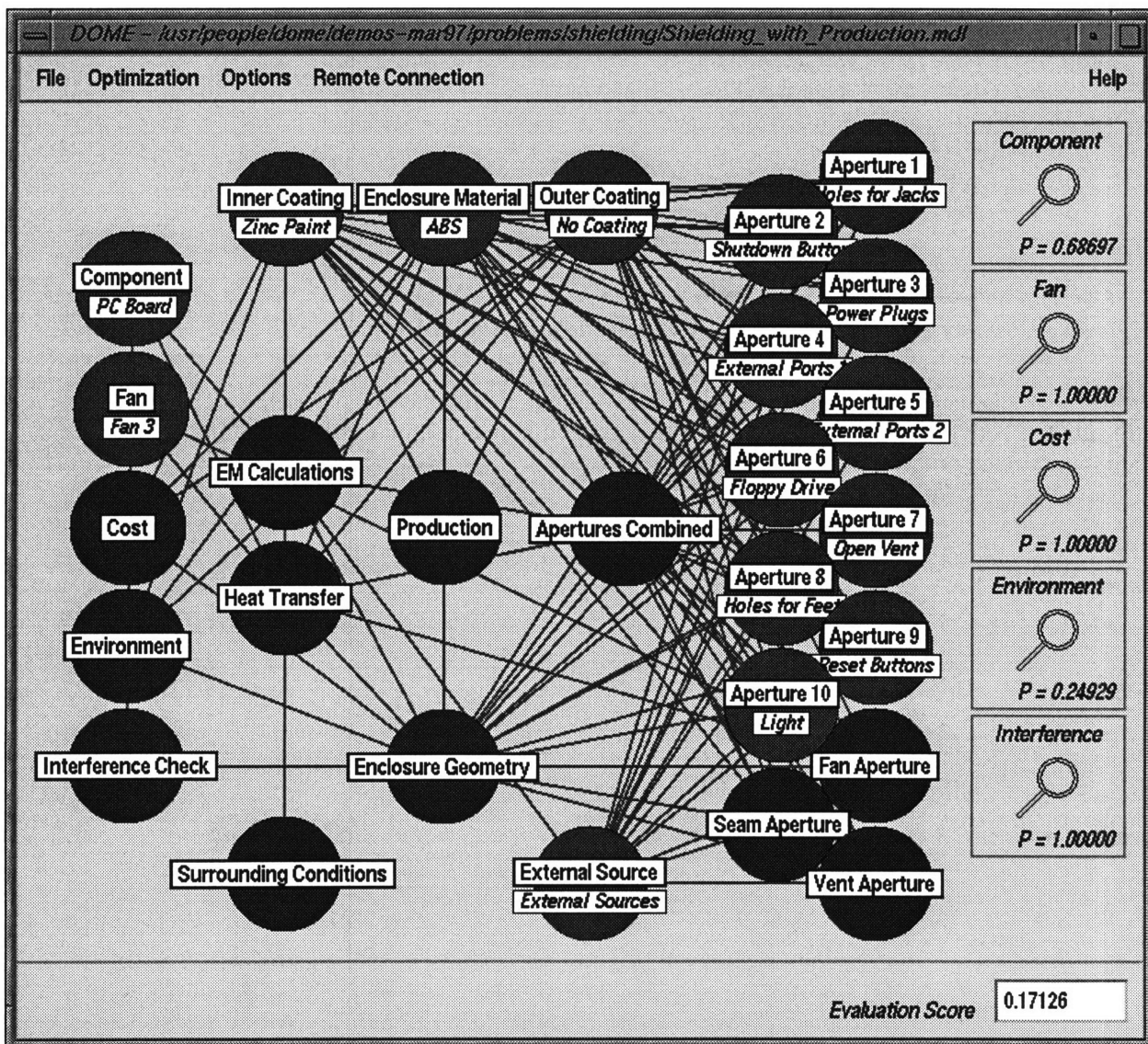


Figure 43: Integrated Design Example including Production Module.

In the current life-cycle model implementation, a separate network must be defined for each combination of enclosure materials to be considered. Figure 44 shows the network for the manufacture of the optimal enclosure design, a zinc-coated plastic enclosure. The connection to the enclosure design problem is achieved through the *User* module. This module specifies the *Overall Demand* for the product life-cycle and uses the resource flow magnitudes calculated by the network to evaluate the enclosure's environmental impact.

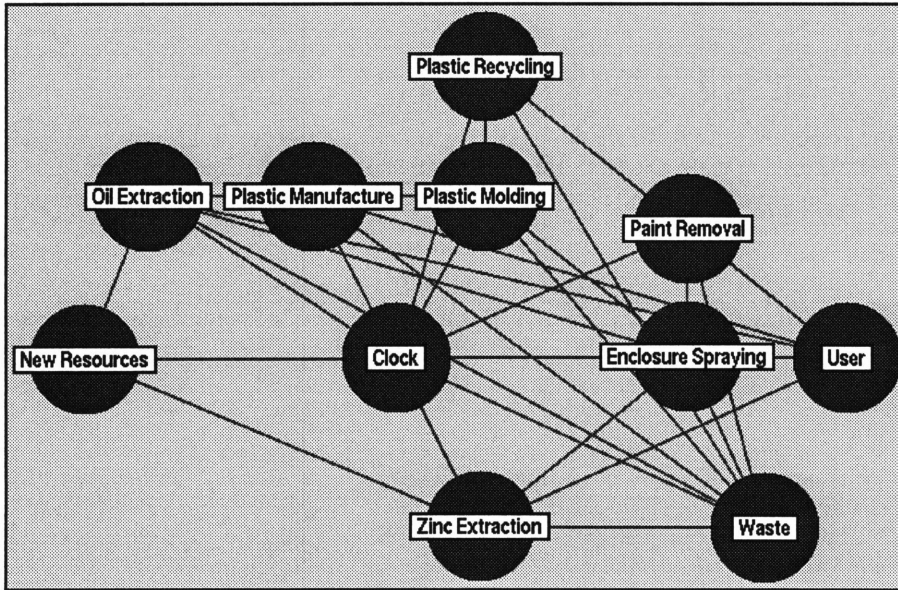


Figure 44: Product Life-cycle Network for Zinc-coated Plastic Enclosure.

While the implementation shown here is evidently limited, it provides an approach which can be utilized to effectively integrate the consideration of environmental impact assessment into a more traditional design procedure.

6. Conclusions

The research presented develops a modular method for modeling the resource flows related to complete product life-cycles as a function of time. The approach decomposes a product's life-cycle network into modular elements. This is accomplished by defining a generalized process module along with its related input and output resource flows. The relationship between a process' input and output flows is determined by the mathematical model embedded within the process module. A specific model is presented to represent "average" process behavior as a function of a set of empirical process parameters. A summary of the equations developed are included in the appendices. The generalized module can represent a wide variety of processes, ranging from material processing to usage, transportation and assembly. By linking process modules together, the user can represent complete manufacturing networks for product life-cycles. The concept of process demand is used to calculate flows in terms of a user-specified product demand, thus causing the life-cycle network to operate as a "pull system". Computer simulation is used to quantify the magnitudes of the required resource flows throughout the network as a function of time. The generality of the process module defined allows sections of a network to be embedded within larger modules, thus simplifying the system and facilitating the re-use of network sections in other product life-cycles.

