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Using Product Architecture to Maximize Environmental Performance

by

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(1990)

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the Department of Industrial and Manufacturing Engineering in the College of Engineering of the Rochester Institute of Technology.

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CERTIFICATE OF APPROVAL

M.S. DEGREE THESIS

The M.S. Degree Thesis of Jeffrey J. Sciortino

has been examined and approved by the

thesis committee as satisfactory for the

thesis requirement for the

Master of Science degree.

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Thesis Title: Using Product Architecture to Maximize Environmental Performance

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Date: 18 June 1999 Signature of Author: ____________________

Dedication

This thesis is dedicated to my grandparents, who taught me to look beyond the horizon, and to my parents, who have always encouraged me to keep asking questions until I get an answer.

Acknowledgments

While it is impossible to give credit everywhere it is due, I would like to acknowledge the assistance of several people without whom this thesis would not have taken the form that it did. I would like to thank my advisor, Professor Paul Stiebitz for his dedication and insights, as well as the other members of my committee, Dr. Brian Thorn and Dr. Frank Sciremammano. I would like to thank Dr. Jacqueline Reynolds-Mozrall for her work in setting up the Master of Science curriculum in time for me to obtain this degree. Thanks to Brian Bishop for the donation of his DeskJet 540 printer for use in the case study. Thanks also to the Department of Industrial and Manufacturing Engineering for financial support of the work presented in this thesis, and to the faculty and staff of the department for their encouragement and insights. Most importantly, thanks to my wife, Colleen Fogarty, whose ongoing love, support, and encouragement brought me through this project in one piece.

Table of Contents

Chapter 1. Introduction

Product architectures have been used to improve time to market, market niche penetration, development costs, production costs, and production flexibility. Architecture development is considered to be as much an art as science and, as such, many different architecting methodologies exist depending on the particular goal one wishes to achieve. These methodologies are codified through heuristics (rules of thumb) and through pseudo-analytic iterative methods. The goal of this thesis is to investigate how product architectures can be used to improve the environmental performance of a system.

In complex systems, analytical methods are not always effective in delivering a product or project on time and on budget. For these systems, it is generally helpful to define a structure, or *architecture*, for the system being designed. This architecture dictates how the system is divided up into subsystems, defines the functionality of these subsystems, and specifies the interfaces (connections and interactions) between subsystems.

The development of an architecture is an iterative process. The partitions of the functional space and the interface definitions are fine tuned throughout the development process.

In developing product architecture heuristics and methodologies to maximize environmental performance, the question arises "what is environmental performance?" While there are several methods available, the streamlined life-cycle assessment (SLCA) methodology developed by Graedel and Allenby to measure environmental performance will be used.

Through the course of this thesis, ways to combine architecture development tools with tools for improving product environmental performance will be investigated. These new tools should improve product environmental performance by changing product architecture.

In Chapter 2, the relevant literature regarding system architecture, the role of the system architect in development of the system, the value of systems architecture, and the important role of certification is reviewed. The literature on improving the environmental performance of products, most particularly Graedel's (1998) streamlined life-cycle assessment methodology is also reviewed.

Chapter 3 contains a review of some of the tools of the product architect's trade. These include various models used to link together different parts, or "domains," of the architecture. These models are essential in communicating with the client and the design community. Some architectural strategies for improving products in various ways are also presented.

Chapter 4 takes a more in depth look at the streamlined life-cycle assessment method of Graedel (1998). Criteria used to evaluate the environmental impact of a product are outlined, and a visualization tool used to help judge the overall environmental performance of a product is discussed.

Chapter 5 contains the bulk of the original work done for this thesis. Material from the architecture and environmental parameters chapters is integrated into a method for improving an existing product by changing the's architecture. Some general architectural strategies that can be used to improve the environmental performance of a product are also discussed.

In Chapter 6, the method and strategies developed in Chapter 5 are applied to the Hewlett Packard DeskJet 540 ink jet printer.

The appendices provide supporting information that, while not central to the discussions in this thesis, are essential to the analysis. Appendix A lists the architectural heuristics used in developing the method in Chapter 5. Appendix B consists of the tables used to link the environmental criteria with the architecting heuristics. Since many terms in architecting may have special meaning, Appendix C provides a glossary of terms for the reader's convenience, annotated with the source of each definition. Appendix D consists of a listing of new heuristics divined by the author for improving the environmental performance of a product.

Chapter 2. Literature Review

The literature search concentrated on two main areas: system architecture development and industrial ecology. The former area examines ways that architectures can be exploited to achieve a more competitive market position, while the latter investigates how better environmental performance might lead to a more competitive market position through treating environmental compliance as a strategic opportunity rather than a liability.

Architecture

What is a System Architecture?

While the term Architecture dates to the 16th century (Webster's 1992), the concept of "Systems" has only been formalized in the last 50 years (Rechtin 1992, 66), and the field of system architecture is still in it's infancy.

Rechtin believes that the merger of architecting and systems has been driven by increased complexity, global scope projects, and the ubiquity of computers in virtually all modern systems, and that the success and failure of many defense, space and civil systems is driven by architecture (Rechtin 1992, 66). The historic emergence of any form of architecting is driven by a design process becoming so technically, financially, politically, and socially complex that it overwhelms the abilities of the builder, and thus requires someone with skills to simplify the problem. People have functioned as architects since ancient Egypt, when the technical, financial, political, and social complexity of pyramid construction created the necessity for an architect (Rechtin and Meier 1997, 7).

It is interesting to note that Rechtin transfers the definition of architecting and complexity from the merely technical realm into the political, social, and financial arena, underscoring the need for a specialist who may not be the best builder, but is the best at getting a system built. This concept of the architect as best project manager exists in building architecture as well. Many building architects act not so much as aesthetic designers but as coordinator of the building process (Lewis 1982, 190).

According to Rechtin, *architecting* defines the form of a system by matching, fitting, balancing, and compromising proposed functions and forms until a practical result can

be achieved. He defines a system as "A collection of different things related in such a way as to produce a result greater than what its parts, separately, could produce" (Rechtin 1992, 66).

McKendree defines a system architect as:

> *The person who creates the conceptual model of the system, translating the clients desires into a technical description the builder can understand. As an agent of the client, the system architect must assure that system integrity is assured throughout the program phases, and that design certification is meaningful and passable* (McKendree 1994).

Sage and Lynch define a system architecture as:

> *The description of system components and their interconnections required for supporting critical operational functions* (Sage and Lynch 1998, 222).

Rechtin also believes that while the term "architecting" may be relatively new in system development, most successful systems have been conceived, built, tested, certified, and operated in a way that ensured integrity and performance. These systems were based on a consistent set of principles and techniques maintained throughout all phases of the project. In other words, an "architecture." Good architectures bring about successful designs which are resilient enough to bend to the inevitable changes brought about by time and circumstances (Rechtin 1992, 66).

Rechtin further states that, by definition, a good architecture will succeed on all fronts - technologically, politically, and economically (Rechtin 1992, 66). To these three measures of optimality, this thesis will add a fourth - environmentally.

Value of System Architecture.

Reinertsen developed a systems architecture view that can drastically reduce the design time of a product or system. He states that in order for product architecture to work, there must be a system architect who is distinct from the system engineer. The primary benefit is derived from the system architect controlling the scope of the project, increasing the design concurrency between system engineers working on various components, and from decreasing the frequency and magnitude of rework through proper interface design. Using a modular system architecture to promote design concurrency has several benefits. For example, modules can be in different phases of development at different times, and work can be transfered from one group to another in small batches, quickly. A good architecture both reduces scope and promotes concurrency (Reinertsen 1996).

Rechtin believes that the use of heuristics are key to architecting successful systems.

Heuristics are rules of thumb which have the "ability to simplify complex problems by discarding out of hand unreasonable options" (Rechtin 1992, 66).

Meyer cites the use of architecture in strong companies to leverage successful products across time and market niches into a stream of value-rich products. This is accomplished through the architectural definition of a product platform that can be extended into new market segments identified as growth areas (Meyer 1997).

It is the belief of the author that a similar strategy could be used to enhance environmental performance by developing product families which share components. Environmental performance could be enhanced by encouraging reuse and remanufacture of components from older, obsolete members of a product family by putting them into new, cutting edge product family members.

Role of the System Architect.

Rechtin states that the role of architect is an important one because it requires a different mindset and skill set from that of an engineer. The system engineer is concerned with hard facts and optimization, while the system architect is concerned with relationships between things, and partitioning the insolvable problem or system so its parts may be analytically solved by the engineer.

Meyer sees the role of the system architect as coordinator of product platform development. The result of the architect's effort is the formulation of a platform development team, a project time line and a budget. This involves in depth knowledge of customer needs, analysis of competing products, and an understanding of the manufacturing and distribution processes of the company. The architect may define and map a current product platform, or develop a clean sheet new product platform. The architect must understand the core competency implications of the new product platform.

Reinertsen sees the architect's role as controlling scope, increasing design concurrency, and reducing the frequency and magnitude of rework. System scope can be controlled by carefully choosing the boundaries of the system, the use of modular structures in the design, and by making careful make vs. buy decisions for subsystems. An architect can enable increased design concurrency by defining a modular architecture, and the interfaces between the system elements. This differs from concurrent engineering in that it puts the design activities in compressed, parallel tracks, whereas concurrent engineering puts design and manufacturing on parallel tracks, but leaves the design activity itself serial. The frequency and magnitude of rework can be reduced through careful interface design, with appropriate coupling of the modules. This

prevents design changes in one subsystem from affecting another subsystem (Reinertsen 1996). These same decisions can be critical to the environmental performance of a system.

McKendree defines the tasks of system architecting as understanding the client's needs, desires and resources, developing the system concept, maintaining system integrity on the project, and providing final certification. He contrasts the role of systems architect with that of system engineer. The architect starts with imprecise, often conflicting overall requirements, considers only the *key* interfaces, and uses partially intuitive approaches to structure a system well enough to allow precise specifications to be determined. The system engineer, on the other hand, is given precise, well-defined functions to achieve, develops detailed specifications for subsystems and components, and must consider all subsystem interfaces (McKendree 1994).

Certification Issues

McKendree raises some interesting certification issues relevant to environmental performance. Certification is difficult in situations where a real test situation for the system performance is not possible. In these cases, systems must be designed to be testable, and tests must be designed to be feasible from the beginning of the project. In the case of mass market goods, internal review may make the certification decision instead of the actual consumer.

Environmental Performance .

Ried Lifset, editor of the *Journal of Industrial Ecology* defined industrial ecology:

> *Industrial ecology - some call it a paradigm shift, or even the next industrial revolution, Even if these claims are overstated, it is clear that we are on the verge of new understandings that can alter the way we think about the environment and the economy.*
>
> *The need is evident. The stresses put on the planet by a growing population, by rapid industrialization in the developing world, and by rising consumption across the globe are daunting. But it is not enough to pursue protection of the environment with greater fervor; we also must seek that protection in sophisticated, intelligent, even artful ways. That is why a systems-oriented approach that integrates economic and environmental phenomena is crucial.*
>
> *Industrial ecology is a promising - and exciting - response to these practical and*

analytic needs. It is a rapidly growing field of science that systematically examines local, regional, and global flows of materials and energy in products, processes, industrial sectors, and economies. It focuses on the role of industry in reducing environmental burdens throughout the product life cycle from the extraction of raw materials, to the production of goods, to the use of those goods, and to the management of resulting wastes.

Lifset goes on to discuss the role of industry in industrial ecology:

> ... *It [industrial ecology] views corporate entities as key players in the protection of the environment, particularly where technological innovation is an avenue for environmental improvement. As an important repository of technological expertise in our society, industrial organizations can provide crucial leverage in attacking environmental problems by incorporating environmental considerations into product and process design* (Lifset 1997).

Industrial ecology addresses environmental problems proactively, using systemic solutions conceived by those who know the process best - industrial leaders, rather than relying on remediation dictated by regulators as the first line of defense against environmental problems.

Applications of Industrial Ecology to Product Development.

There are several applications of industrial ecology concepts on product design in the literature, however, none of these applications address these challenges from the perspective of architecture. Most center around the improvement of the environmental performance of some aspect of a product already in production, or discerning which design options already under consideration are more environmentally benign. None consider architecture to be the lever on which to lean to improve environmental performance.

For example, Chouinard and Brown outline the concerted effort made by Patagonia clothing to lower their environmental impact as a company. Patagonia hired a consultant to study which activities of the company had the highest environmental impacts by performing a life-cycle assessment. Of those high impact activities, the company determined which they had the most influence over, and chose to convert all cotton products over to organically grown cotton. They outline the process used in making this decision, the implementation and marketing strategy, and some of the lessons learned (Chouinard and Brown 1997). While an interesting study with some valuable insights in terms of implementation strategies, it is fundamentally a material choice solution. It does not address deeper design issues, but examines material choice after the designs

are already made.

A more design oriented study was undertaken by Hoffman at Motorola. He attempted to integrate industrial ecology principles into the existing Motorola design process. The process consisted of three phases: Concept Development – Predesign and Specifications; Detail Design – Design of Components, Parts, Subassemblies, and Process Steps; and Prototype Manufacture. Architecture development takes place in Phase 1 – Concept Development. While Hoffman outlines ways in which different design possibilities can be compared, he does not explore any new methods of concept development which will lead to better environmental performance. Given the nature of Hoffman's study – to improve the product's environmental impact – it is understandable why he would try to integrate environmental factors into the existing evaluation methods used in product design at Motorola. This design process is basically serial, and does not address platform issues (Hoffman 1997). It is interesting to note that work has been done at Motorola on using architectures to improve market niche penetration using platforms (Dell 1996), but Hoffman does not mention platform strategies in his article.

Carnahan and Thurston developed a methodology which integrated pollution prevention and concurrent engineering. They developed a mathematical model which integrated statistical manufacturing process control into a multi-objective design optimization formulation. A case study looking at optimizing the formulation of Armstrong floor tiles is presented from the manufacturers viewpoint. This study uses a house of quality analysis to assess the effect of the key parameters identified by the objective design optimization formulation on environmental impact, cost and quality. The authors cite problems with the unavoidable trade-offs between pollution, manufacturing cost and quality. One interesting finding was that increasing the recycled content of the product results in greater air pollution levels (Carnahan and Thurston 1998). This article focused on the quantifiable aspects of the design process. Architecting is well upstream in the design process of where Carnahan and Thurston start their analysis. Their concurrent engineering approach is also much more limited than the concurrent design approach that highly modular architectures allow an organization to pursue (Reinertsen 1996).

Klausner, Grimm, and Hendrickson study the use of an electric data log (EDL) which can be added for a few dollars to a motor in an appliance or home power tool. The data log helps to assess the suitability of the motor for reuse when the products useful life has ended. They discuss the economic viability of the EDL. The article goes on to discuss how EDLs may fit in with product take back legislation in Europe. They also discuss consumer surveys regarding product return behavior patterns, and how that can influence the profitability of EDLs in various types of products given different reasons for leaving service (Klausner, Grimm, and Hendrickson 1998). While the article brings up

many interesting facets of component reuse, the technology discussed is just an addition to a generic motor, in order to facilitate reuse in new products. There is no examination of how architectures might be used to encourage the reuse of motors, perhaps by using the same motor across a product line, how product architecture might enable motor reuse through easy tear down, or how components might be clustered in a module by service life to enable easy replacement. The business cases are interesting in terms of how economically viable such a change would be.

In a study of American made automobile instrument panels, Keolian examines the impact of several improvement strategies: lightweighting, elimination of painting, and reduction of material complexity. These were analyzed in terms of their impact on the energy that goes into the assembly, the solid waste generated over the life of the assembly, the air pollution, water pollution, and life-cycle costs. No assessment is made as to how these improvement strategies can be achieved using architectures (Keolian 1998).

Sheng and Worhach present an interesting spin on LCAs in their analysis of the effects of the structure of the manufacturing chain on environmental performance. They consider batch size and machine idle time, and the environmental impact of each stage of the product manufacturing chain, then add all of these impacts together. Fundamentally, a manufacturing oriented study, not a design oriented one, and certainly not architecturally oriented.

Lave et al studied factors which contribute to recyclability of post-consumer floor carpeting. The study is primarily focused on the economic, logistical, and technical challenges of recycling currently installed carpet. They found that it was difficult to economically recycle a product not designed for recyclability. Specifically, they cite lack of content labeling, failure to consider fiber removal in specifying adhesives, and mixing materials in such a way that they are difficult to separate, as major hindrances to economical recyclability. These factors are good to keep in mind when considering what makes a product architecture more environmentally sound. While the authors do bring up some of the aforementioned issues which are affected by architectural decisions, particularly the adhesive issue, the authors present no architectural angle per se in their study (Lave et al. 1998).