This work is part of an ongoing effort to develop a framework to facilitate integrated product design. The current realization of this effort is the Distributed Object-based Modeling Environment software tool (DOME). A summary of the underpinnings of this framework is included for reference purposes. A simple product life-cycle example, modeled in DOME, is used to illustrate the implementation of the method. The example uses the generalized process module to represent different processes and illustrates the flexibility of the implementation by including additional functionality into the model. The resulting network is used to validate the product life-cycle model by observing its time-dependent response to various specifications of product demand. The inventory information derived from the time-based simulation is intended to be used in conjunction with specialized life-cycle assessment (LCA) tools to perform an environmental impact assessment which accounts for time-related effects.

Another example is also presented to illustrate the use of DOME for creating an integrated design tool. In the example, an integrated tool is developed for designing enclosures for electronic components. Electromagnetic (EM) radiation, heat transfer, environmental impact, cost and geometric interference are considered in the evaluation of the enclosure. The problem is decomposed into modules which are modeled independently. Summaries of the EM shielding and heat transfer models used are provided in the appendices. The completed tool is used to interactively investigate the relationships inherent in the enclosure design problem and to optimize the design. Existing LCA techniques are not designed to utilize the time-dependent inventory information provided by the product life-cycle method. Nevertheless, the example illustrates how the life-cycle method and specialized LCA software could be integrated to provide improved assessment of environmental impact. We believe that this information will become important for future impact assessments, especially in fields like toxicology where emission rates and material concentrations are critical factors.

The product life-cycle method presented has certain implementation issues which must be addressed before it can be fully utilized. A number of suggestions are provided for future work which will increase the flexibility of the network implementation and improve the ease with which networks can be built and altered.

7. Future Work on the Representation of Product Life-cycles

In order for a product life-cycle network to be useful as a design tool, it is necessary that the designer be able to change parts of the system without having to reconstruct a new network for each scenario. The current system allows the manipulation of parameters within individual processes (e.g., cycle time of a specific process) but it does not permit seamless changes such as: substituting a material, exchanging a module for an alternative process or replacing whole sections of a life-cycle network.

This section describes a number of proposals which require extensive research to be carried out before they can be included as part of the method presented. Nevertheless, their implementation would greatly enhance the use of the life-cycle representation as a design tool. Once implemented, these concepts will assist in allowing designers to carry out substitutions of materials and process alternatives without needing to redefine other aspects of the system.

7.1 Vector Mathematics in DOME

One of the limitations of the current product life-cycle implementation is its inability to handle multi-dimensional parameters. In particular, it is necessary to be able to efficiently handle multiple-resource flows. This was clearly seen in the implementation of the *Assembly* module in section 4.2.2. To address this issue, it is suggested that all the resource flows in the network be treated as vectors. Consequently, the ratios between input and output flows would be stored in the form of a *transformation matrix*. The transformation matrix should contain the performance parameters to define both linear (diagonal elements) and coupled (off-diagonal elements) flow relationships. By utilizing matrix algebra, the embedded model could rapidly interpret complex relationships between the various flows. This approach to process modeling lends itself to the application of state-space techniques and provides additional capacity for data manipulation and visualization.

7.2 Developing Material-Specific Definitions of Process Modules

Within any product, there are specific materials which are crucial in determining the product's characteristics. This is true when considering structural characteristics, but it is also true when considering the manufacture of the product. We will refer to these materials as *primary materials*. A product's primary materials affect the functioning of each of the processes within its life-cycle network. For example, a milling job using steel consumes significantly more energy than the same job using aluminum. To develop "intelligent" processes, it is essential that their embedded models reproduce this process-material dependency. Process models should be defined in terms of material-specific parameters. In some cases these relationships can be derived based on theory while in other cases, empirical regression models can be used to define the process model. This enhancement would permit the substitution of a product's primary materials which would initiate the adjustment of performance parameters throughout its life-cycle network.

The interdependency of processes and materials is also applicable when considering the substitution of processes or even whole sections of a life-cycle network. Many products could be manufactured using different process combinations. At present, a designer would need to define a separate network for each combination of processes to be considered. The implementation of material-dependent process models would permit the substitution of sections of a product's life-cycle in certain situations.

However, there is a limitation to the scope of this suggestion. Most processes have a set of secondary resource flows (e.g., solvents, lubricants and energy) which might also be material-dependent. It is conceivable that a completely different set of secondary flows might be required for different primary materials. For example, a cleaning process might use different chemicals for cleaning different materials. Material-dependent process models could adjust the magnitudes of existing secondary flows but they would be inadequate in situations where a change in primary material required a change in the secondary resources used. The development of resource modules, discussed in the next section, may be the key to finding a solution to this problem.

7.3 Developing Resource Modules

As was mentioned before, most resource flows do not represent a single material. For example, the output from a network may be specified in *automobiles-per-year*. However, for environmental assessment purposes, it is necessary to determine the quantities of specific chemicals flowing into and out of a network. This requires the translation of automobiles-per-year into kilograms of steel, copper, plastic etc. The obvious solution is to define each flow as a vector containing only base chemicals. However, this is not very useful from the designer's perspective. Imagine trying to represent a disassembly process where your input is in automobiles and your output is in individual components of the vehicle (e.g., tires, doors, etc.). The designer would have to define the chemicals composition of each component as a function of the quantity of chemicals composition of the complete vehicle.

A more elegant solution is to represent each resource as a module which contains the information required to re-construct its *history*. This information could be in the form of raw materials (e.g., kilograms of steel) or in the form of "smaller" modules representing product components (e.g., number of doors). In this way, the components of a resource module could be assembled, disassembled or even changed in a way which is intelligible to the designer. In addition, the chemicals contained within each module could be computed by summing the chemical constituents of all its parts. This representation would make it possible to consider complex products comprising numerous component parts which contain multiple materials.

By extending the concept of resource modules to secondary resources it may be possible to overcome the limitation on the material-specific process modules mentioned above. This could be achieved by defining standard secondary resource modules which include the inputs and outputs from their own manufacturing life-cycles. Primary materials could then contain a process parameter to specify which secondary resource module should be used for a given process. As a result, when a primary material was selected, the appropriate secondary resource modules would automatically be included into the network.