None of the articles concerning improving environmental performance through more ecologically sound product design focused on the architectural aspect of product design. While some included the architecting process in their measurement of a product's environmental impact, none looked at the architecting process itself, or opportunities during partitioning and interface definition.

Life Cycle Assessments

Graedel examines the drivers behind the LCA, which he enumerates as: Ω_1, Maintaining the existence of the human species; Ω_2, Maintaining the capacity for sustainable development; Ω_3, Maintaining the diversity of life; Ω_4, Maintaining the aesthetic richness of the planet. Graedel relates specific environmental concerns to each of the grand objectives, and then groups the concerns by relative importance into crucial, highly important, and less important environmental categories. This prioritization takes into account the following: spatial scale of the impact, severity of the hazard, degree of exposure (how readily mobilized the pollutant is), and the penalty for being wrong (or how long remediation will take.) He then lists each of the crucial environmental concerns, and identifies activities targeted for examination which may contribute to each concern. The grand objectives are decided by "Social Consensus". The concerns, activities, and recommendations for activity modification are determined by environmental scientists, who understand the natural systems, in concert with life cycle analysts who understand the industrial world, and how to integrate recommendations into design for environment methodologies. Graedel presents a weighting methodology which weighs elements of a streamlined life-cycle assessment (SLCA) or life-cycle assessment (LCA) with higher weights for those items most affecting grand objectives. He also suggests listing the recommendations for change with the grand objectives they affect, and the name of the relevant crucial environmental concern(s), using bold typeface to prioritize recommendations. This presentation makes the weighting more transparent, and helps designers understand why it is important to follow these recommendations (Graedel 1997).

Ehrenfeld explores the weaknesses of (LCAs). He lists the following major arguments made against the LCA: lack of objectivity, particularly in defining the boundaries of the study; opacity of the procedure, which obscures the arbitrary assumptions on which it is based; expense and high degree of effort limiting applicability; inseparability of the purely objective steps from the subjective and political; the process excluding key stakeholders, and thus is biased by the interest who pays for the study. For these reasons, many argue LCAs should not be used instead of price for determining the value of a good or service. Ehrenfeld argues that while most of these arguments are true, there is no better alternative. Ehrenfeld defines two different dimensions of LCA use. The analytic or content dimension is one which quantifies environmental impact, and uses a scoring system in which one product or process is analytically compared with another. This score can be used to compare alternatives in design for environment

applications, or may be used in advertising or Eco-Labeling. Since this score is essentially making a claim, supposedly based on analytic reason, but is in fact based on a pseudo-analytic process, it can be the source of great controversy. Ehrenfeld categorizes the question an LCA asks as "trans-science" questions, "which can be asked of science and yet which cannot be answered by science." (Ehrenfeld 1997, 45). The framing, or context, dimension of the LCA centers more on the process of design. The mere act of performing the LCA frames the development activity in a more ecologically sound manner. Whether or not the data from the LCA is actually used, the environmental performance of the resulting design will benefit from the heightened awareness of the environmental impact of design choices. (Ehrenfeld 1997).

Streamlined Life-Cycle Assessment

Graedel suggests a series of scoring guidelines and protocols to judge the impact a product has over 5 life stages for 5 different types of impacts. These guidelines lead to 25 (5×5) categories of environmental impact, each with a score from 0 to 4, 0 being the worst environmental impact, and 4 being the least harmful environmental impact (Graedel 1998, 235-249). These guidelines can be used to measure the environmental effectiveness of any design change.

In reviewing the literature on life-cycle assessments, many references to general aspects of product and system development were found, and some even included the phase of design in which architecting takes place. However, none of the authors looked at how to integrate strategies used in life cycle assessments with the architectural processes of partitioning and interface specification.

Value of Product Improvement to Environmental Performance.

Ryan points out that in order to make the serious gains in environmental performance needed to achieve sustainability, analysts need to move beyond studies of only products, and look at the system in which the product operates (Ryan 1997). In another article, Ryan identifies product redesign as an ideal opportunity to quickly reduce the "environmental load" of economic activity. Since products tend to "churn" more than transportation systems or buildings, innovation can be disseminated rapidly. In order to have a sustainable economy, the environmental impact of products must be reduced by 95% in the next 30 to 50 years. To achieve this, products must change in fundamental ways. An important element in this change is the need to identify new design strategies, including: dematerialization, the reduction of the material content in a product or service ; service-products, services which do the job of a product; product life extension; product and component cycling, closing resource loops and improving remanufacturing.

Ryan points out that there is a conflict between long life and efficiency. How can the designer take advantage of more efficient technologies if the product lasts for thirty years? By making the product upgradeable. Ryan cites mutable software as the best way to improve upgradability. He also points out that businesses are going to need to build themselves around the idea that they will make most of their money on upgrades, not initial sales (Ryan 1998). Though Ryan does not state it, most of these changes, particularly upgradability, can be best effected through the use of architectures in product design.

Systems Perspective.

Ruth considers ecological effects of systemic changes and the need to look at environmental impacts on the system level, but not at the level of products, and not from an architectural perspective (Ruth 1998).

Summary of Literature Review.

The review of the literature revealed many studies of ways to improve environmental performance of products, but none using product architecture. Numerous articles studying how system architectures can be used to improve product reliability, market penetration, time to market, etc. were found, but none looking at ways to improve environmental performance.

Chapter 3. Product Architecture

Erens and Verhulst define product architecture:

> *The composition of a product from a number of component products is a product architecture. It describes the components, together with their interfaces and operation. Each level in the product hierarchy has its own architecture. Depending on the type of components, we speak about a functional, technology or physical architecture.*

While there are few universal definitions of anything in the systems architecture field, this should suffice as a working definition. With this groundwork laid, the process which produces a product architecture can be addressed.

The Architecting Process.

To say that there is one generic architecting process would be simplistic. Architecting is the process of transforming an intractable problem into one which can be solved using the engineer's tools. It is as much art as it is science. Just as painting by the numbers does indeed produce a painting that few would call art, developing a "simplify by the numbers" method might in fact bring about a solution, but it would most likely be far from optimal, and would certainly not be architecting.

That being said, this section will summarize a simplified architecting process which can be applied to many product development problems and was developed by Erens and Verhulst (1997, 165-173).

Before addressing the nuts and bolts of the method, some terms wil be defined, and some relevant concepts discussed.

Concepts

Domains and Models

Webster defines domain:

do•main \do¯-'ma¯n, də-\ *n*
[ME *domayne,* fr. MF *domaine, demaine,* fr. L *dominium,* fr. *dominus*]
(15c)
...

4: a sphere of influence or activity ⟨the *domain* of art⟩ ...

The closest relevant definition of the term is sphere of influence or activity. The activity is whatever one is trying to accomplish using the product, which can be represented in three domains:

- Activity in the **Functional Domain** concentrates on describing the task to be accomplished in terms of its functions.
- Activity in the **Technological Domain** concentrates on describing the task to be accomplished in terms of the technologies used to accomplish it.
- Activity in the **Physical Domain** concentrates on describing the task to be accomplished in terms of how it will be physically accomplished.

For each of these domains Erens and Verhulst define a model of the product under development.

- The **functional model** describes how the product accomplishes it's design objectives in terms of the functions and subfunctions it performs.
- The **technology model** describes how the product accomplishes it's design objectives in terms of the technology and subordinate technologies used.
- The **physical model** describes how the product accomplishes it's design objectives in terms of how it is physically composed and put together.

The view of models presented above is considerably simplified, but will serve for the product development exercise.

Models

Rechtin and Maier present a much more comprehensive view of the role that models play in architecting generic systems. They believe that models are the sole true product of an architect's labors. While it may be tempting to think of the product as it comes off the production line as the architect's product, that is the builder's deliverable, not the architect's.

The model is the medium through which the architect communicates with the client, the user, and the builder. As such, models "carry out their roles of maintaining design integrity and assisting synthesis" (Rechtin and Maier 1997, 138).

Architects need to have more than one way of looking at a system, so several specialized models are necessary.

The basic models include:

- Objective and purpose models are generally the first ones developed. They show what the system or product is trying to accomplish, in other words, what the client wants.This "goal setting" is an invaluable tool to make sure that the client agrees with the architect about what the system must accomplish.
- Form models describe the physically identifiable elements of the system, the interfaces to the system, and what the system will be integrating with. These could be:
  - a scale model which might be used in a product design, or
  - a block diagram where each block corresponds to a physical portion of the system. A good example of a system we would use a block diagram for would be a microprocessor where we would like to identify the physical components of the chip, but a scale model would be confusing.
- Behavior or functional models describe what patterns of behavior the system will exhibit. Rechtin and Maier (1997, 128) identify five views of the behavior model:
  - Threads and scenarios show all the non-branching sequences of system operation under various scenarios.
  - Data and event flow networks are a short hand way of representing the information in threads and scenarios in cases where there are two many thread permutations to list. Instead, we collapse many of the threads in the same family and describe them using a hierarchical diagram.
  - Mathematical systems theory can be applied in instances where a mathematical theory exists to predict a system's behavior.
  - Autonomous agent, chaotic systems used for systems where there are many identical subsystems which interact to create an emergent (arising unexpectedly) behavior.
  - Public choice and behavior models ad hoc methods widely used in marketing analysis for consumer product companies.
- Performance models are used to predict how well a system or product will perform a given function. The internal structure falls into three categories:
  - Analytical models which consist of lower level system parameters which are related by a mathematical equation. This equation can be used to predict the systems performance for different values of the lower level parameters.
  - Simulation models are used when we can identify the lower level system parameters, but not the mathematical function used in an analytic model. Instead, a continuous or discrete event simulation is used to predict system performance.
  - Judgmental methods are used when analysis or simulation can't be applied.

Instead, heuristics, "common sense," and/or intuition are used.

- Data models are used to track the data needed to run the system, and the relationships between the data in the system. These models were initially developed for object oriented program development, but as all systems become more and more data driven, they are finding wider application.
- Management models describe how the system or product will be integrated into the current managerial structure, particularly regarding implementation strategies.
- Integrated models combine the views presented in the above models. These show how effects in multiple domains are manifested, and are required for maintaining the consistency and integrity of the architecture.

Modularity

Again, turning to Webster:

mod•u•lar \'ma¨j-ə-lər\ *adj* (1798)
1: of, relating to, or based on a module or a modulus
2: constructed with standardized units or dimensions for flexibility and variety in use...

Notice the date of origin of the word, 1798, the word (and presumably the concept) date to the same year that Eli Whitney first used interchangeable parts in musket production. The concept of modularity and some of the cornerstone concepts in modern product development are contemporaneous.

Relative to architectures, a modular architecture is one which is flexible and whose components are standardized.

An example of a modular architecture is the professional photographer's Hasselblad camera (see Figure 3-1.) The owner can change film backs to shoot pictures on a multitude of film formats including instant film. Lenses can be changed depending on what perspective or special effects the photographer desires. Viewfinders can be exchanged to allow the photographer to compose pictures in a multitude of ways, with a multitude of metering systems. Different type of film advance winders can be used depending on whether light weight or speed are essential.

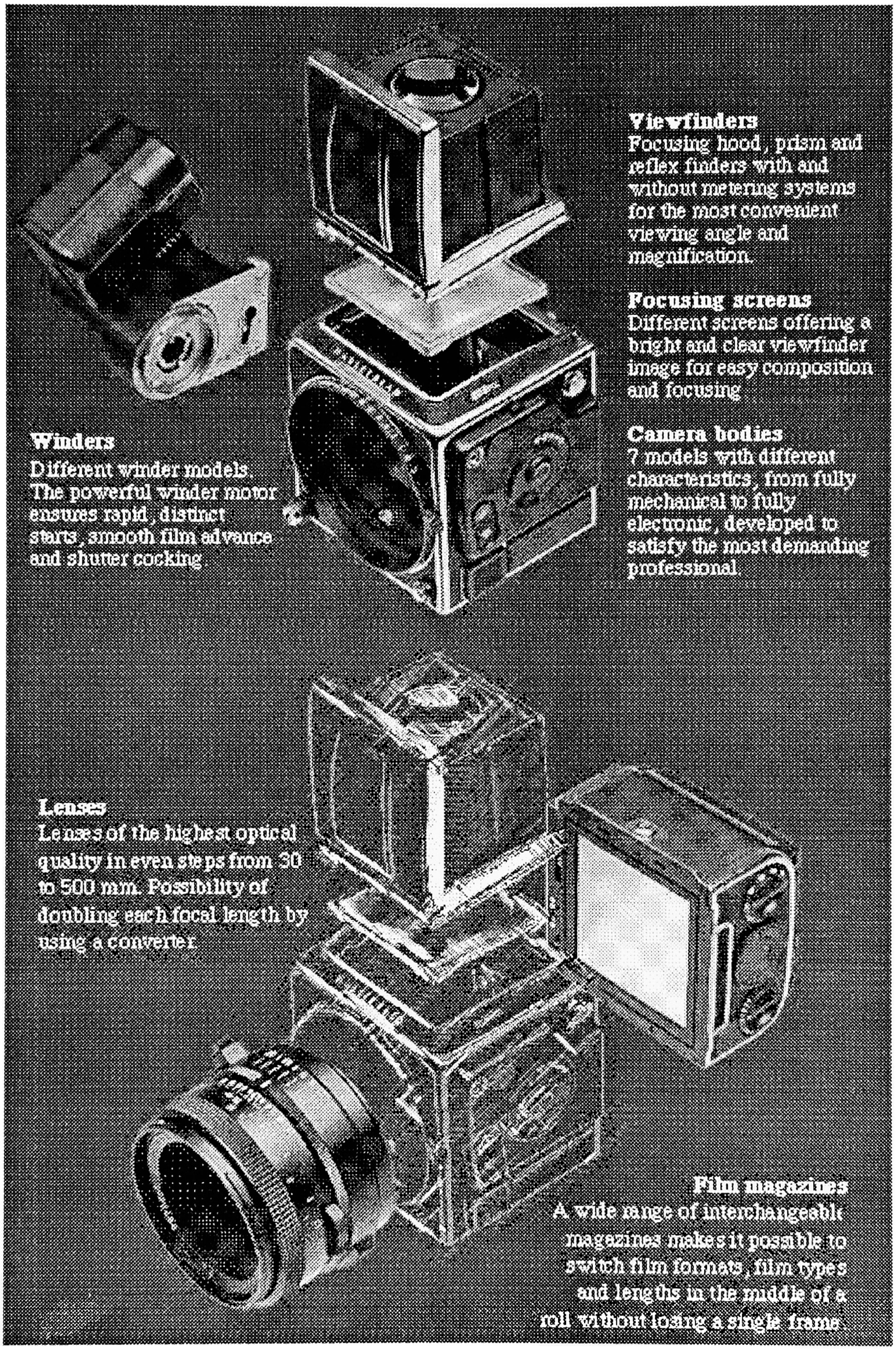


Figure 3-1. Hasselblad camera.

Integration

Webster defines integration:

in•te•grate \'int-ə-ˌgrāt\ *vb* **-grat•ed; -grat•ing**
[L *integratus,* pp. of *integrare,* fr. *integr-, integer*]
vt
(1638)
1: to form, coordinate, or blend into a functioning or unified whole: UNITE...

Highly integrated systems are a unified whole, and can't be easily broken down into their constituent subsystems.

An example of a highly integrated system would be a single use point and shoot camera. The user has none of the flexibility of the more modular Hasselblad camera.

For a given single purpose, and a high production run, an integrated design tends to be less expensive to produce than a highly modular design, and can be much more reliable since there are fewer degrees of freedom over which to fail.

Interface

The interface between two modules defines what their relationship is to each other and how they interact. Interfaces can be physical, defining how the two parts are fastened; logical, defining how the logical operations of one effect the other; thermal, including cooling requirements; electrical, defining power supply requirements; hydraulic; etc.

Coupling

The degree of interdependence between the modules of a system is expressed by how tightly coupled the modules are.

Consider, for example, the power requirements of a disk drive and the capacity of the power supply in a computer. If the power supply produces just enough power for the disk drive, the drive and power supply are tightly coupled. If the disk drive is redesigned and requires 10% more power, the power supply must be redesigned as well. This higher capacity power supply may then require greater cooling capacity, etc. If we specify that the power supply have a capacity 20% greater than the load we intend to put on it, we have a more loosely coupled system. We can change our disk drive in such a way that it draws 20% more power without effecting the rest of our system.