8. References

- [1] T. Lenau, "The Missing Element in Design for Manufacture," *Annals of the CIRP*, vol. 45, pp. 105-108, 1996.
- [2] O. Jolliet and P. Crettaz, "Critical Surface-Time 95 - A Life Cycle Impact Assessment methodology including fate and exposure.," ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE, Lausanne, Switzerland, Technical Report 12 November 1996.
- [3] D. O. Scharfstein and P. L. Williams, "Design of Developmental Toxicity Studies for Assessing Joint Effects of Dose and Duration," *Risk Analysis*, vol. 16, pp. 1057-1071, 1994.
- [4] N. Borland, "Building a design using DOME," CADLab, Massachusetts Institute of Technology, Cambridge, MA, User's Manual <http://cadlab.mit.edu/~nborland/documentation>, 1997.
- [5] P. Jackson and D. Wallace, "An analytical method for integrating environmental and traditional design considerations," *Annals of the CIRP*, 1997.
- [6] P. Jackson and D. Wallace, "A Modular Method for representing Product Life-cycles," presented at ASME Design Engineering Technical Conferences, Sacramento, CA, 1997.
- [7] F. Pahng, N. Senin, and D. Wallace, "A distributed object-based modeling and evaluation framework for product design," presented at ASME Design Engineering Technical Conferences, Sacramento, CA, 1997.
- [8] F. Pahng, N. Senin, and D. Wallace, "Distributed Object-based Modeling and Evaluation," *Accepted for publication by CAD*, 1997.
- [9] N. Senin and D. Wallace, "A framework for mixed parametric and catalog based product design," MIT CADLab, Cambridge, MA, Technical Report 97.02, 1997.
- [10] L. Alting and J. B. Legarth, "Life Cycle Engineering and Design," *Annals of the CIRP*, vol. 44, pp. 569-580, 1995.
- [11] J. Fiksel, *Design for Environment*. New York: McGraw-Hill, 1996.
- [12] T. E. Graedel and B. R. Allenby, *Industrial Ecology*. Englewood Cliffs, New Jersey: Prentice Hall, 1995.
- [13] L. Batelle and Franklin Associates, "Life-Cycle Assessment: Inventory Guidelines and Principles," Environmental Protection Agency, Columbus, Ohio January 1993.
- [14] M. Menke, G. A. Davis, and B. W. Vigon, "Evaluation of Life-cycle Assessment Tools," Environment Canada - Hazardous Waste Branch, Ottawa, Canada August 1996.
- [15] Delft University of Technology, "IDEMAT," 19 ed. Delft, The Netherlands: Delft University of Technology, 1995.
- [16] ifu and ifeu, "Umberto - An Interactive Program for creating Eco-balances on the Basis of Material Flow Networks," 1.5 ed. Hamburg and Heidelberg, Germany: ifu and ifeu, 1995.
- [17] S. Onkvisit and J. J. Shaw, *Product Life Cycles and Product Management*. New York: Quorum Books, 1989.
- [18] L. H.-L. Shu, "Application of a Design-for-Re manufacture Framework to the Selection of Product Life-Cycle Fastening and Joining Methods," in *Mechanical Engineering*. Cambridge: Massachusetts Institute of Technology, 1996, pp. 75.
- [19] B. A. Ogunnaik and W. H. Ray, *Process Dynamics, Modeling, and Control*. New York: Oxford University Press, 1994.
- [20] A. Carrie, *Simulation of Manufacturing Systems*. New York: John Wiley & Sons, 1988.
- [21] J. L. Peterson, *Petri net theory and the modeling of systems*. Englewood Cliff, New Jersey: Prentice-Hall, 1981.
- [22] C. Y. Wong, T. S. Dillon, and K. E. Forward, "Timed Places Petri Nets with Stochastic Representaion of Place Time," *IEEE - International Workshop on Petri-Nets*, 1985.
- [23] J. G. Miller, *Living Systems*. New York: McGraw-Hill, 1978.
- [24] P. N. Koch, J. D. Peplinski, J. K. Allen, and F. Mistree, "Configuring Systems at the Functional Level of Abstraction. A Conceptual Exposition," *Engineering Design and Automation*, vol. 1, pp. 73-91, 1995.

- [25] P. Sheng and A. A. Munoz, "Analytical approach for determining the environmental impact of machining processes," *Journal of Materials Processing Technology*, vol. 53, pp. 736-758, 1995.
- [26] C. H. Amon, S. Finger, F. B. Prinz, and L. E. Weiss, "Modeling Novel Manufacturing Processes," *ASME*, vol. 68, pp. 535-546, 1994.
- [27] H. Ott, *Noise Reduction Techniques in Electronic Systems*. New York: John Wiley, 1976.
- [28] R. Perez, "Handbook of Electromagnetic Compatibility," . New York: Academia Press, Inc., 1995.
- [29] J. L. Violette, *Electromagnetic Compatibility Handbook*. New York: Van Nostrand Reinhold Company, 1987.
- [30] D. R. J. White, *A handbook on shielding design methodology and procedures: Interference Control Technologies*, 1986.
- [31] D. R. Wallace, M. Jakiela, and W. Flowers, "Design search under Probabilistic Specifications using Genetic Algorithms," *Computer-aided Design*, vol. 28, 1996.
- [32] R. Mills, "Are There Objects in Your CAD Future?," in *Computer-Aided Engineering*, 1996, pp. 50-56.
- [33] R. L. Keeney and H. Raiffa, *Decisions with Multiple Objectives: Preferences and Value Tradeoffs*. New York, NY: John Wiley and Sons Inc., 1976.
- [34] T. L. Saaty, *The Analytic Hierarchy Process*. New York, NY: McGraw-Hill Book Company, 1980.
- [35] N. P. Suh, *The Principles of Design*. New York: Oxford University Press, Inc., 1990.
- [36] T. Gruninger and D. Wallace, "Multimodal optimization using genetic Algorithms," *Submitted to Evolutionary Computing for review*, 1997.
- [37] N. Senin, D. R. Wallace, and M. J. Jakiela, "Mixed Continuous Variable and Catalog Search Using Genetic Algorithms," presented at Proceedings of the ASME Design Technical Conferences, Irvine, CA, 1996.
- [38] Y. Iwasa, *Case Studies in Superconducting Magnets*. New York: Plenum Press, 1994.
- [39] J. P. Holman, *Heat Transfer*, 6th ed. New York: McGraw-Hill Book Company, 1986.

Appendices

Appendix A : Definition of Equations for Generalized Process Module.	62
Appendix B : Development of Electromagnetic Shielding Models.	65
Appendix C : Development of Heat Transfer Models.	74

Appendix A: Definition of Equations for Generalized Process Module.

This section contains the set of difference equations which are embedded within the generalized process module in the body of the thesis. Refer to Figure 9 for a summary of the steps performed during each time step. The equations given provide the basic equations to be used for a single-material process. Loops and error checking have been omitted for the purpose of clarity. Table 6 provides an explanation of the variables used in these equations.

Table 6. Definition of Variables for Embedded Equations.

Variable	Description
t	Time
dt	Time increment for each iteration
tCycle	Process cycle time
tStart	Start time (sum of cycle times for processes upstream)
Capacity	Maximum quantity of resources produced at any point in time
Max%Recycled	Maximum percentage of input to comprise recycled resources
Product/Input	Quantity of Product produced per unit of input
Recyclable/Input	Quantity of Recyclable output produced per unit of input
Waste/Input	Quantity of Waste produced per unit of input
Demand(t)	Total output required from process - as a function of time
NewDemand(t)	New resources required by process - at each time step
ExcessDemand(t)	Shortfall in process production - to be recouped as soon as possible
InputDemand(t)	Total input required to meet process demand - at time (t)
NewSupply(t)	Product output from an upstream process
RecSupply(t)	Output from an upstream recycling process
NewBuffer(t)	Quantity of new resources available to process
RecBuffer(t)	Recycled resources available to process
Input(t)	Total input at time (t) - (Input(t) < Capacity)
NewInput(t)	New resources used at each time step
RecInput(t)	Recycled resources used at each time step
ProductOut(t)	Product output as a function of time
RecyclableOut(t)	Recyclable resources exiting process at each time step
WasteOut(t)	Resources exiting process which designer considers as waste

The structure shown here can be adapted and altered to represent whatever process is being modeled. For processes with multiple materials (vectors), a transformation matrix should be used to define the interactions between the input and output vectors.

DEMAND PULSE.

Calculate the process' output demand:

$$Demand(t) = NewDemand_{downstream}(t) \quad 1$$

Calculate the quantity of new resources required:

$$NewDemand(t) = \frac{Demand(t)}{Product/Input} - RecBuffer(t) \quad 2$$

SUPPLY PULSE.

Calculate the total quantity of input required to meet the specified demand:

- If Capacity > Demand(t-tStart):

$$InputDemand(t) = \frac{Demand(t - tStart) + ExcessDemand(t - dt)}{Product/Input} \quad 3$$

- Otherwise:

$$InputDemand(t) = \frac{Capacity}{Product/Input} \quad 4$$

Set the values for the process buffers:

$$\begin{aligned} RecBuffer(t) &= RecBuffer(t - dt) + RecSupply(t - dt) - RecInput(t - dt) \\ NewBuffer(t) &= NewBuffer(t - dt) + NewSupply(t - dt) - NewInput(t - dt) \end{aligned} \quad 5$$

Calculate the input values for the process.

- If both New and Recycled buffers contain sufficient material to meet demand at maximum % recycled material:

$$\begin{aligned} Input(t) &= inputDemand(t) \\ RecInput(t) &= [Max\%Recycled][Input(t)] \\ NewInput(t) &= [1 - Max\%Recycled][Input(t)] \end{aligned} \quad 6$$

- If Recycled buffer has insufficient material to meet demand at maximum % recycled material, But New buffer has sufficient material to meet demand anyway:

$$\begin{aligned} Input(t) &= inputDemand(t) \\ RecInput(t) &= RecBuffer(t) \\ NewInput(t) &= Input(t) - RecInput(t) \end{aligned} \quad 7$$

- If there is insufficient material to meet demand at maximum % recycled material, And the ratio of recycled material to new material is greater than the maximum allowable ratio:

$$\begin{aligned} NewInput(t) &= NewBuffer(t) \\ Input(t) &= \frac{NewInput(t)}{1 - Max\%Recycled} \\ RecInput(t) &= [Max\%Recycled][Input(t)] \end{aligned} \quad 8$$

- If there is insufficient material to meet the demand, And the ratio of recycled material to new material is less than the maximum allowable ratio:

$$\begin{aligned} NewInput(t) &= NewBuffer(t) \\ RecInput(t) &= RecBuffer(t) \\ Input(t) &= NewBuffer(t) + RecBuffer(t) \end{aligned} \quad 9$$

Set the value of ExcessDemand for the next time step:

$$ExcessDemand(t) = [InputDemand(t) - Input(t)][Product/Input] \quad 10$$

Set values of process outputs:

$$ProductOut(t) = [Product/Input][Input(t - tCycle)]$$

$$RecycleableOut(t) = [Recyclable/Input][Input(t - tCycle)] \quad 11$$

$$WasteOut(t) = [Waste/Input][Input(t - tCycle)]$$

Minimizing Cost:

If the objective is to minimize cost instead of maximizing recycled material usage and the cost of recycled resources greater than cost of new resources, then replace the section for “calculating the input values” with:

- If there is sufficient material in the New buffer to meet demand:

$$NewInput(t) = InputDemand(t)$$

$$Input(t) = NewInput(t)$$

$$RecInput(t) = 0 \quad 12$$

- If there is insufficient material in the New buffer to meet demand,
But there is sufficient material in the Recycled buffer to make up the shortfall without exceeding the maximum allowable % recycled material:

$$NewInput(t) = NewBuffer(t)$$

$$RecInput(t) = InputDemand(t) - NewInput(t)$$

$$Input(t) = NewInput(t) + RecInput(t) \quad 13$$

- If there is insufficient material in the New buffer to meet demand,
And the ratio of recycled material to new material is greater than the maximum allowable ratio:

$$NewInput(t) = NewBuffer(t)$$

$$Input(t) = \frac{NewInput(t)}{1 - Max\%Recycled}$$

$$RecInput(t) = [Max\%Recycled][Input(t)] \quad 14$$

- If there is insufficient material to meet the demand,
And the ratio of recycled material to new material is less than the maximum allowable ratio:

$$NewInput(t) = NewBuffer(t)$$

$$RecInput(t) = RecBuffer(t)$$

$$Input(t) = NewBuffer(t) + RecBuffer(t) \quad 15$$

Appendix B: Development of Electromagnetic Shielding Models.

It is well known that even a thin layer of metal can provide adequate electromagnetic (EM) shielding for all but the most sensitive electronic components. However, the occurrence of apertures compromises the integrity of an enclosure. Equations to predict the levels of shielding effectiveness (SE) and to estimate the effects of apertures on the integrity of a single layer of shielding material have been developed and are presented by Perez, Violette and White [28-30]. The variables used in this appendix are provided for reference in Table 7, followed by the development of the relevant EM shielding equations.

Table 7: Variables for Shielding Effectiveness Calculations.

Symbol	Definition	Units
λ	wavelength	m
c	speed of light	3e8 m/s
f	frequency	Hz
r	distance from EM source to target	m
μ	magnetic permeability	Henries/m
μ_0	magnetic permeability of free space	$4e-7 \times \pi$ Henries/m
σ	electrical conductivity	$(ohm.m)^{-1}$
σ_o	electrical conductivity of copper	$5.8e7 (ohm.m)^{-1}$
ϵ	permittivity	Farads/m
ϵ_0	permittivity of free space	$(36e9 \times \pi)^{-1}$ Farads/m
Z	electromagnetic impedance	ohms
Z_0	impedance of Free Space	377 ohms
Z_a	effective aperture impedance	ohms
Z_w	wave impedance	ohms
K_{ij}	ratio of impedances at interface - between materials (i, j)	
p_{ij}	normalized reflected EM field at interface - between materials (i, j)	
γ	propagation constant for specific material	
Γ	EM field strength	V/m
t	thickness of individual shielding layers	m
l	depth of aperture (sum of thicknesses)	m
w	maximum width of rectangular aperture	m
D	diameter of circular aperture	m
d	distance between holes for multiple apertures	m
δ	skin depth	m
SE	shielding effectiveness	
A	aperture absorption loss	dB
R	aperture reflection loss	dB
B	aperture re-reflection loss correction	dB
K1	multiple aperture correction	dB
K2	Low Frequency field penetration correction	dB
K3	coupling between holes	dB

Derived Variables for the Electromagnetic calculations.