The object oriented software development field has a well developed definition of coupling. (Yourdon and Constantine 1979, 84-104)

Applying data processing coupling concepts from Yourdon and Constantine to product

architectures, coupling appears to be effected by several factors:

- *Type of connection between modules.* Is the connection one way or two way? Will failure of either module cause the failure of the other one?
- *Complexity of the interface.* How many different connections are there?
- *Type of flow along the connection.* Is data being passed, or control, or a combination of the two? A data connection is less coupled than a control connection which is less coupled than a hybrid of the two.
- *Binding time of the connection.* At what point does the interface need to be specified? When the system is initially laid out, only when the software is written, when it is tested, or not until the user puts it into their application? The later the interface can be specified, the less coupled the two modules are.

Cohesion

Cohesion is another term which is borrowed from the data processing field and applied to system and product architectures.

Modules have high cohesion if they are functionally highly interconnected. Two modules that are both needed to execute every system function either module is used to perform have very high cohesion between them (Yourdon and Constantine 1979, 105-141).

For example, the stapling unit on a xerographic copier would have a solenoid component and a staple magazine component. These two modules have high cohesion because stapling, the only function either is concerned with, will not occur without both of them working properly.

The document feeder motor and the stapler solenoid are much less cohesive, since documents can be stapled without the feeder motor working, and documents may be duplicated without the stapler solenoid operating. Of course, they do have some cohesion between them since they are both needed to duplicate and staple a document.

Steps in creating an Architecture

Architecting is an iterative process. Like most arts, it is often hard to know when it is "good enough." This is due in part to the fact that there is usually no one ideal architecture which is optimal for all parameters (Rechtin 1992, 67).

Scoping

The architect begins by scoping the problem, or defining its boundaries. This can be the most critical step in the whole process, and the one through which the most benefit or harm can be brought about. Since systems are inherently unbounded, it is impossible

to include all the factors which will effect the system when scoping. The goal is to include all the factors which will effect the system's primary mission, and leave out those factors which have secondary or no effect on the system.

The importance of proper scoping is reflected in the popularity of Robert Spinrad's heuristic:

> *All the really important mistakes are made on the first day*
>
> (Rechtin and Maier 1997, 146).

Rechtin and Maier (1997, 146) identify four primary activities related to scoping:

- purpose expansion and contraction,
- behavioral definition and consideration,
- large scale alternative consideration, and
- client satisfaction-builder feasibility.

Decomposition or Partitioning

Decomposition adds detail to a model by dividing it's components into smaller units. For example, in the functional domain, functions are decomposed or partitioned into sub-functions. Erens and Verhulst consider decomposition in a given domain complete when the pieces are small enough to be easily and completely mapped to the domain of next lowest abstraction.

Rechtin and Meier (1997, 148) list six activities as part of the partitioning task:

- behavioral-functional decomposition,
- physical decomposition (to lower level design),
- performance model construction,
- interface definition/analysis,
- decomposition to cyclic processes, and
- decomposition into threads [independent functional units].

Allocation

Rechtin and Maier (1997, 148-150) split the allocation task between partitioning and aggregation. Erens and Verhulst (1997) define it as a separate task which creates relationships between different product architecture models. For example, several functions from the functional model may be mapped or allocated to a particular technology module. Likewise, there may be several technology modules which can be

allocated to an assembly within the physical model.

Composition or Aggregation

Erens and Verhulst address composition as a way of re-simplifying the decomposed model, but over different lines. For example, after the functional model has been decomposed, it becomes clear that there are several functions that do similar things. These functions can be composed into a family of functions, thereby simplifying the model, and presumably making it easier to map these functions over to the technical model.

Rechtin and Maier (1997, 148-150) associate six tasks with aggregation:

- functional aggregation (abstract),
- functional aggregation (to physical units),
- physical components to subsystems,
- interface definition/analysis,
- assembly on time-lines or behavioral chains, and
- collection into decoupled threads.

Validation or Certification

Validation is a way of checking the quality level of a product model, usually through comparison with a previous model. Erens and Verhulst (1997,172) validate a composed module against the original uncomposed function, or validate an assembly by comparing it to the original technology module.

Rechtin and Maier (1997, 150-152) identify five activities which are part of the certification process:

- operational walk-throughs,
- test and evaluation,
- verification,
- formal methods verification, and
- failure assessment.

Architectural Objectives

Architectures can be used to pursue many objectives in product development. These

objectives can be accomplished through establishing product families, enabling concurrent design, and reducing interface complexity.

Product Families

When a common architecture is used for more than one product, the products which use that common architecture are considered to be within the same product family. Members of the product family will share many components. This will increase the production runs for a given part, which should lower the overall cost of all the products in the family.

Market Niche Penetration (Geographic and Economic)

Platforms enable market niche penetration in areas which would otherwise not be profitable. These niches could be for different geographic markets. For instance, a product for Europe and North America might share a common platform. An Opel and its Chevrolet counterpart are one example.

Alternatively, niches could be for products which are sold at different price levels. A Chevrolet, Pontiac, Buick, Oldsmobile, and Cadillac may all share a common platform, but have different levels of features which will appeal to people in different price ranges.

In each case, these products are much less expensive to produce, thus more competitive and profitable, than if they were developed independently (Dell 1996).

Platform Longevity (Temporal)

By architecting a system well, we can increase the longevity of the platform by making it modular and flexible enough to grow. As the market and technology change, the system can change with it, maintaining the underlying architecture and the components which are not affected. As in market niche penetration, products are much less expensive to produce than if you were working off a "clean sheet" design every time (Meyer 1997).

Concurrent Design

Concurrent engineering improves time to market by developing the product and manufacturing process simultaneously. A well defined, modular product architecture enables concurrent design, the development of multiple parts of the system at the same time. This drastically reduces time to market (Reinertsen 1996).

Reduced Interface Complexity

One of the guiding principles in developing a good architecture is the maximization of

internal complexity and the minimization of external complexity of modules. This strategy leads to simpler interfaces between modules which improves the reliability of the system, and makes it easier to isolate problems when they occur.

Better Environmental Performance

The purpose of this thesis is to explain how improving the environmental performance of a product can be added to this long list of architectural objectives. Before tieing together architecting and environmental objectives, some established concepts on how to improve the environmental performance of products need to be explored.

Chapter 4. Environmental Parameters

A quantitative method of measuring the environmental performance of a product is at best controversial, and at worst libelous (Udo de Haes 1999, 5). This is due to the subjective nature of any life-cycle assessment (LCA) which attempts to include different types of environmental impacts. There are numerous life cycle assessment methods available to the interested reader (Graedel 1998, 89-95). These approaches agree (more or less) about which environmental problems to address, they only differ in how they prioritize and measure these impacts.

In order to avoid the complications inherent in presenting a quantified result to an inherently subjective analysis, the analysis will be limited to subjective criteria.

Streamlined Life-Cycle Assessment (SLCA)

Graedel (1998) uses a streamlined life-cycle assessment (SLCA) matrix for product development which assesses the influence the product has over five life stages on five environmental stressors. For easy reference, each combination of stressor and life stage are referenced by the indices of their respective row and column in the matrix (Figure 4-1).

Figure 4-1 The Environmentally Responsible Product Assessment Matrix (Graedel 1998, 101)

	Environmental Stressor				
Life Stage	Material Choice	Energy Use	Solid Residues	Liquid Residues	Gaseous Residues
Premanufacture	1,1	1,2	1,3	1,4	1,5
Product Manufacture	2,1	2,2	2,3	2,4	2,5
Product Delivery	3,1	3,2	3,3	3,4	3,5
Product Use	4,1	4,2	4,3	4,4	4,5
Refurbishment, Recycling , Disposal	5,1	5,2	5,3	5,4	5,5

Each cell receives a score between zero and four. Zero represents a very negative impact on the particular environmental stressor during that life stage, while a four represents negligible impact on that stressor during that life phase.

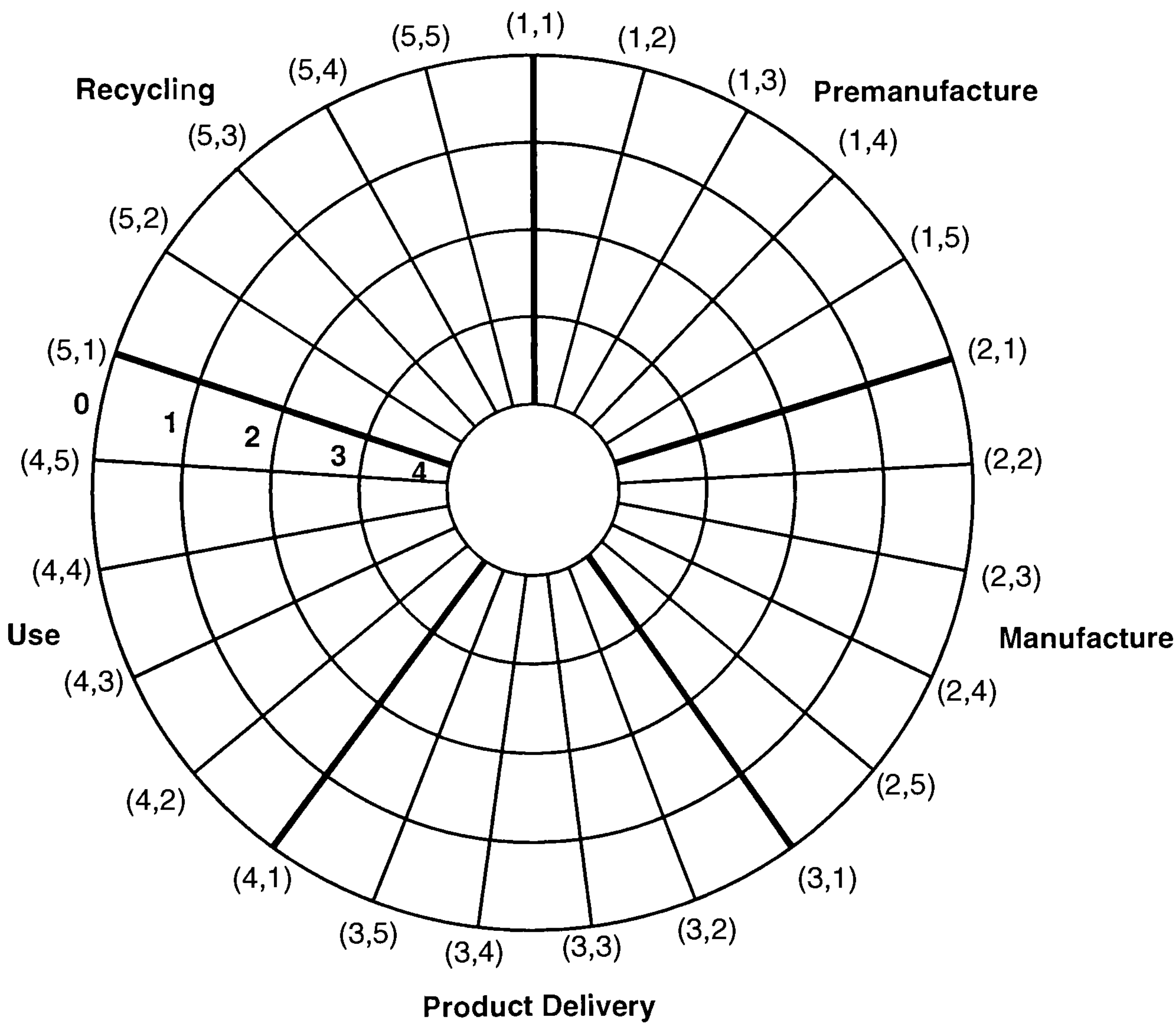
Target Plots

The result of this analysis is best summarized using a target plot. For each matrix

element there is a radial line labeled with the index of each cell. For example, (2,3) would represent the impact of product manufacture on Solid residues. There are five concentric circles the radii run through representing the scores. The outer circle represents a score of zero, the next circle in represents a one, etc. (see Figure 4-2).

The analyst can then clearly see how well a system performs by how well clustered the data points are toward the center of the plot. A poorly performing product will have the points scattered around the outside (Figure 4-3), while a product with good environmental performance will have the points clustered toward the center(Figure 4-4).

Figure 4-2 Target Plot (Graedel 1998, 102)



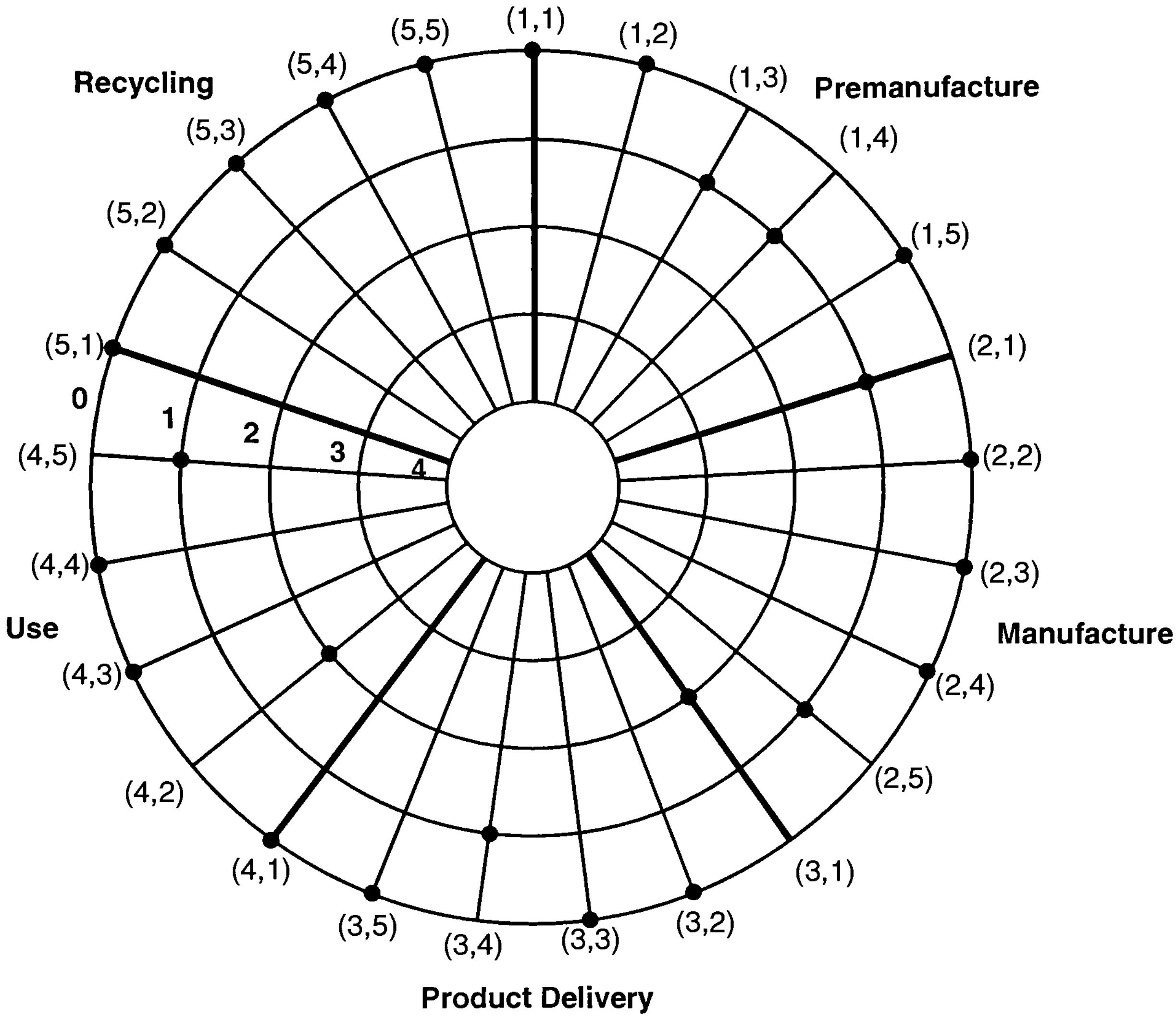


Figure 4-3 Target Plot for product with poor environmental performace.

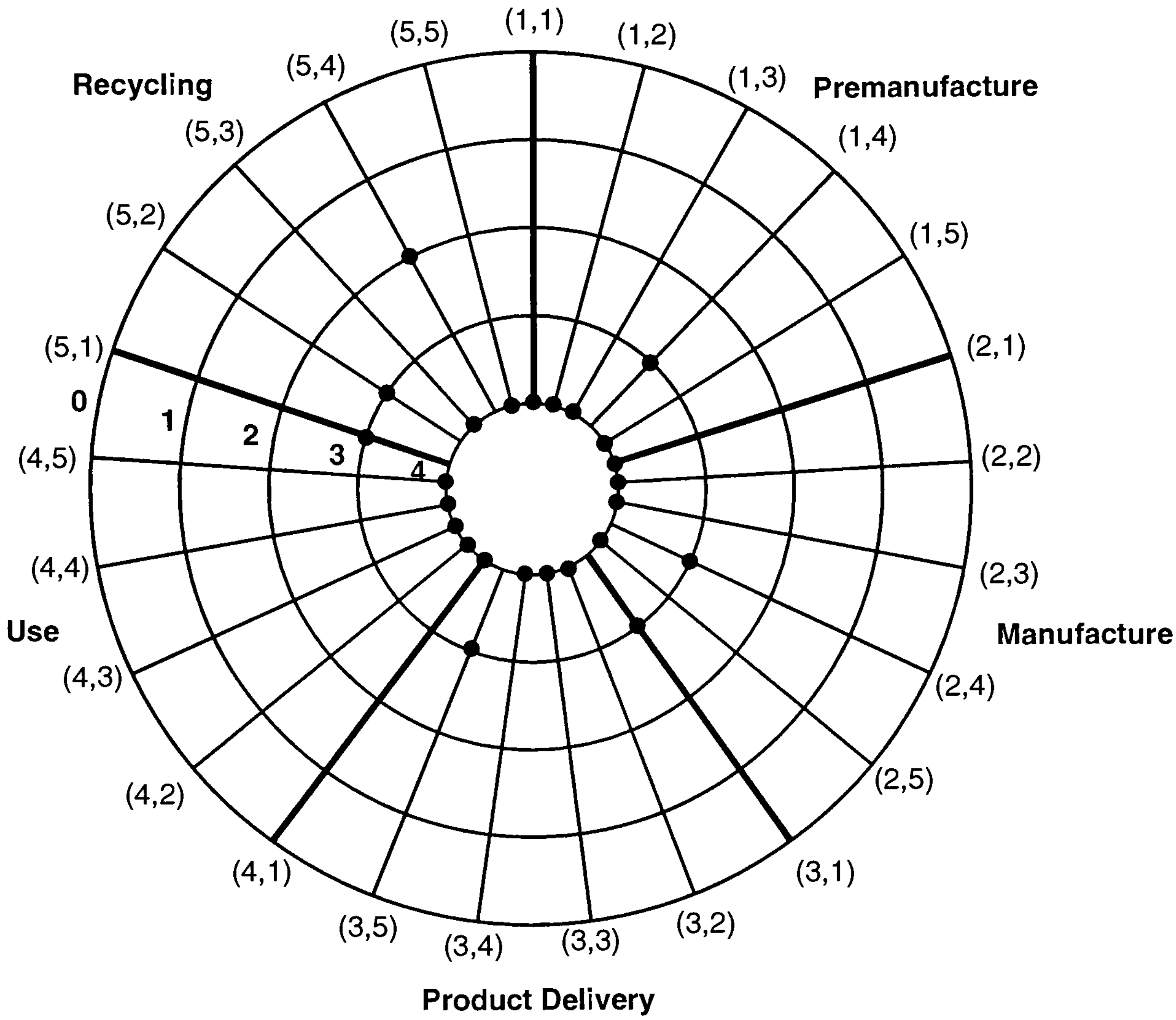


Figure 4-4 Target Plot for product with good environmental performace.

Scoring

A product which scores a zero in any given category is capable of considerable improvement, and one which scores a four has realized the best environmental performance possible at the time the study was carried out. These scores are not a measure of the absolute environmental performance of the product, but rather a measure of how much the environmental performance of the product could be improved. Note that as the state of the art progresses, and there is more opportunity for

improvement, the score for the same system may change.

Graedel (1997, 235-249) outlines criteria for scoring products in each life stage for the impact on each environmental stressor. these criteria are summarized to better understand how the environmental performance of a product may be improved.

Premanufacture Life Stage

Matrix Element: 1,1
Environmental Stressor: Materials Choice

To Improve Environmental Performance:

- Minimize the use of materials in limited supply.
- Design product to utilize recycled materials or components wherever possible.

Matrix Element: 1,2
Environmental Stressor: Energy Use

To Improve Environmental Performance:

- Minimize the the use of energy intensive virgin materials.
- Minimize the the use of high density materials which will cost more to transport.
- Minimize distance over which raw materials and components are transported.

Matrix Element: 1,3
Environmental Stressor: Solid Residues

To Improve Environmental Performance:

- Minimize use of materials whose extraction and refining result in the production of large amounts of solid residues.
- Minimize use of materials whose extraction and refining results in the production of toxic solids.
- Totally reuse or recycle incoming packaging, or minimize its volume and weight .

Matrix Element: 1,4
Environmental Stressor: Liquid Residues

To Improve Environmental Performance:

- Minimize the use of materials whose production produces large amounts of liquid residues.
- Minimize the use of materials whose production results in toxic liquid residues.
- Use refillable/reusable containers for incoming liquid materials.
- Minimize use of incoming components which require cleaning with high volumes

of liquids.

Matrix Element: 1,5
Environmental Stressor: Gaseous Residues

To Improve Environmental Performance:

- Minimize the use of materials whose production involves the generation of large amounts of gaseous residues.

Product Manufacture Life Stage

Matrix Element: 2,1

Environmental Stressor: Materials Choice

To Improve Environmental Performance:

- Avoid manufacturing processes which use materials in restricted supply.
- Avoid the use of toxic materials in manufacturing process.
- Avoid the use of radioactive materials in manufacturing process.
- Avoid the use of virgin materials in the manufacturing process.
- Minimize chemical treatment of materials and components.

Matrix Element: 2,2
Environmental Stressor: Energy Use

To Improve Environmental Performance:

- Minimize energy intensive processing steps.
- Minimize energy intensive evaluation and testing.
- Use co-generation, heat exchanges, and/or other techniques for utilizing otherwise wasted energy.
- Power down manufacturing facility when not in use.

Matrix Element: 2,3
Environmental Stressor: Solid Residues

To Improve Environmental Performance:

- Minimize the amount of solid residues resulting from manufacture
- Maximize the percentage of solid residues which are recycled.
- Investigate the resale of all solid residues as feedstocks for other products or processes.
- Minimize the production of solid residues without resale value.

Matrix Element: 2,4

Environmental Stressor: Liquid Residues

To Improve Environmental Performance:

- investigate and implement minimization of the use of solvents and oils in manufacturing.
- Investigate and implement sale of any liquid residues as feedstocks for other products or processes.
- Maximize the use of recycled liquids and the recycling of liquids in the process.

Matrix Element: 2,5
Environmental Stressor: Gaseous Residues

To Improve Environmental Performance:

- Minimize the use of HCFCs in manufacture of product.
- Minimize emissions of greenhouse gases in production of product.
- Investigate and implement the resale of gaseous residues for use in other processes or products.

Product Packaging and Transportation Life Stage

Matrix Element: 3,1
Environmental Stressor: Materials Choice

To Improve Environmental Performance:

- Minimize the number of different materials used in packaging.
- Minimize the weight of the packaging.
- Maximize recycled content of packaging.
- Maximize recyclability and reusability of packaging, and label as such.
- Use materials with a functioning recycling infrastructure in place.
- Include a packaging engineer and product installation personnel in product design.

Matrix Element: 3,2
Environmental Stressor: Energy Use

To Improve Environmental Performance:

- Avoid energy intensive packaging procedures.
- Minimize energy use in component supply system and product distribution and installation.
- Avoid energy intensive installation procedures.

- Avoid or minimize long distance, energy intensive product transportation.

Matrix Element: 3,3
Environmental Stressor: Solid Residues

To Improve Environmental Performance:

- Maximize ease of separation of packaging into constituent materials.
- Avoid use of materials which require special disposal when product is unpacked.
- Minimize product packaging and weight.
- Arrange to take back packaging for reuse and/or recycling

Matrix Element: 3,4
Environmental Stressor: Liquid Residues

To Improve Environmental Performance:

- Use refillable or reusable containers for liquid products.
- Design packaging operations which minimize the need for cleaning / maintenance procedures that generate large amounts of liquid residues.
- Avoid requirements for unpacking or installation procedures which result in large amounts of liquid residues.

Matrix Element: 3,5
Environmental Stressor: Gaseous Residues

To Improve Environmental Performance:

- Avoid release of pressurized gas during transport or installation.
- Minimize gaseous emissions from transport vehicles during distribution.
- Minimize toxic gas emissions if packaging material is to be incinerated.

Product Use Life Stage

Matrix Element: 4,1
Environmental Stressor: Materials Choice

To Improve Environmental Performance:

- Minimize use of consumables.
- Avoid one use designs.
- Avoid materials which require environmentally inappropriate maintenance.
- Avoid materials which may allow an unintentional release of toxic materials into the environment during use.
- Maximize recycled content of consumables.

Matrix Element: 4,2
Environmental Stressor: Energy Use

To Improve Environmental Performance:

- Minimize energy use of product over service life.
- Minimize energy use during maintenance and repair.
- Incorporate energy saving features (e.g. auto-powerdown, super-insulation)
- Incorporate ability to monitor and display products energy use or efficiency while in use.

Matrix Element: 4,3
Environmental Stressor: Solid Residues

To Improve Environmental Performance:

- Avoid or minimize periodic disposal of solid materials as part of design. (e.g. toner cartridges, batteries)
- Investigate alternatives to solid consumables.
- Investigate less environmentally harmful alternatives for intentional dissipative emissions.

Matrix Element: 4,4
Environmental Stressor: Liquid Residues

To Improve Environmental Performance:

- Avoid periodic disposal of liquid materials associated with use and/or maintenance of product.
- Investigate alternatives to liquid consumables.
- Investigate less environmentally harmful alternatives to designs which result in intentional dissipative emissions to water.
- Incorporate appropriate measures to avoid unintentional dissipative liquid emissions during use or repair of the product.

Matrix Element: 4,5
Environmental Stressor: Gaseous Residues

To Improve Environmental Performance:

- Avoid or minimize periodic emission of gaseous materials during use or maintenance of product.
- Investigate and implement use of alternatives to gaseous consumables.
- Investigate less environmentally harmful alternatives to intentional dissipative emissions to air.

- Incorporate appropriate preventative measures if there is a potential for unintentional dissipation of gaseous materials.

Recycling and Disposal Life Stage.

Matrix Element: 5,1
Environmental Stressor: Materials Choice

To Improve Environmental Performance:

- Choose materials with a plan for the desired recycling or disposal of the product.
- Minimize the number of different materials used in manufacture.
- Make different materials easy to identify and separate.
- Avoid the use of batteries.
- Avoid materials containing PCBs or PCTs.
- Avoid polybrominated flame retardants or heavy metal-based additives in plastics.

Matrix Element: 5,2
Environmental Stressor: Energy Use

To Improve Environmental Performance:

- Minimize the use of energy intensive process steps in disassembly by design.
- Maximize the amount of high-level reuse of materials.
- Minimize the energy intensity of transportation for recycling by minimizing weight and volume as well as centrally locating recycling facilities.

Matrix Element: 5,3
Environmental Stressor: Solid Residues

To Improve Environmental Performance:

- Minimize the use of chemical bonds or welds in deference to mechanical fasteners such as clips or hook and loop attachments.
- Avoid joining dissimilar materials in ways which are difficult to reverse.
- Use ISO marking to identify the content of all plastic components.
- Try to establish a dominant species of plastic parts which make up over 80% by weight of the plastics used.
- Try to develop products which will be leased rather than sold.

Matrix Element: 5,4
Environmental Stressor: Liquid Residues

To Improve Environmental Performance:

- Ensure that liquids contained in the product can be recovered at disassembly .
- Minimize liquid residues generated during disassembly, recovery, and reuse.
- Minimize the amount of liquid residues generated during materials reuse and recovery.

Matrix Element: 5,5
Environmental Stressor: Gaseous Residues

To Improve Environmental Performance:

- Facilitate easy recovery of gases contained in product at disassembly.
- Minimize gaseous residues generated during material recovery and reuse.
- Choose plastics which can be incinerated without requiring sophisticated air pollution devices.

Summary

The SLCA method of Graedel provides a concise, concrete framework for measuring environmental performance of a product while it is being designed. While the absolute values of the outcome may not be meaningful, the relative values of different design alternatives will be. The target plot is a good visualization tool we can use to assess at a glance the environmental performance of a product over all twenty five criteria defined by Graedel. The task now is to establish architecting principles which will create systems which tend to comply with the environmental criteria set forth by Graedel.

Chapter 5. Environmental Architectures

In this chapter the two areas of systems architecture and improving product environmental performance will be integrated into a set of guidelines for using product architecture to maximize environmental performance.

Architecting is an iterative process, and as such it's often hard to determine where to begin the process and where to terminate it. It is rare to be presented with a "clean sheet design" to solve a given problem. There is almost always a current product from one's own organization or a competitor's whose functionality you will be trying to preserve and improve upon. For this reason, and for the purpose of focusing this study, discussions will be limited to those which apply to modifications of an existing architecture. Many of the concepts developed here would also readily apply themselves to a clean sheet design.

Architecture Concepts and Environmental Performance

Scoping

Recall from Chapter 3 that the scoping part of the architecting process establishes the boundaries of the problem. Scoping can dramatically impact the environmental performance of a product.

Scoping the architecture both functionally and temporally must be considered. When functionally scoping the product's architecture, it must be decided which natural and human-made systems to consider in our design. The temporal scope defines which life stages of the product and the natural systems effected are considered in the design. Including the natural systems and all the life stages of the product that the analyst has influence over in the scope of the architecture forces him or her to address all the environmental impacts of his or her activities.

Models

As the medium through which the architect communicates with the client, a model that links the architecture with environmental impacts is crucial. Following the work of Graedel (1998), a simple model will be used that indicates the environmental stressors

affected during each life stage of a product (Figure 5-1). Links will be drawn between this model and other models in the functional and technological domains.

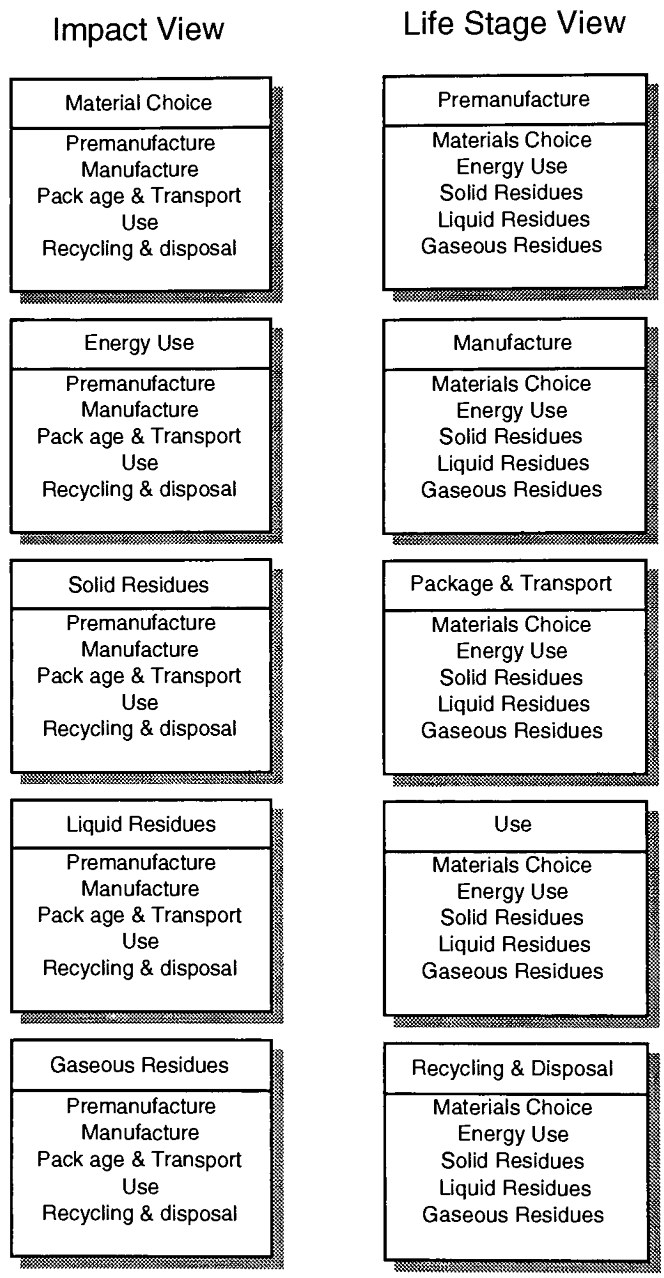


Figure 5-1. Environmental Models

Heuristics

Architectural heuristics are the guidelines an architect uses to develop a good architecture. Rechtin and Maier(1997) list over 180. Which of these architectural heuristics should be used to improve the environmental performance of our product? Of Rechtin and Maier's heuristics about 50 which could impact the environmental performance of a system were identified. In addition to these, some architecting principles and new heuristics tailored to improve the environmental performance of a system were considered. These 69 heuristics and architecting principles are listed in detail in Appendix A.