Wavelength of incident waves: [29, p 311]

$$\lambda = \frac{c}{f} \quad 16$$

Wave Impedance: [29, p 314-317]

$$\begin{aligned} \text{for: } r > \frac{\lambda}{2\pi} \quad Z_w &= Z_0 \\ \text{for: } r \leq \frac{\lambda}{2\pi} \quad Z_w &= Z_0 \left(\frac{\lambda}{2\pi r} \right) \quad \text{High impedance source (electrical waves)} \\ Z_w &= Z_0 \left(\frac{2\pi r}{\lambda} \right) \quad \text{Low impedance source (magnetic waves)} \end{aligned} \quad 17$$

Intrinsic Impedance of materials: [29, p 317-318]

$$Z_i = \sqrt{\frac{j2\pi f \mu_i}{\sigma_i + j2\pi f \epsilon_i}} \quad 18$$

for metals:

$$\epsilon \cong 0$$

$$Z = \sqrt{\frac{j2\pi f \mu_i}{\sigma_i}} \quad 19$$

for non-metals:

$$\sigma \cong 0 \quad \text{and} \quad \epsilon \cong \epsilon_0$$

$$Z \cong \sqrt{\frac{\mu_0}{\epsilon_0}} \quad \text{(based on assumed values)} \quad 20$$

Ratio of Impedances at interface between materials: [29, p 312]

$$K_{ij} = \frac{Z_i}{Z_j} \quad 21$$

Normalized reflected Electromagnetic field at interfaces: [29, p 312]

The fraction of the incident field which is reflected by an interface between two materials with different intrinsic impedances.

$$P_{ij} = \frac{1 - K_{ij}}{1 + K_{ij}} = -P_{ji} \quad 22$$

Propagation constant for shielding layers and resulting propagation ratio: [29, p 323-325]

This quantity determines the ratio between the amplitudes of the field propagated through a material and the incident field.

$$\gamma_i = \sqrt{j2\pi f \mu_i (\sigma_i + j2\pi f \epsilon_i)}$$

$$\text{propagation ratio}_i = e^{-\gamma_i t_i}$$

23

for metal layers:

$$\epsilon \cong 0$$

$$\gamma = \sqrt{j2\pi f \mu \sigma}$$

24

for non-metal layers:

$$\sigma \cong 0 \text{ and } \epsilon \cong \epsilon_0$$

$$\gamma \cong j2\pi f \sqrt{\mu_0 \epsilon_0}$$

(based on assumed values)

25

SE Equations for Single Shielding Layer.

Figure 46 illustrates the attenuation of EM radiation for a single layer of material [29, p 322-324].

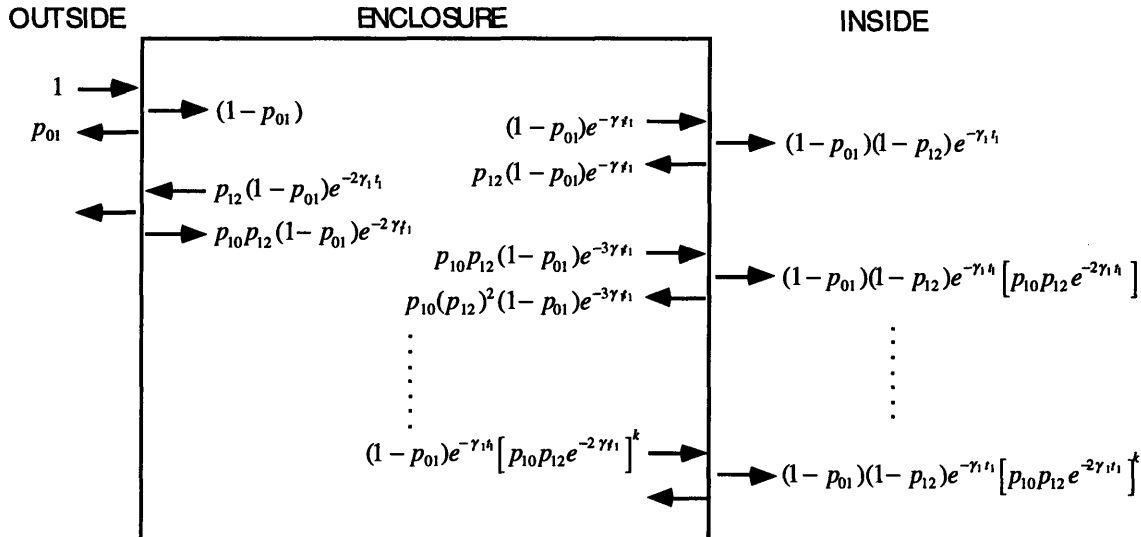


Figure 46: Transmission of EM Radiation through a Single Layer of Material.

The following equation results:

$$\frac{\Gamma_{\text{transmitted}}}{\Gamma_{\text{incident}}} = \sum_{i=0}^{\infty} \left[(1-p_{01})(1-p_{12})e^{-\gamma_i t_i} (p_{01} p_{12} e^{-2\gamma_i t_i})^i \right]$$

but this is a convergent geometric series:

$$\therefore \frac{\Gamma_{\text{transmitted}}}{\Gamma_{\text{incident}}} = \frac{(1-p_{01})(1-p_{12})e^{-\gamma t_1}}{1-p_{01} p_{12} e^{-2\gamma t_1}} = \frac{(1-p_{01})(1-p_{12})e^{-\gamma t_1}}{1+p_{10} p_{12} e^{-2\gamma t_1}}$$

26

The shielding effectiveness (SE) of a single layer of shielding material without apertures is thus defined as:

$$SE = \frac{\Gamma_{incident}}{\Gamma_{transmitted}} = \frac{1 + p_{01}p_{12}e^{-2\gamma_1 t_1}}{(1 - p_{01})(1 - p_{12})e^{-\gamma_1 t_1}} \quad 27$$

Equations for Aperture Losses in a Single Layer of Shielding Material.

Skin Depth of material: [29, p 320]

$$\delta = \frac{\sqrt{2}}{\sigma Z} = \frac{1}{\sqrt{\pi f \mu \sigma}} \quad 28$$

As was stated above, the existence of apertures undermines the shield's ability to limit the level of radiation transmitted. Table 8 contains a set of empirical equations which estimate the effect of apertures on the integrity of a single layer of shielding material [29, p 330].

Table 8: Aperture Equations - The Effect of Apertures on Shielding Effectiveness.

	Rectangular	Circular
Aa	$27.3 \left(\frac{l}{w} \right)$	$32 \left(\frac{l}{D} \right)$
Ra	$20 \log_{10} \left[0.785 \left(\frac{r}{w} \right) \right] \quad Z_w \ll 377 \Omega$ $20 \log_{10} \left[\frac{1 + (1.7 \times 10^{-4} fw)^2}{4(1.7 \times 10^{-4} fw)} \right] \quad Z_w \cong 377 \Omega$	$20 \log_{10} \left[0.92 \left(\frac{r}{D} \right) \right] \quad Z_w \ll 377 \Omega$ $20 \log_{10} \left[\frac{1 + (1.47 \times 10^{-4} fD)^2}{4(1.47 \times 10^{-4} fD)} \right] \quad Z_w \cong 377 \Omega$
Ba	$20 \log_{10} [1 - 10^{-A/10}] \quad \frac{w}{\pi r}, \frac{D}{3.686r} \ll 1$	
K1	$-10 \log_{10} [an] \quad r \gg w, D$ $0 \quad r \ll w, D$	
K2	$-20 \log_{10} \left[1 + 35 \left(\frac{d}{\delta} \right)^{-2.3} \right]$	
K3	$20 \log_{10} \left[\coth \left(\frac{A_a}{8.686} \right) \right]$	

The reduction in shielding effectiveness due to the existence of apertures is calculated by combining the various factors in the following way:

$$SE_{apertures} [dB] = A_a + R_a + B_a + K_1 + K_2 + K_3 \quad 29$$

and,

$$SE_{aperture} = 10^{\left(\frac{SE_{aperture} [dB]}{20} \right)} \quad 30$$

Calculating the Overall Shielding Effectiveness.

The overall shielding effectiveness is determined by adding the fields transmitted through the enclosure and apertures in parallel [29, p 334-335].

$$SE = \frac{1}{\frac{1}{SE_{enclosure}} + \sum \frac{1}{SE_{apertures}}}$$

31

Limitations of single-layer equations.

The fundamental problem with the equations shown is their limited applicability to single-layer metal enclosures. Thus, the equations can not be used to represent the common case of multiple-layer enclosures (e.g. metal coated plastic enclosures). As a result of the inadequacy of the models available, the design of EM shielding is typically done by adapting existing enclosure designs or by trial-and-error.

In order to implement a mathematical design process, it is essential to be able to accurately model the EM shielding capability of multiple-layer shields. For solid-enclosures, it is possible to extend the single-layer equations described above. However, the empirical equations used to describe the effect of apertures can not be extended without carrying out an extensive experimental design. An attempt has been made to overcome this problem by modeling the multiple-layer shield as a single “equivalent” layer for the purposes of aperture loss calculations. Both of these extensions to the single-layer equations are described and evaluated below.

SE Equations for Multiple-Layer Enclosures without apertures.

The derivation of the multiple-layer SE equations is based on the electromagnetic theory used for the derivation of the single-layer equations shown above.

To extend the single-layer equations to enclosures with multiple layers of material, it was assumed that all re-reflections are only significant within an individual layer (no secondary re-reflections considered). Hence the EM radiation transmitted through each layer is calculated based on the single-layer equations for that layer. The derivation is summarized by the values shown in Figure 47. The values shown represent the fraction of the incident field which is transmitted past each interface.

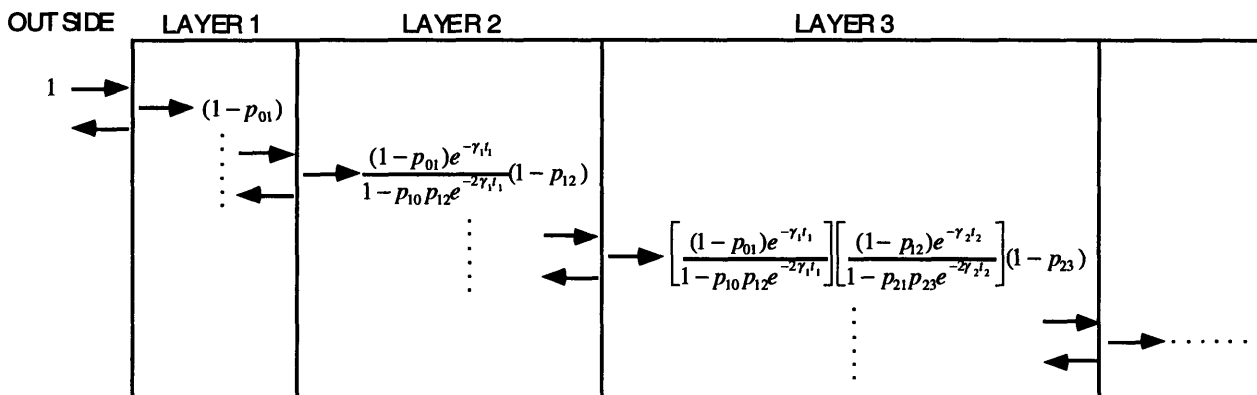


Figure 47: Derivation of Multiple-layer Equations.

Hence, the shielding effectiveness for an enclosure consisting of N adjacent layers is calculated as follows.

$$SE = \frac{\Gamma_{incident}}{\Gamma_{transmitted}} = \frac{1}{(1 - p_{01})} \left[\prod_{i=1}^N \frac{1 + p_{(i-1)(i)} p_{(i)(i+1)} e^{-2\gamma_i t_i}}{(1 - p_{(i)(i+1)}) e^{-\gamma_i t_i}} \right] \quad 32$$

Note: This value of SE is different from the value obtained by adding the SE of the individual layers. This is because the EM reflection from a material-material interface is less than from the separate material-air interfaces .

Accounting for Apertures in Shields with Multiple Layers.

The method used to extend the single-layer shielding equations can not be applied to the empirical aperture equations. As an alternative, an attempt was made to represent multiple-layer enclosures as a single layer with “equivalent” material properties in order to make use of the single-layer aperture equations. Once the equivalent material properties have been derived, the single-layer aperture equations can be used and the overall shielding effectiveness can be calculated as for the single-layer case. While these equations are limited in their accuracy they represent the best method available for approximating the effect of apertures in multiple-layer shielding designs.

The effective values of magnetic permeability and electrical conductivity are obtained by adding the values for the individual layers in series. The equations derived are based on work by Iwasa [38], and are summarized below.

For magnetic permeability:

$$\mu_{equ} = \frac{\sum_{i=1}^N \mu_i t_i}{\sum_{i=1}^N t_i} \quad 33$$

For electrical conductivity:

$$\sigma_{equ} = \frac{\sum_{i=1}^N \sigma_i t_i}{\sum_{i=1}^N t_i} \quad 34$$

Assessment of the multiple-layer model.

No physical data are readily available for the validation of the multiple-layer models developed. However, it is stated in the literature [28] that summing the values of shielding effectiveness (SE) for individual layers produces an over-estimation of the capability of the multiple-layer enclosure. This is because the reflective capabilities of material-air interfaces are higher than those between adjacent material layers.