Graedel's Guidelines

In order to establish a link between these heuristics and architecting principles and impacts on the environment, each heuristic or principle was examined and matched with Graedel's 91 guidelines given in Chapter 4. The exercise revealed 1099 links between heuristics or principles and Graedel's guidelines, establishing plausibility for the claim that there is a link, albeit a subjective one, between product architecture and environmental performance. The results are presented in Appendix B.

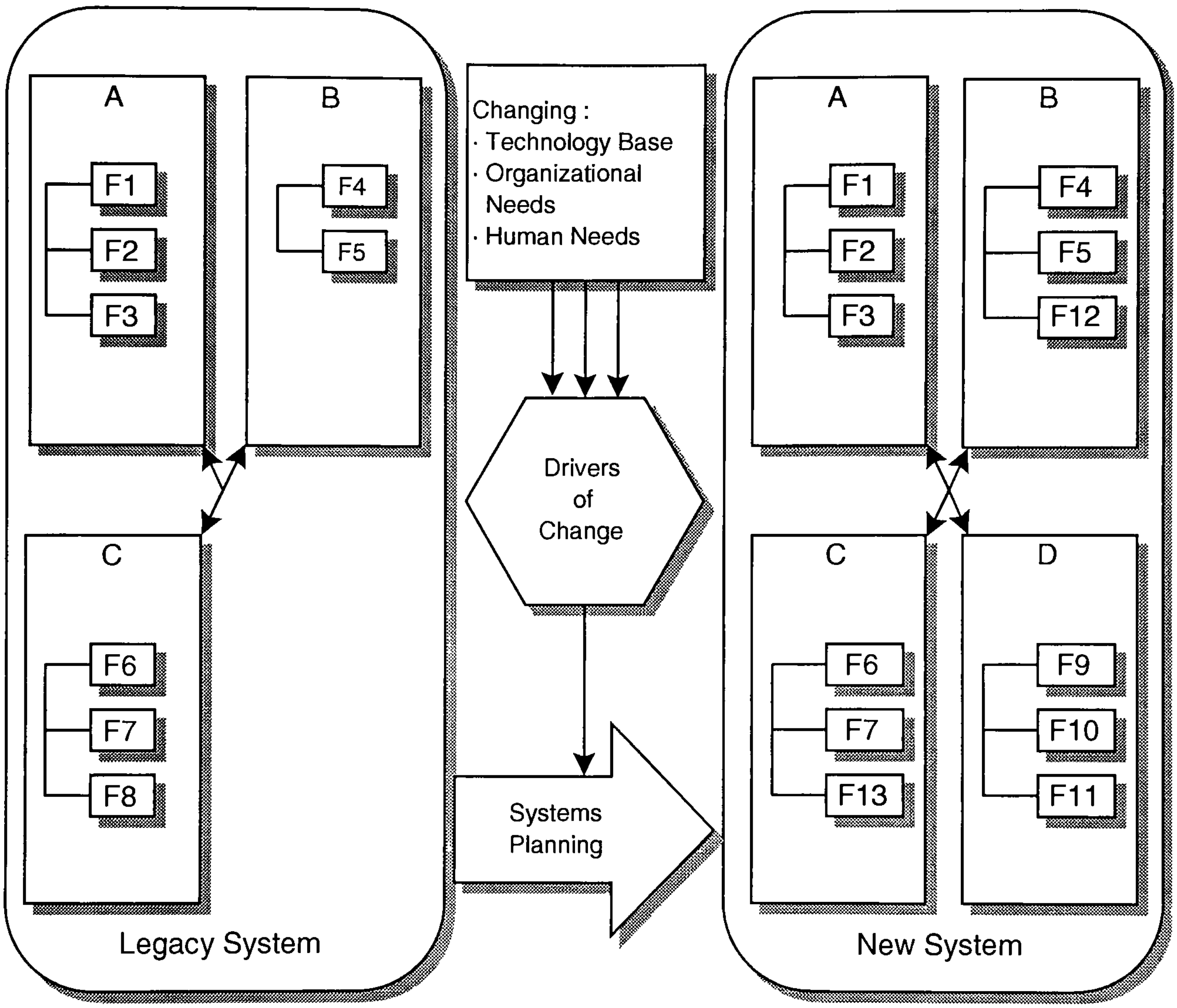


Figure 5-2. Evolution of product architecture

Methods

How are systems rearchitected? Figure 5-2 (Sage and Lynch 1998) shows an example of how system architectures may change over time. The legacy system in the diagram consists of three subsystems, each with a number of functions. Driven by a changing technology base, organizational needs and human needs, this legacy system is rearchitected into a new system. The new system is much like the old one, with a few changes. Subsystem A has moved to the new system with its original functionality.

Subsystem B has moved to the new system with an added function F12. Subsystem C has lost the function F8 but gained a new function F13. The new system has an added subsystem, D with three new functions.

This example illustrates some of the many forms of change which can be produced by rearchitecting a product. The architect can reallocate the functions among subsystems, remove or add functions, add new subsystems, change the acceptance criteria, or expand a product architecture to a platform architecture.

Sage and Lynch (1998) name three drivers for architectural change: a changing technology base, changing organizational needs, and changing human needs. To these three drivers, a fourth is added in this thesis: environmental degeneration.

The method to re-architect a system for higher environmental performance developed

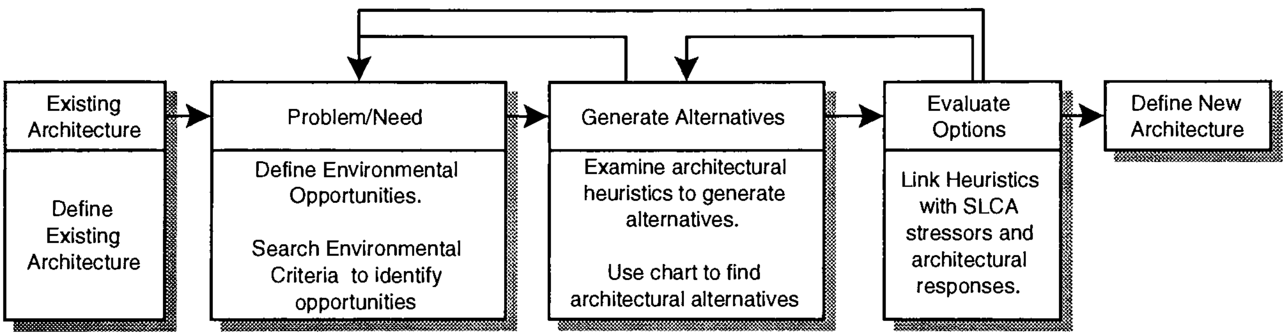


Figure 5-3. Process for re-architecting an exisiting product to improve environmental performance.

for this thesis is represented by Figure 5-3. Since the analyst must understand the architecture in order to change it, he or she begins by defining the existing architecture. The analyst can then evaluate the current product design in light of the criteria outlined in Chapter 4. When the areas in which the product has the greatest opportunity for environmental improvement have been identified, he or she is ready to identify heuristics to guide the architectural changes which will lead to improved environmental performance. These changes may be identified by using the chart in Appendix B to match the environmental deficiencies with relevant architectural heuristics. Once these architectural alternatives have been identified, the analyst evaluates the options, and defines a modified product architecture guided by these heuristics.

Figure 5-4 shows the flow of information during the problem definition and alternative generation phases of the process. Note that consideration extends beyond the current state of the system. In order for the architecture to perform well in the environmental

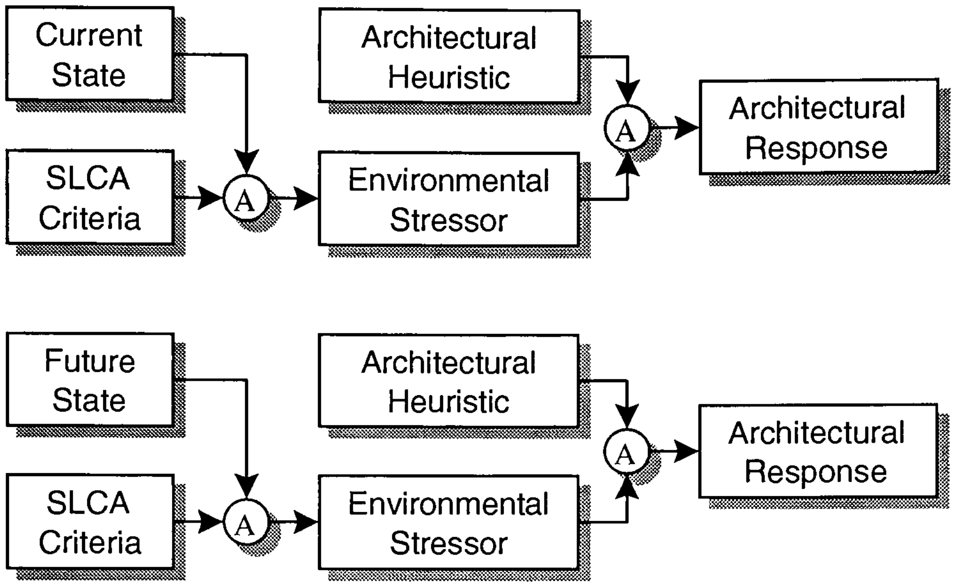


Figure 5-4. Generating the architectural response.

domain, it must be able to change as environmental conditions change, and thus must be open to reanalysis given future states of the system.

An architecture can be larger than just one product. Therefore, in addition to this method of identifying a product's architectural deficiencies and modifying the product architecture in response to them, one can use several other strategies to maximize the environmental performance of the product by expanding the architecture beyond just the product.

Platforms

Looking beyond the product itself, and thinking about how it can fit into a family of products sharing a common platform of subsystems can yield many benefits (Reinertsen 1992, Erens and Verhulst 1997, Morris and Ferguson 1993). Platforms can lead to higher environmental performance in several ways. For example, by extending the production life of existing subsystems, one can reduce waste and costs due to redesign and re-tooling. Alternatively, by maximizing components reuse over a product line, economies of scale and production and transportation efficiencies can be increased as well as create a more favorable environment for component reuse and remanufacture. Platforms can also be leveraged to extend the usable life of a product by lowering the cost and effort required to upgrade the system.

Strategies for Establishing Platforms.

The first step in establishing a platform is modularizing the architecture. A modular architecture can usually be identified by each medium level function of the system being performed by a minimum of subsystems, certainly no more than two, preferably one.

Beating Obsolescence.

Once the architecture is modular, evaluate each module in light of how it might be effected by changes in the state of the art as well as market forces. Specify in the module certification criteria that there be a plan for upgrading or modifying the module if market forces or the state of the art should change. The product architecture can then be extended into a platform architecture which spans multiple generations of products. Environmental impact are lowered, as well as re-tooling and setup costs, by increasing the production life of the unaffected components.

One effective way of evaluating how market forces may affect the product is to examine similar products. Evaluate how the architecture might accommodate the niches occupied by those other products, and specify that the effected subsystems be built to accommodate the added functionality necessary to occupy those niches. The product architecture can then be extended into a platform architecture which occupies multiple market niches. In this way, environmental impact can be lowered, as well as costs, through increasing the economies of scale for the shared components of these products.

Upgradability, Component Reuse, and Remanufacturability.

Upgradability

By lengthening the service life of a product by upgrading it, its environmental performance can be improved over nearly all life stages and environmental stressors. One notable exception is when an upgraded product consumes more energy or consumables than a state of the art redesigned product. An example of this exception would be a meticulously maintained and updated 1950 Buick Roadmaster. No matter how efficient the upgrades make the engine, a car weighing that much will consume far more fuel than a modern day Cadillac weighing much less.

The strategy for designing a platform to be easily upgradeable is similar to that previously used for beating obsolescence. Now, however, one does not have the liberty of specifying that a quick redesign accommodate the change. The portions of each of the subsystems which are effected by the market or technology change must be

replaced or augmented in the field.

Platforms and Reuse of Components.

By defining a product architecture which spans multiple product generations, the door is opened to the possibility of reusing or remanufacturing common components from older obsolete products in newer state of the art products in the same family. The larger the quantity of a given component in obsolete products, the more economical recovery and reuse in a new product will be. Reusability of a component is highly dependent on the component's service life and conditions. (Klausner, Grimm and Hendrickson 1998)

Design for Certification and Test Beds

Specifying certification criteria for a system or subsystem is an integral part of the architecting process. This certification process may involve a test bed in which the subsystem is tested outside of the product we are architecting. The next step toward architecting systems with higher environmental performance is to specify these same certification criteria and test bed designs to test parts for reuse.

Conclusion

In this chapter a method for architecting systems was developed which yields a product architecture with improved environmental performance. Criteria Graedel (1998) used in his streamlined life-cycle assessment method was combined with architecting principles from several sources, most prominently Rechtin and Maier (1997). In addition to this synthesis, strategies for improving environmental performance using platforms for products spanning both market segments and product generations was discussed, as well as the importance of certification standards and test beds.

Now that these architectural strategies for improving environmental performance have been established, they will be applied to a case study.

Chapter 6. Case Study – Ink Jet Printers

In this case study the architecture of the Hewlett Packard DeskJet 540 ink jet printer will be examined, and the methods described in Chapter 5 will be used to rearchitect the printer for improved environmental performance. Before rearchitecting the printer, some background about how ink jet printers work must be laid.

How Ink Jet Printers Work.

Evolution

Ink Jet printers have been around since the late 1960's, but were rarely used outside of industrial settings due to their high cost and maintenance requirements. One of the primary technical barriers to making a consumer grade ink jet printer was an inability to keep the jets from clogging. This was due to conflicting requirements of the ink. In order to print quickly, the ink needed to dry quickly, but to keep the jets from clogging, the ink needed to dry slowly. This problem could be minimized in an industrial setting by controlling the environment in which they operated, using them in applications which did not require rapid drying, and using them for applications in which the jets were continuously printing. None of these solutions were practical in the consumer market.

Hewlett Packard overcame this obstacle in the mid-1990's by devising a way to manufacture the heads inexpensively enough to make them disposable. The ink jets were incorporated into a module with the ink, some circuitry, and a heating element used to fire each jet. This approach to implementing "Thermal Ink Jet" printing has been widely used by several manufacturers, including Canon and Lexmark.

The Printing Process

A computer can send a print request to the printer by passing it a document description file, or by sending it more primitive commands and a bitmap dot by dot (See figures 6-1 and 6-2). The two dominant document description file formats are PostScript (PS) and Printer Control Language (PCL). Printers which take more primitive commands usually comply with the Graphic Display Interface (GDI) standard (Wylie 1999).

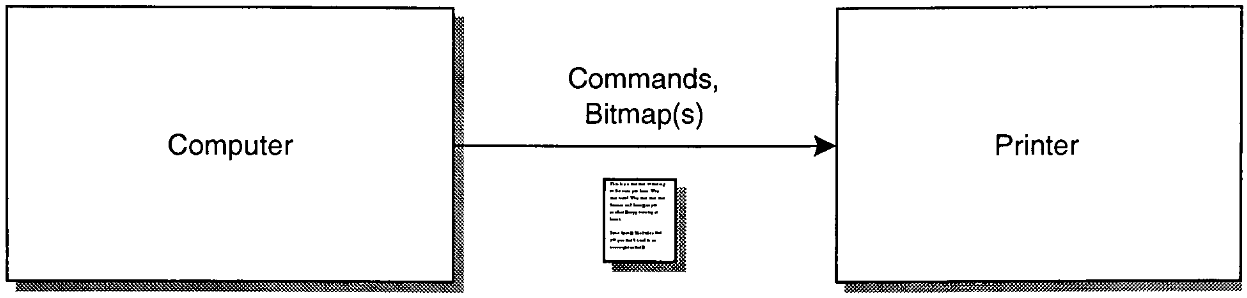


Figure 6-1. GDI (Graphic Display Interface) printer interface.

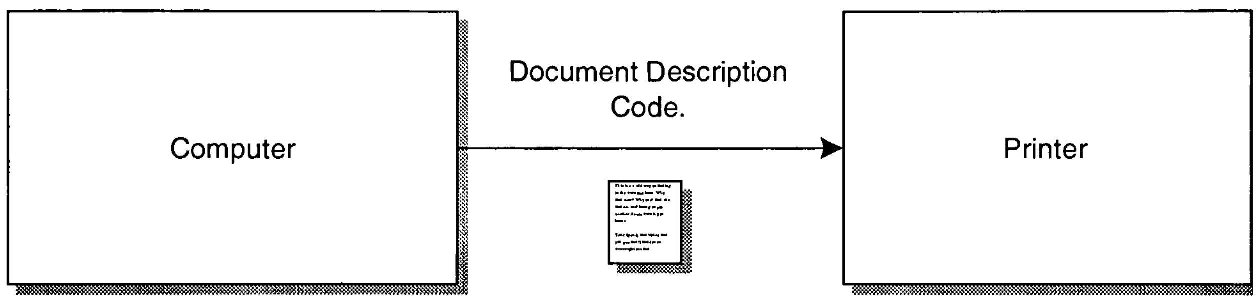


Figure 6-2. PCL (Printer Control Language) or PostScript (PS) printer interface.

GDI is used in less expensive printers. Most of the image processing is done on the computer, with only very low level commands sent to the printer. After the computer processes the image, a portion of the bit map for each color is passed to the printer.

Using a document description file to pass information to the printer requires considerably more processing ability of the printer than does GDI. PCL or Postscript document description files contain a text or binary description of the document. These files are processed in the printer by the pinter controller which contains it's own memory and cpu . The information in the description file consists of layers of geometric shapes and characters. The description file is used to generate a display list. The display list represents what the actual printout will look like. The display list is used to generate the bitmap of the printout. This bitmap is sent to the hardware controller that generates commands for the paper feed, ink jets, and other hardware in the printer to actually print the image (See Figure 6-3).

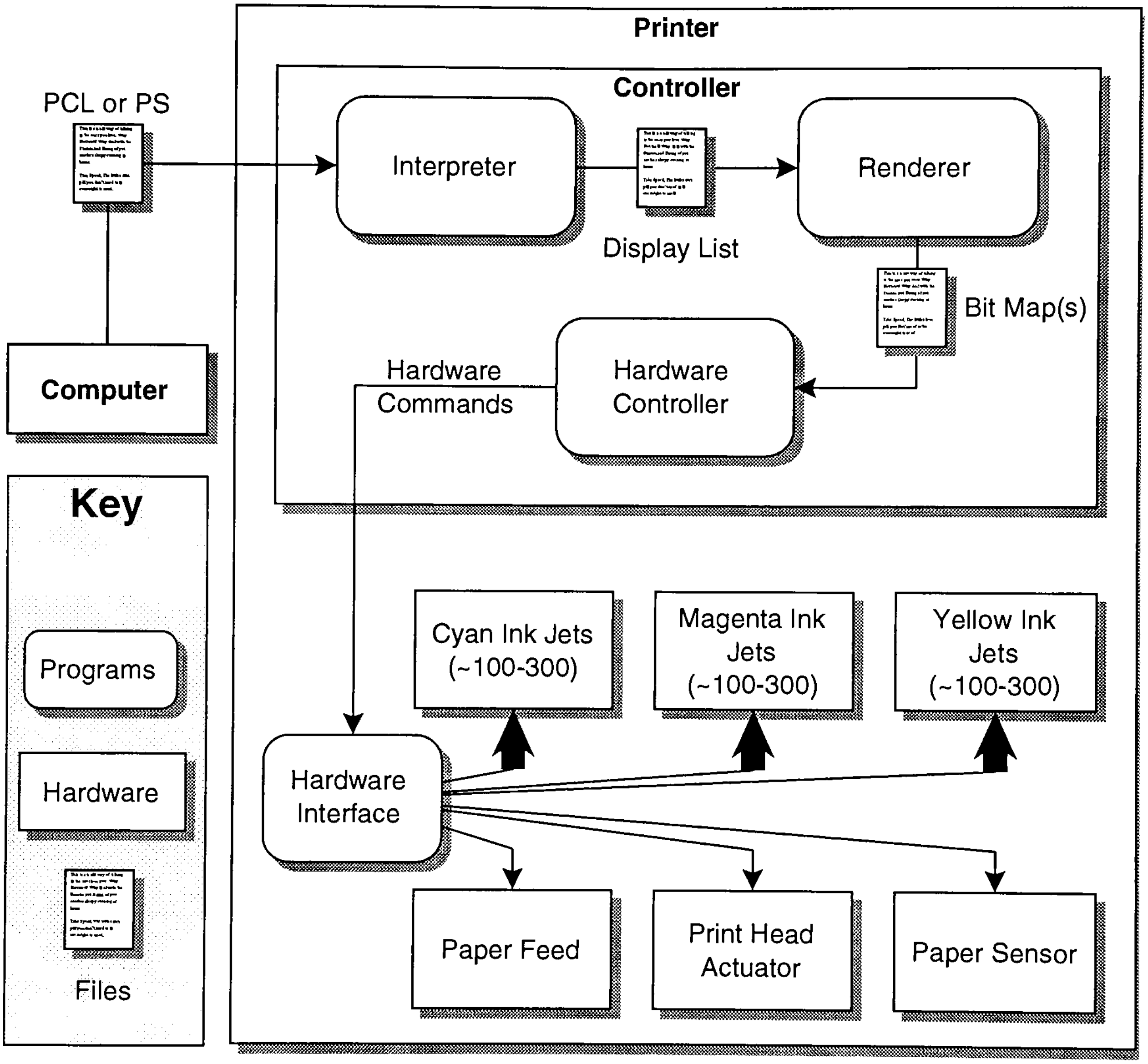


Figure 6-3. PCL or Postcript Printer Architecture.

Now that the reader has a basic understanding of how an ink jet printer operates, the case study, which investigated ways to improve the architecture of the Hewlett Packard DeskJet 540 printer, can be reviewed.

Scoping

In Chapter 3, scoping was defined as the process by which boundaries of the system

are set. Everything considered when architecting the system resides within these boundaries.

Before looking at the DeskJet 540, the investigator took a step back to look at the "big picture." Were there other ways in which the same ends could be accomplished with a lower environmental impact? Could technologies outside of those currently used in the existing system be included within the scope of our project?

The task of the printer is to convert information described in the computer into a portable, high resolution format. This same end might be accomplished by developing an inexpensive ultra-high resolution portable display which could hold and display several pages of information at once. Another possibility considered was to design a system around a reusable paper substitute which could be used, then cleaned and reused with very little quality degradation.

The architect should be aware of technologies available through the research and development arm of the company. If this type of technology was not available, it could be a fruitful area for further research and development.

For the case study, the scope of technologies was limited to those previously used in the DeskJet 540. The functional and temporal scope of the architecture was largely that used by Graedel, as outlined in Chapter 4. This scope would be passed down to the subsystem designers through certification criteria. A streamlined life-cycle assessment requirement was added to the specifications for certification of each subsystem. The result of this assessment was required to be presented at each design review.

With the preliminary scoping done, the architecting methodology discussed in Chapter 5 (See Figure 6-4) was applied.

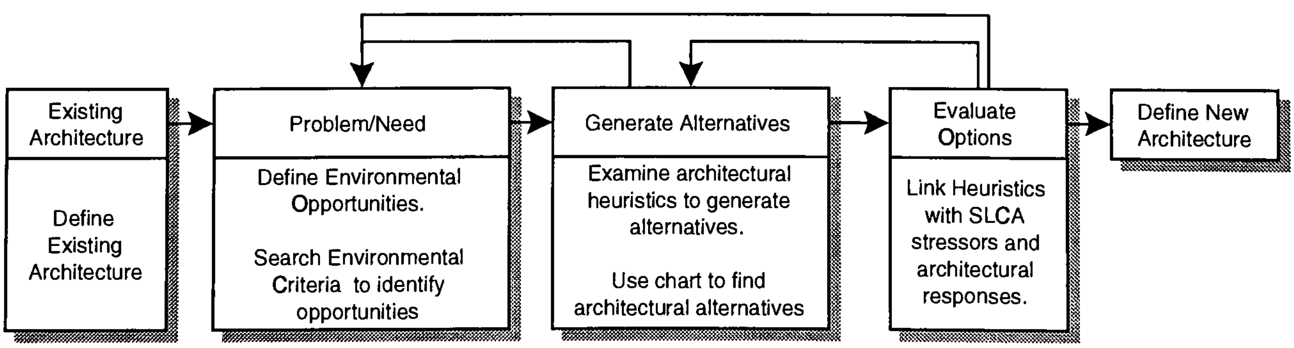


Figure 6-4. Process for re-architecting an exisiting product to improve environmental performance.

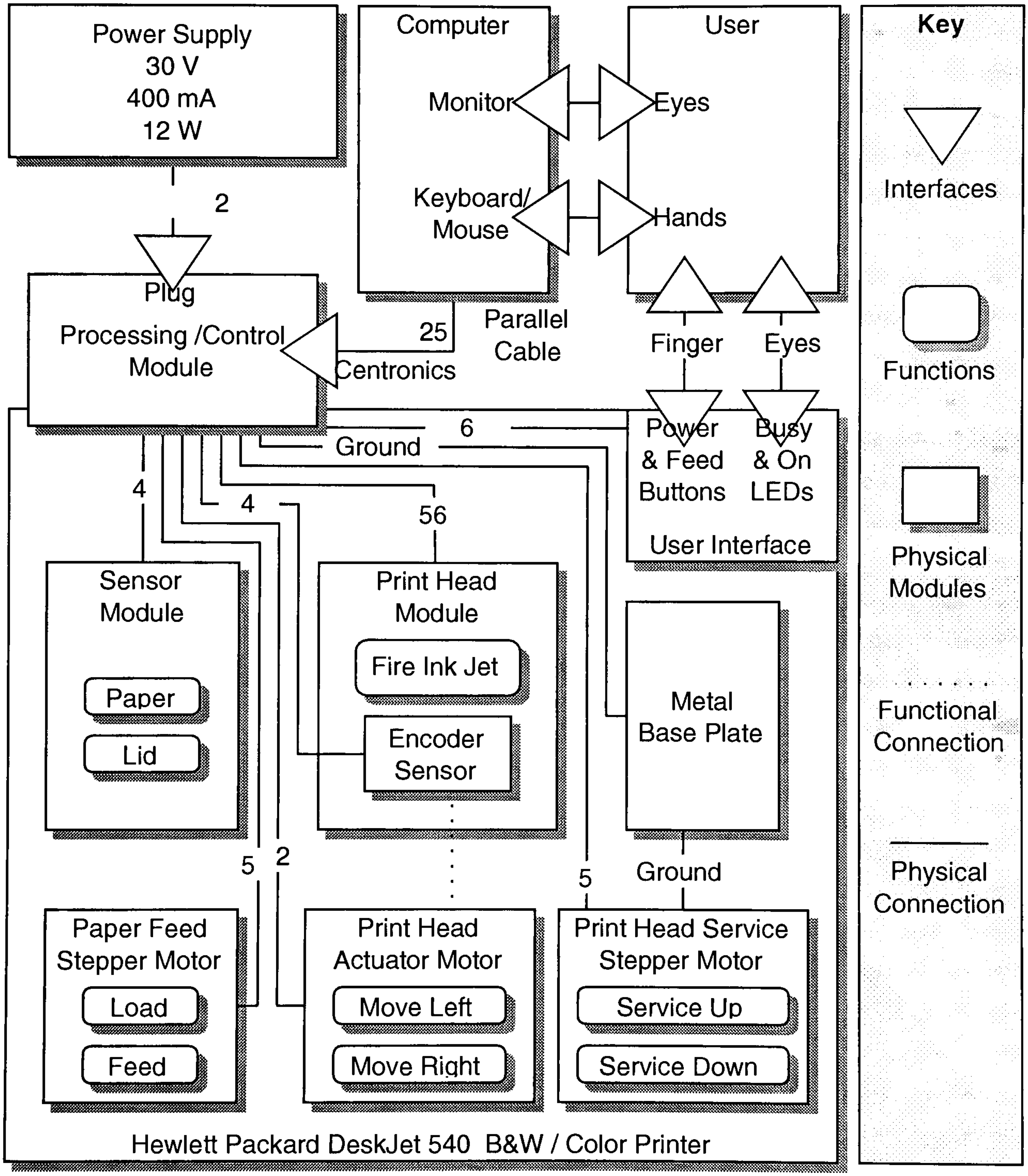


Figure 6-5. Physical Model of HP DeskJet 540 B&W / Color Printer

Models

As the reader will recall from Chapter 3, models are the tools the architect uses to define the architecture, track it during development, and communicate with the client. Since an existing physical product is used as the starting point, the definition of the existing architecture began by defining the physical model, and proceeded from the concrete to the abstract.

Physical Model

In order to divine the physical model for the existing product, the connections between the subsystems in the DeskJet 540 were mapped. Figure 6-5 represents the resulting physical model of the existing system. Since the printer is a well integrated system, certain subsystems were difficult to define, so relatively low level descriptions of some components were used. The number by each connecting line indicates the number of wires which connected components.

The physical model revealed an architecture that is very shallow since just about all of the components in the system are controlled directly by the controller subsystem.

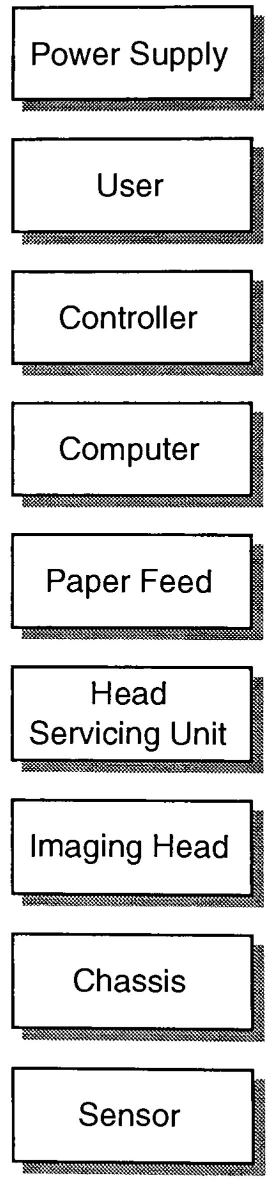


Figure 6-6. Subsystem model of existing printer.

Subsystem Model

From the physical model, the investigator stepped up a level of abstraction to the subsystem model. Figure 6-6 is a subsystem model of the printer. Subsystems necessary to perform certain tasks were identified. A great deal of subjective judgment was required in defining these subsystems due to the highly integrated nature of this design, but that is part of the art of architecting.