In the light of this observation, it was decided to assess the models developed by comparing their respective values of shielding effectiveness (SE) to those predicted by the single-layer equations. A two-layer enclosure (copper and steel) were selected to perform the comparison. The *multiple-layer* and *equivalent material* models were used to estimate the SE of the two-layer enclosure and the results were compared to the sum of the SE from the two individual layers. The values used in the models are summarized in Table 9.

Table 9: Material Constants for Assessment of Multiple-layer Models.

Layer	Copper	Steel	Equivalent Material
Rel. Electrical Conductivity	1.0	0.1	0.55
Rel. Magnetic Permeability	1.0	1.0	1.0
Relative Permittivity	0	0	0
Thickness (inches)	0.01	0.01	0.02

Comparison Results.

Figure 48 shows the predicted values of shielding effectiveness for the two-layer enclosure described, based on the various modeling techniques being compared.

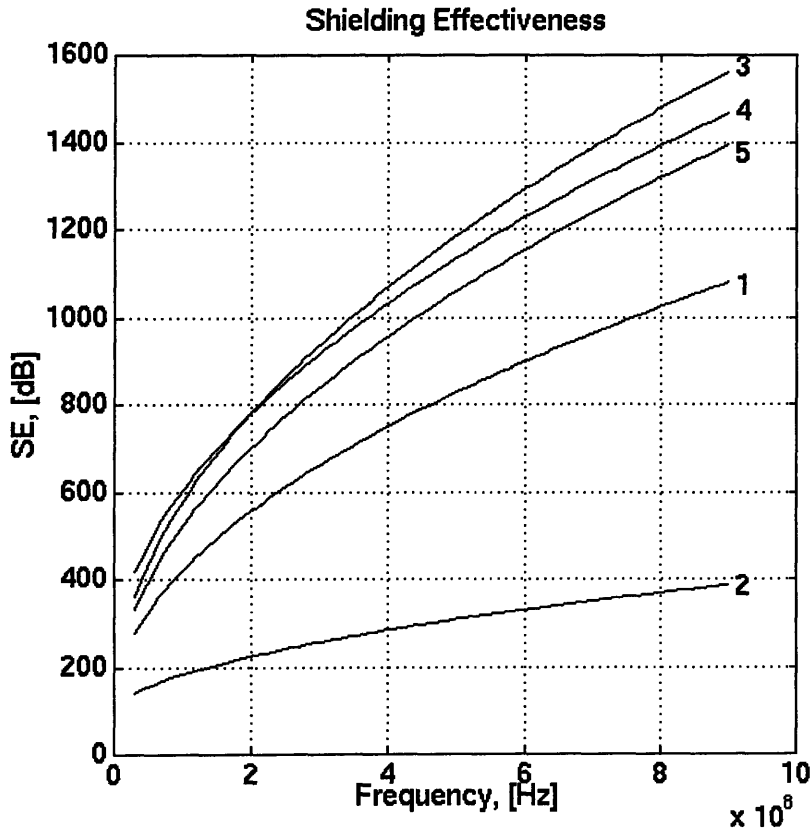


Figure 48: Comparison of Shielding Effectiveness values from Different Models.

Key:

1. Single-layer Equations: Copper
2. Single-layer Equations: Steel
3. Single-layer Equations: Equivalent Material
4. Sum-of-layers (1) & (2)
5. Multiple-layer Model - Layers (1) & (2)

In this figure, the values for shielding effectiveness (SE) predicted by both the equivalent material and multiple-layer models follow the trend displayed by the single-layer equations, viz. SE increases with frequency. The multiple-layer model (5) predicts SE values which are lower than those calculated by summing the single-layer values (4). This agrees with the practical observations cited above and suggests that the multiple-layer model is a realistic estimate of the overall shielding effectiveness. By comparison, the equivalent material model (3) predicts a higher SE than the sum-of-layers model (4) which is known to be an over-estimate. This implies that the equivalent material model over-estimates the shielding capability of multiple-layer enclosures.

Figure 49 shows separate graphs for the two major contributors of shielding effectiveness, viz. *Absorption* and *Reflection*. These plots are constructed to further illustrate the discrepancy which is evident in the equivalent material model.

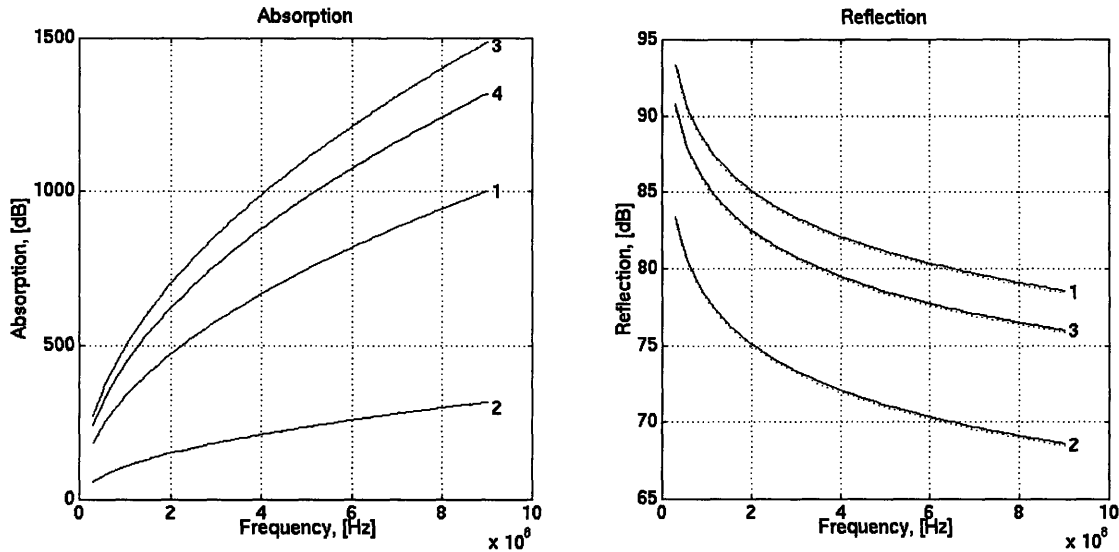


Figure 49: Absorption and Reflection values from Different Models.

Key:

1. Single-layer Equations: Copper
2. Single-layer Equations: Steel
3. Single-layer Equations: Equivalent Material
4. Sum-of-layers (1) & (2)

As can be seen from the plots:

- The overestimation of the equivalent material model (3) is caused by a discrepancy in the value calculated for the *absorption* component of the SE.
- For the *reflection* component it is of little value to use the sum-of-layers model for comparison purposes as we expect the reflective capability of the shield to be reduced in the multiple-layer case. However, the plot shows that the value of *reflection* for the equivalent material model falls between the values for the individual layers which is quite feasible. Thus, although the exact effect of the *reflection* component can not be identified, it is clear that it does not provide a significant contribution to the over-estimation of the equivalent material model.