Functional Model

Next, the investigator moved up to the next level of abstraction, and developed the functional model describing how this PCL based printer works. Since the printer has several functions, a number of different use cases representing different situations in which the printer might be operated were considered. Figure

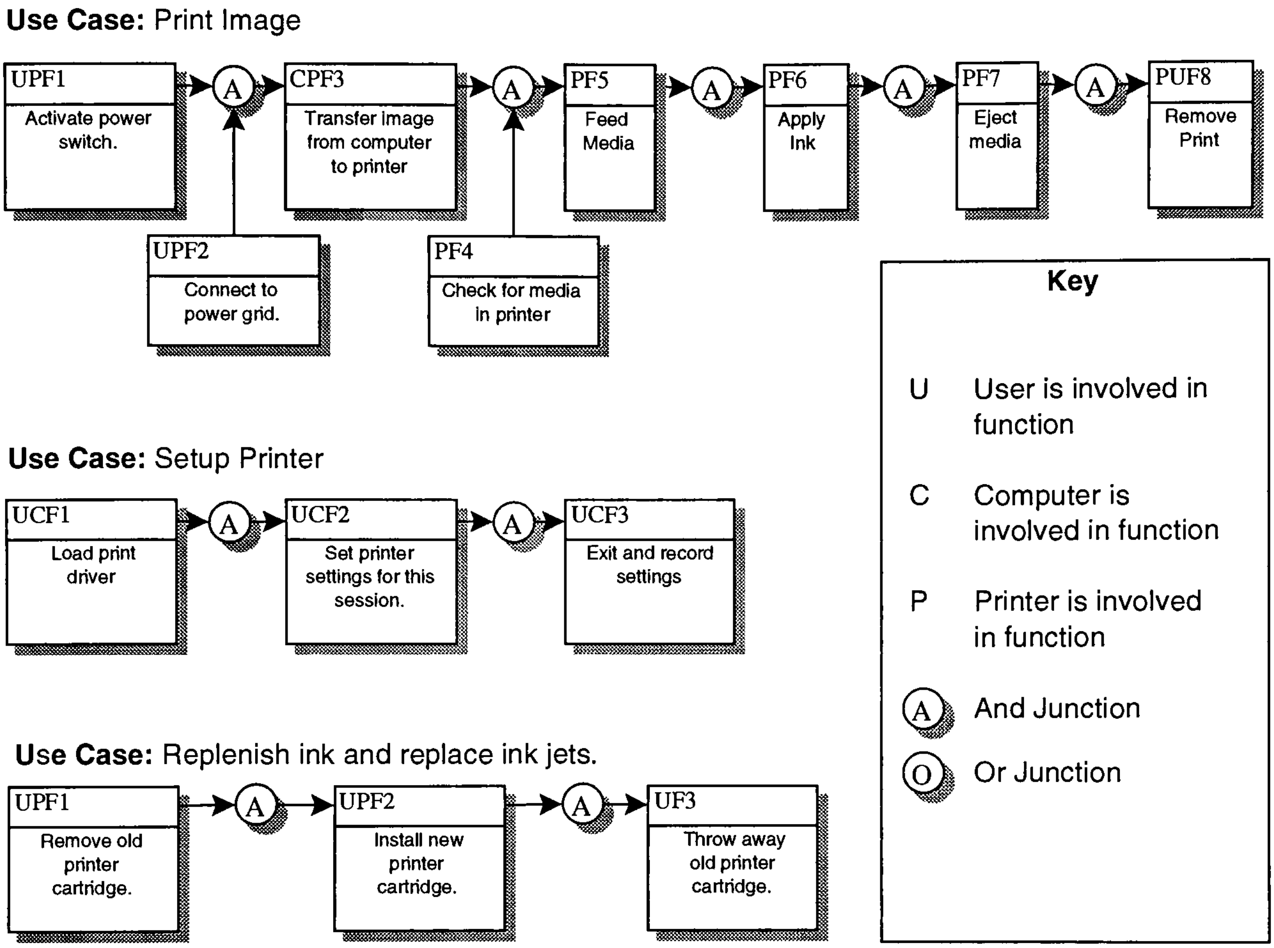


Figure 6-7. Level 1 functional flow diagram of existing DeskJet 540 printer for three use cases

6-7 represents the level 1 functional model for several use cases.

A very high level map between the functional model and the physical model was made. Functions were denoted using a code letter of U, C, or P depending on whether the user, computer, or printer are involved in the function. A function containing more than one of these codes is a "compound function."

With this many compound functions, it was difficult to understand exactly what functions the printer was responsible for. To go a little deeper, the print image use case was examined more closely. The second level functional model of this use case, shown in Figure 6-8, clarified which functions were performed by the printer, the user, and the computer.

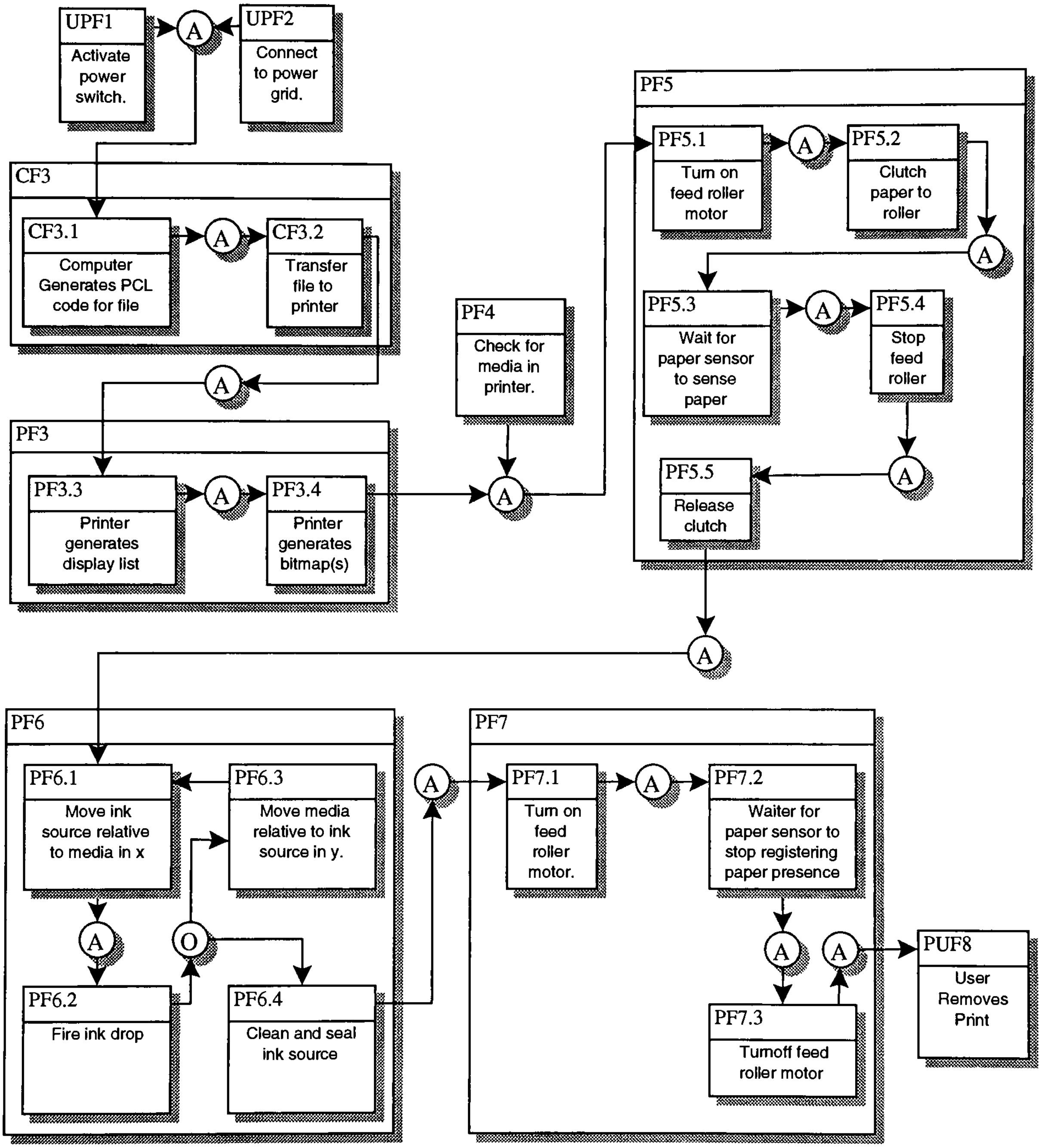


Figure 6-8. Level 2 functional model of print image use case of DeskJet 540 printer

Mapping Between Models

It was then possible to map functions to subsystems, as shown in Figure 6-9. The astute reader may notice that for just about every level 1 function there was more than

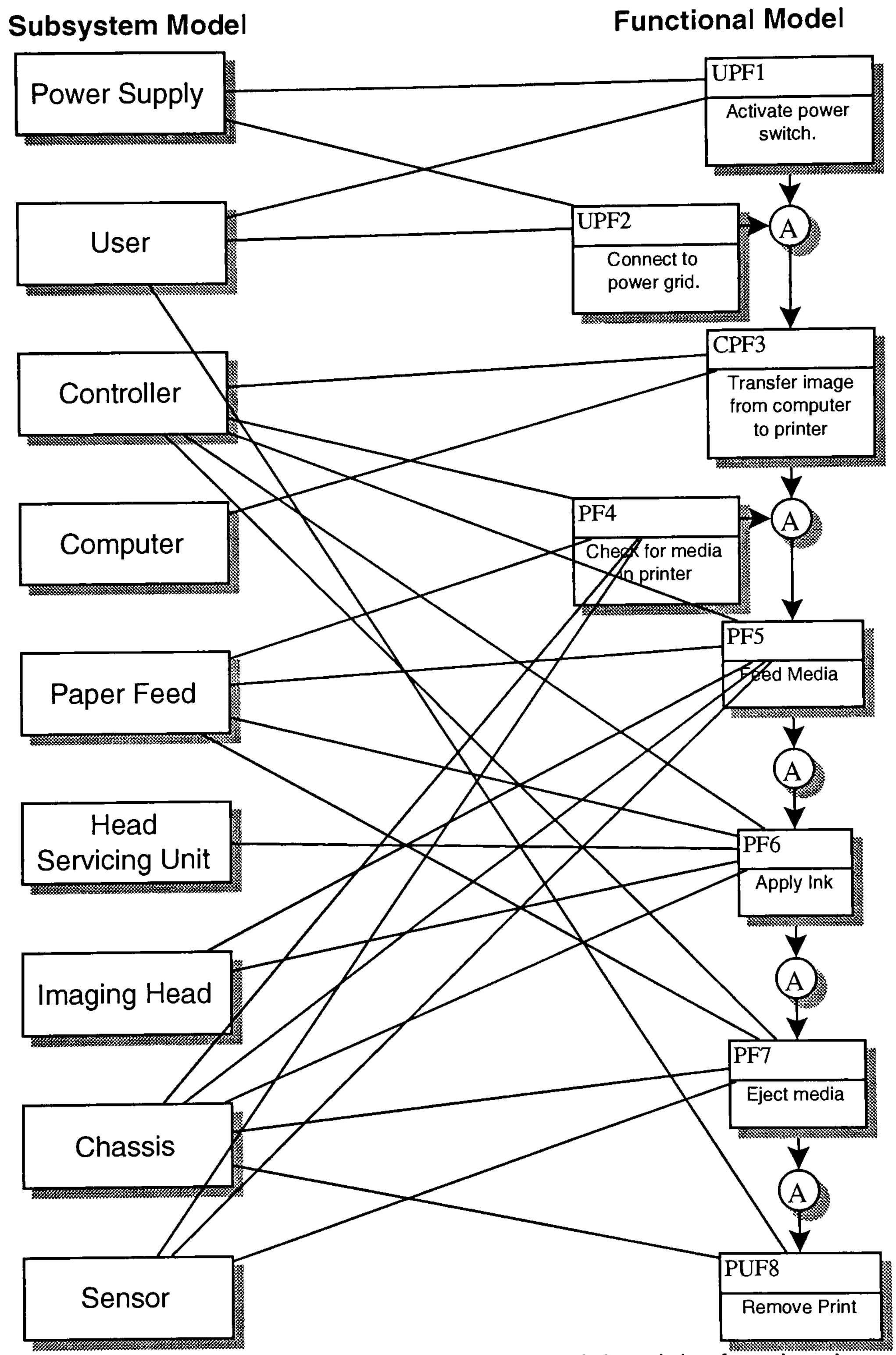


Figure 6-9. Mapping between the subsystem model and the functional model.

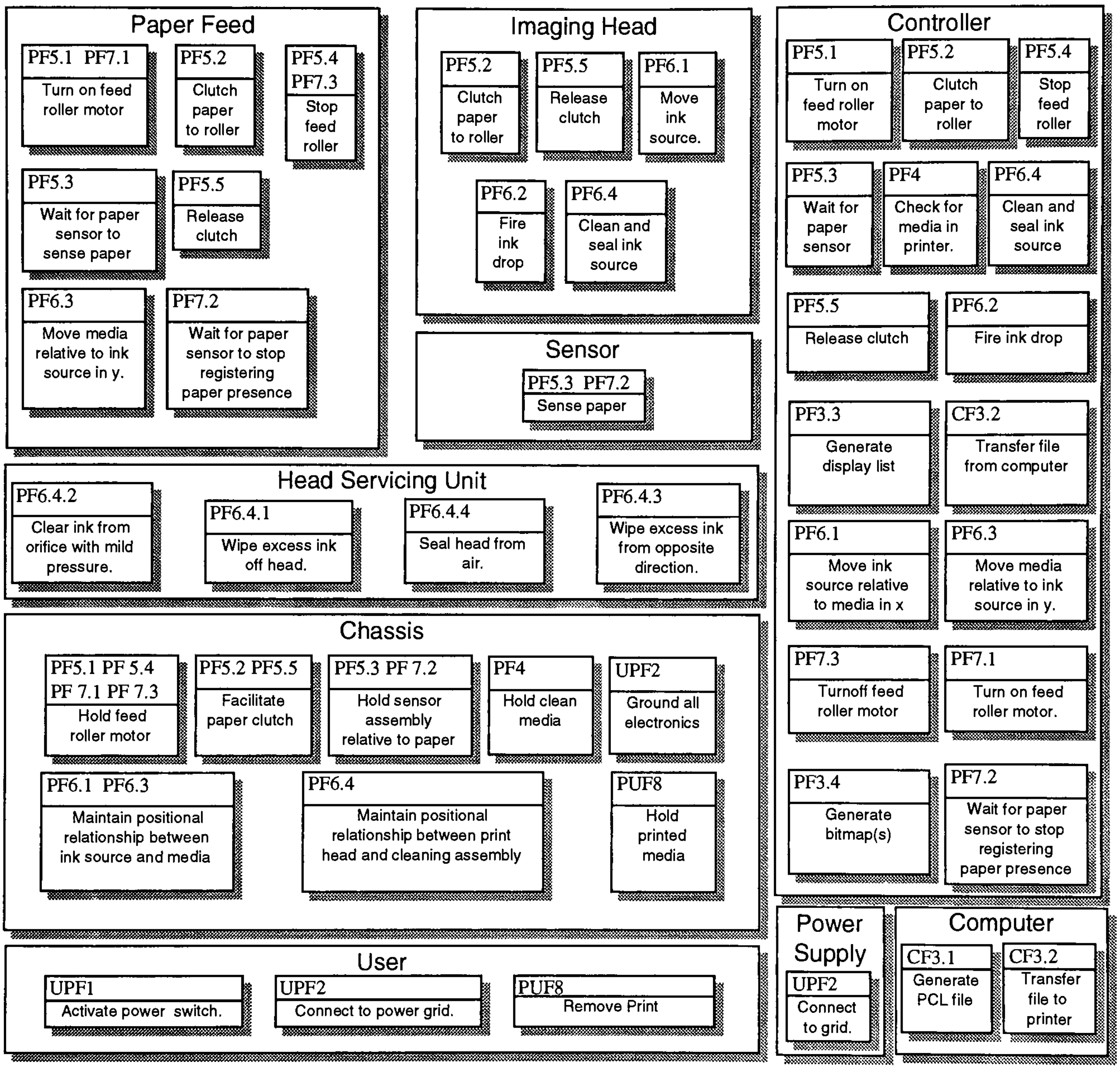


Figure 6-10. Integrated functional-subsystem model of the HP Deskjet 540 printer.

one subsystem used to perform that function. In two cases, five subsystems were required to perform a function. This indicated, by the definition in Chapter 3, that there was high external cohesion between subsystems, which usually indicates an integrated architecture.