While these observations do not explain the cause of the discrepancy in the model they may prove useful for the future assessment and extension of this work.

Note: The discrepancies observed are accentuated in enclosures containing non-metal layers. This is due to the poor correlation of the single-layer equations for non-metal enclosures in general.

Summary of Comparison Results.

By comparing the various models available, it was shown that the multiple-layer model derived provides a realistic representation of the shielding effectiveness of a multiple-layer shielding enclosure without apertures. This is true for all the cases considered, despite the assumption made in generating the model (to ignore secondary re-reflections between layers).

However, the comparisons also show that the “equivalent material” model provides a poor model for representing the overall shielding effectiveness of a multiple-layer enclosure. The comparisons suggest that the dominant contribution to the error in the model is from in the calculation of the *absorption* component of the SE. However, the observations do not suggest what the specific error in the model is or how it could be corrected.

Appendix C: Development of Heat Transfer Models.

This appendix contains a summary of the heat transfer equations used in the integrated design example. The model used considers the enclosure as a rectangular prism which is cooled by free convection (by the walls, roof and vents) and by forced convection when a fan is included in the design. The various heat transfer paths are modeled in parallel by means of a resistance analogy. The equations derived below are based on the theory and techniques presented by Holman [39] and make use of the variables listed in Table 10.

Table 10: Variables for Heat Transfer Calculations.

Symbol	Definition	Units
l	length of enclosure	m
b	breadth of enclosure	m
H	height of enclosure & characteristic length of Walls	m
t	thickness of individual shielding layers	m
L	characteristic length of Roof	m
X	characteristic length of Vent	m
n	number of free-flow vent holes	
D	diameter of free-flow vent holes	m
A	area	m ²
k	thermal conductivity	W/(m.K)
ρ	density	kg/m ³
μ	viscosity	kg/(m.s)
ν	kinematic viscosity	m ² /s
c_p	specific heat	kJ/(kg.K)
p	pressure	Pa
α	thermal diffusivity	m ² /s
Pr	Prandtl number	
β	coefficient of thermal expansion (1/T)	K ⁻¹
Gr	Grashof number	
Nu	Nusselt number	
h	convective heat transfer coefficient	W/(m ² .K)
m	mass flow rate of air for forced convection	kg/s
N	number of layers of material	

Derived Atmospheric Variables.

[39, p xvii - xx]

$$\nu = \frac{\mu}{\rho}$$

$$\alpha = \frac{k_{air}}{\rho c_p}$$

$$Pr = \frac{\nu}{\alpha}$$

Derived Geometric Variables.

The heat transfer model assumes that all “free-flow” vents occur in the form of a single circular opening situated on the roof of the enclosure. While this assumption is physically inaccurate it is conceptually realistic for the purposes of the heat transfer calculations. This affects the related geometric quantities in the following ways:

- The maximum free-flow vent area (for heat transfer calculation purposes) is equal to the total roof area.
- The roof area available for heat transfer is equal to the total roof area minus the free-flow vent area.

The free convection calculations rely on *characteristic lengths* for the enclosure which are based on these assumptions. The resulting relationships are summarized in Table 11.

Table 11: Derived Geometric Variables for Heat Transfer Calculations.

	Walls	Vent (circular)	Roof
Area	$A_{walls} = 2H(l + b)$	$A_{vent} = \sum A_{free-flow\ apertures} \leq l \times b$	$A_{roof} = lb - A_{vent}$
Characteristic Length	H	$X = \sqrt{\frac{A_{vent}}{\pi}}$	$L = \frac{lb}{2(l + b)}$

Free Convection Thermal Resistances. [39, p 332-343]

The enclosure is modeled as a rectangular prism with parallel paths of heat transfer through the walls & roof (by conduction and free convection) and through the “free-flow” apertures (by free convection). A summary of the resulting thermal resistance calculations is shown in Table 12:

Table 12: Equations for Thermal Resistance Calculations.

Variables	Walls	Vent	Roof
Gr	$\frac{g\beta(T_i - T_o)H^3}{v^2}$	$\frac{g\beta(T_i - T_o)X^3}{v^2}$	$\frac{g\beta(T_i - T_o)L^3}{v^2}$
Nu	$0.68 + \frac{0.67(\text{Pr} Gr_H)^{1/4}}{[1 + (0.492/\text{Pr})^{9/16}]^{4/9}}$	for $\text{Pr} Gr_x \leq 2 \times 10^8$ $= 0.13(\text{Pr} Gr_x)^{1/3}$ for $\text{Pr} Gr_x > 2 \times 10^8$ $= 0.16(\text{Pr} Gr_x)^{1/3}$	for $\text{Pr} Gr_L \leq 2 \times 10^8$ $= 0.13(\text{Pr} Gr_L)^{1/3}$ for $\text{Pr} Gr_L > 2 \times 10^8$ $= 0.16(\text{Pr} Gr_L)^{1/3}$
h	$\frac{Nu_H k_{air}}{H}$	$\frac{Nu_X k_{air}}{X}$	$\frac{Nu_L k_{air}}{L}$
Rconv	$\frac{1}{h_H A_{wall}}$	$\frac{1}{h_X A_{vent}}$	$\frac{1}{h_L A_{roof}}$
Rcond	$\frac{1}{A_{wall}} \left(\sum_{i=1}^N \frac{t_i}{k_i} \right)$		$\frac{1}{A_{roof}} \left(\sum_{i=1}^N \frac{t_i}{k_i} \right)$
R	$R_{cond}_{wall} + R_{conv}_{wall}$	R_{conv}_{vent}	$R_{cond}_{roof} + R_{conv}_{roof}$

Forced Convection Thermal Resistance Calculations. [39, p 274]

Additional heat transfer can be achieved by including a fan into the system. The thermal resistance of the forced convection is based on the heat capacity of the air flow induced by the fan.

$$\text{for } A_{vent} \geq A_{fan} : R_{forced} = \frac{1}{(\dot{m}c_p)}$$

$$\text{for } A_{vent} > A_{fan} : R_{forced} = \frac{A_{vent}}{A_{fan}(\dot{m}c_p)}$$

36

Note: If the free-flow vent area is smaller than the fan vent area; then the forced convection resistance is scaled to account for the decreased flow-rate.

Total Thermal Resistance. [39, p 27-29]

The overall thermal resistance is calculated as the equivalent resistance for the four paths of heat transfer in parallel.

$$R_{tot} = \frac{1}{\frac{1}{R_{wall}} + \frac{1}{R_{vent}} + \frac{1}{R_{roof}} + \frac{1}{R_{forced}}}$$

37

Overall Heat Transfer with only Free Convection. [39, p 34-36]

Finally, the rate of heat transfer is calculated as the difference in thermal potential (from the inside to the outside of the enclosure) divided by the total thermal resistance.

$$Q = \frac{(T_i - T_o)}{R_{tot}}$$

38

6/1/2020