This mapping is reflected in the combined functional-subsystem model shown in Figure 6-10. Each subsystem contains the functions mapped to them, and a description of

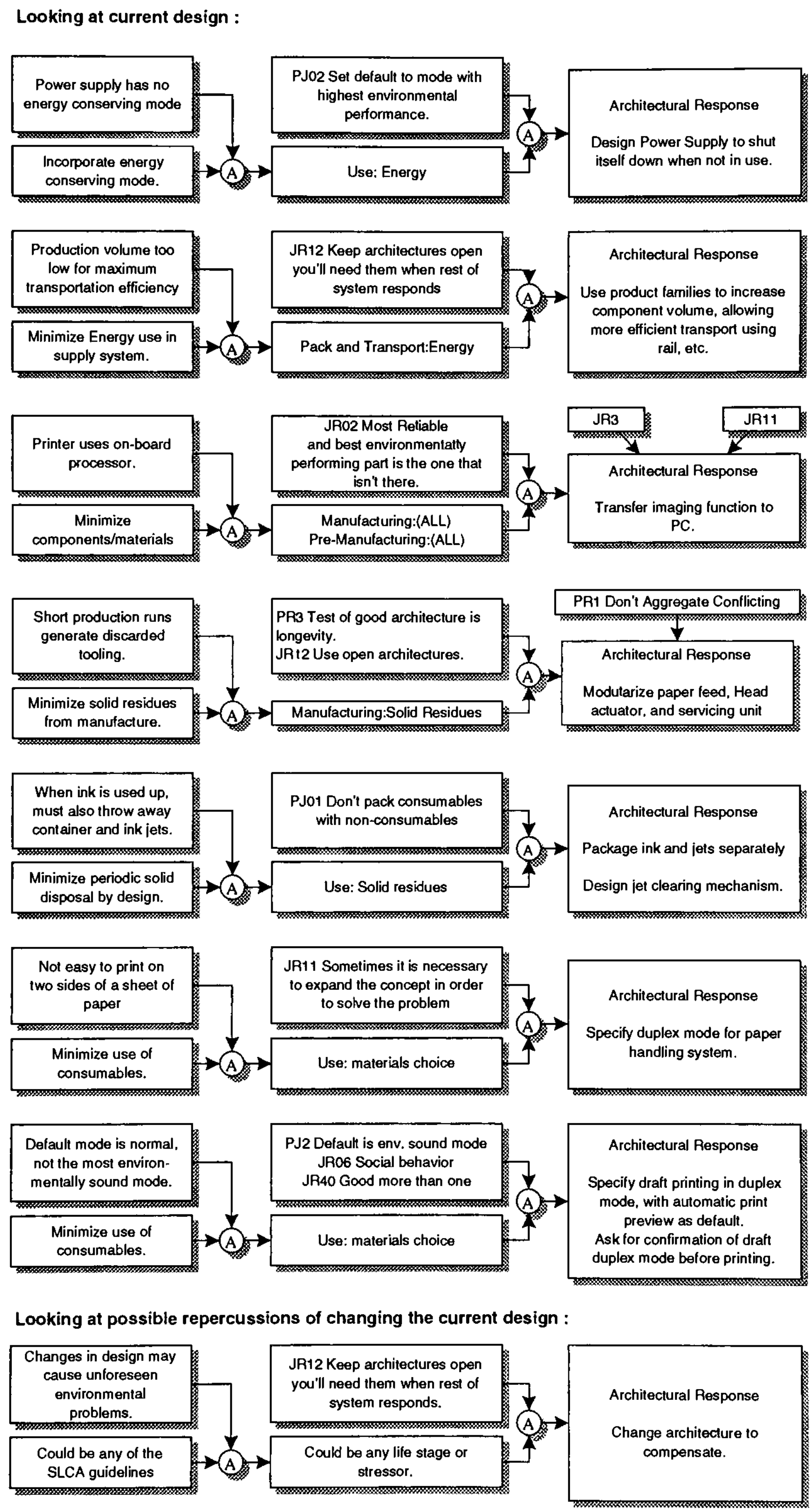


Figure 6-11. Identifying environmental opportunities and generating architectural responses.

how the mapped printing functions are related to subsystem functions.

Through these four models, the current architecture was defined well enough to move on to the next step in the rearchitecting process, defining the opportunities for improving environmental performance.

Generating Architectural Responses

Identifying Environmental Deficiencies

The SLCA criteria from Chapter 4 were were used to identify environmental deficiencies in the current architecture. Seven specific deficiencies in the current design were located, and one possible issue with the future state of the system. These are shown using the information flow diagrams from Chapter 5 in Figure 6-11. The environmental stressor identified by the lower box in the center of the information flow diagrams corresponds to a portion of the environmental model. This can be thought of as a map between the information flow diagram and the environmental model.

Finding Appropriate Architectural Responses

Next, the architecting heuristics were examined in an attempt to locate one which will ameliorate the environmental deficiencies. By applying this heuristic to the current architecture, an architectural response to the environmental opportunity was generated.

Defining a New Architecture

Allocation

To implement these architectural responses, some functions were reallocated from one subsystem to another, new functions were added to some subsystems, and some subsystems were absorbed into other subsystems. The architectural responses were implemented through the reallocation of functions and absorption of subsystems indicated by the arrows in Figure 6-12.

The result of the functional reallocation is shown in Figure 6-13. Notice that several subsystems have stacks of functions. These stacks are the result of functions which were spread over multiple subsystems being consolidated into one subsystem.

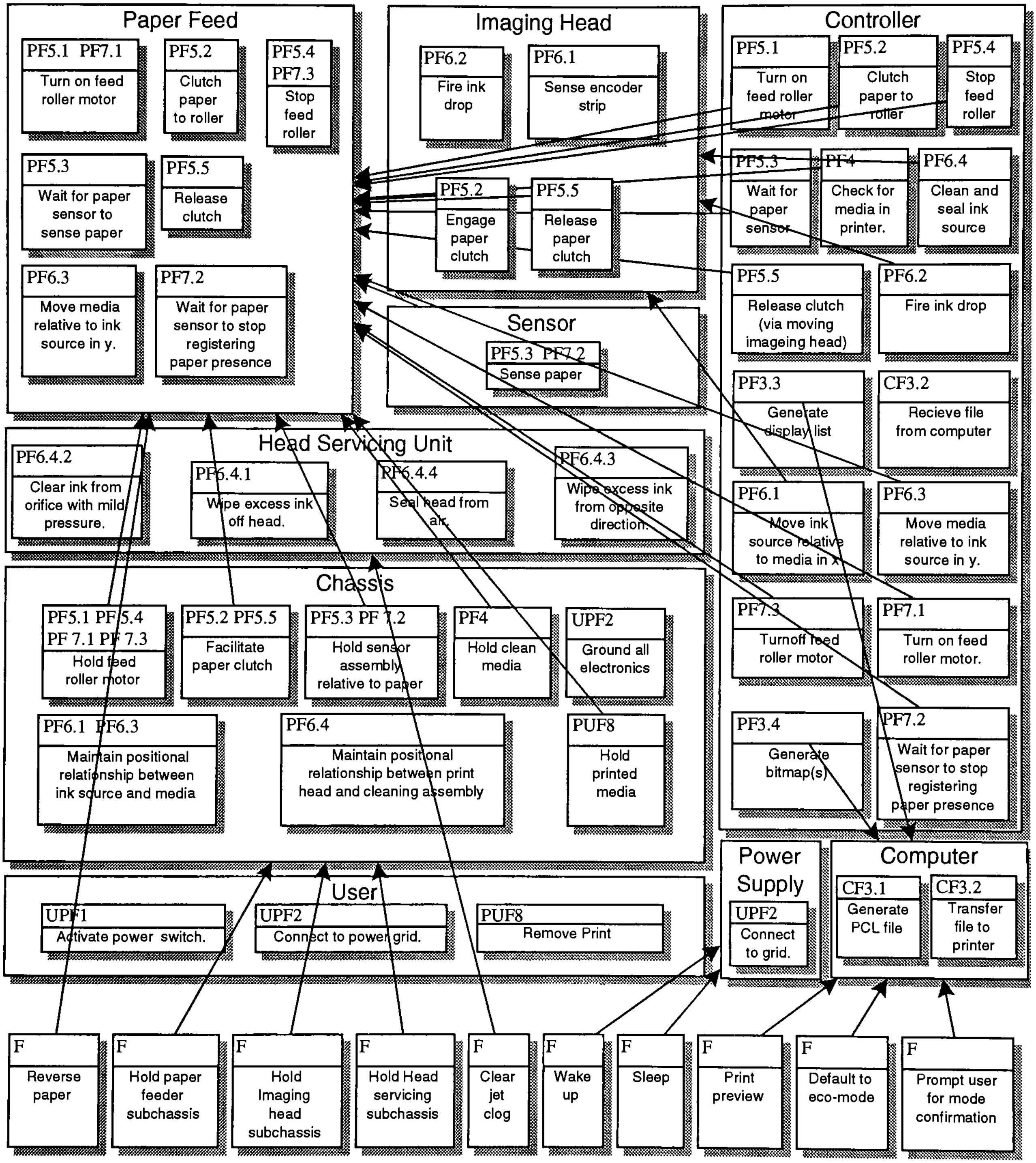


Figure 6-12. Reallocation of subsystem functions of HP DeskJet 540 Printer

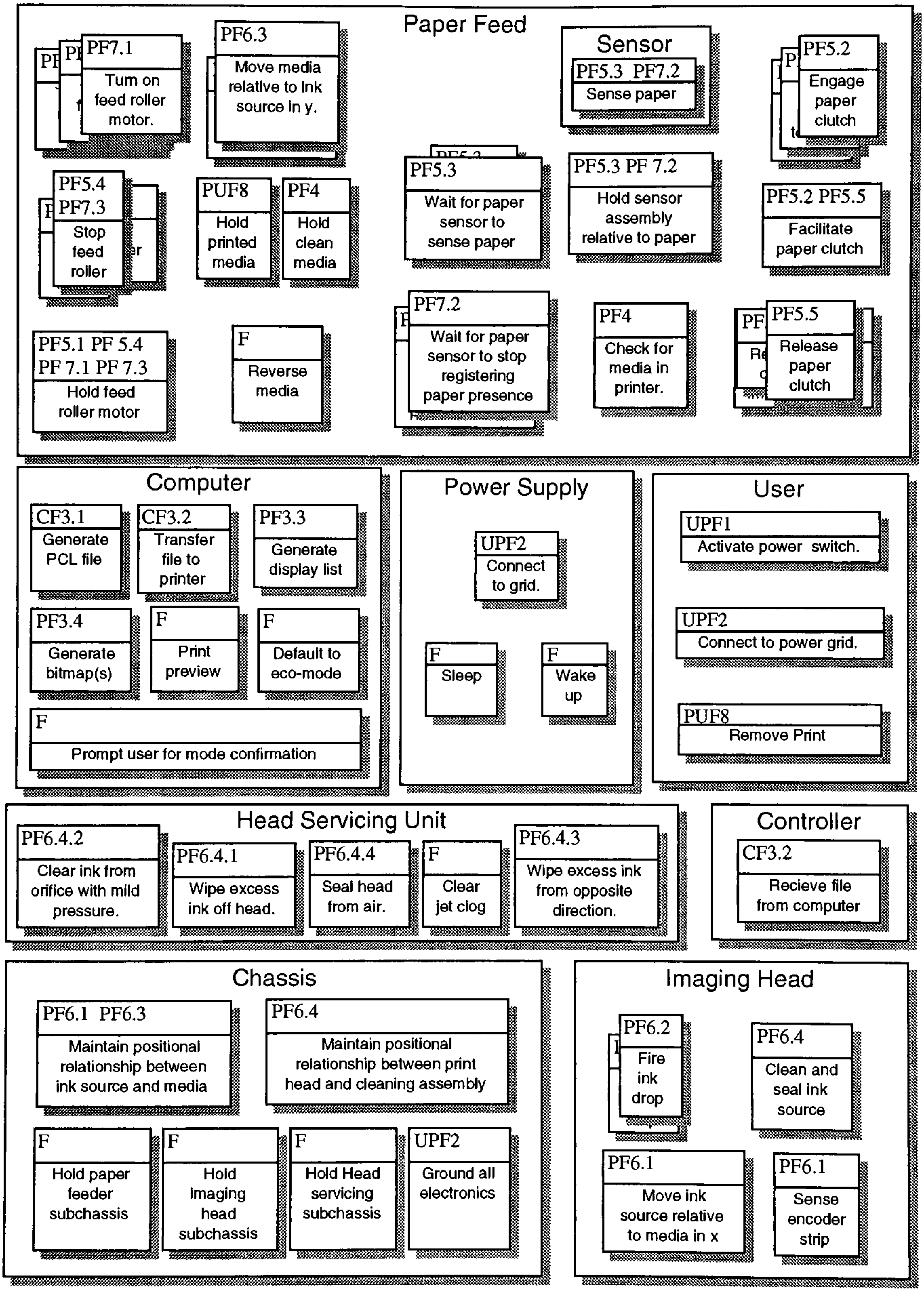


Figure 6-13. Reallocated subsystem functions of HP DeskJet 540 Printer

Aggregation

The job of the architect is to provide guidelines which will prevent teams developing different subsystems from interfering with one another. At the same time, the architect must make the guidelines as flexible as possible, allowing the engineering team to squeeze the most performance out of their subsystem for the least cost. The functional

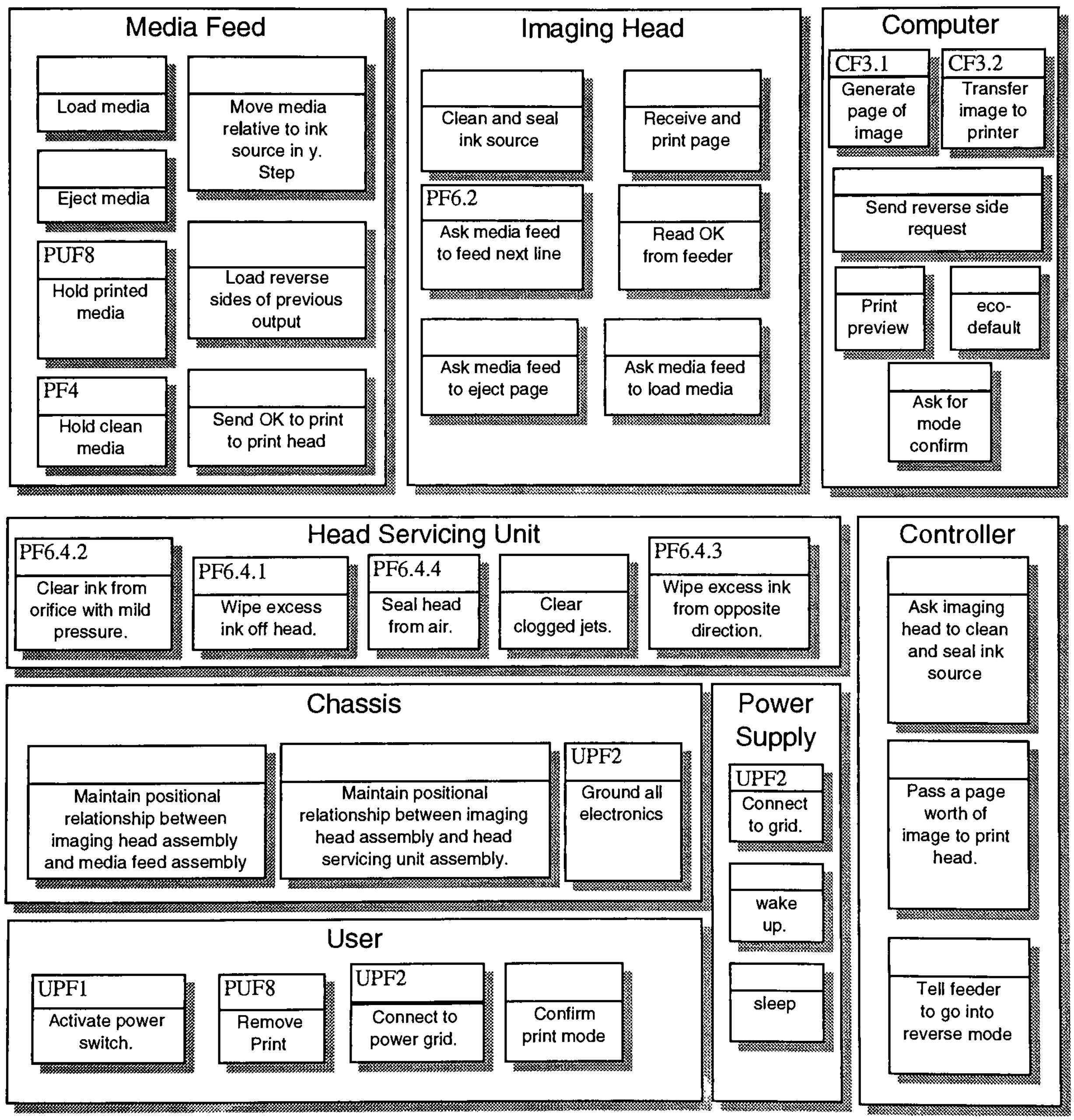


Figure 6-14. Re-aggregated subsystems of HP DeskJet 540 Printer

specifications in the reallocated printer were too specific to act as guidelines for the subsystem development team. These functions had to be aggregated into higher level subsystem requirements, as shown in figure 6-14.

Platforms

The increased modularity of the architecture should enable the extension of the product architecture into a product family platform. The next step was to identify which subsystems needed to be defined as mutable to accommodate adding functionality in the family.

Looking across the current range of printers, the features one might want to add to different models in the same printer family were identified as: capacity for larger media; capacity for feeding several different types of media; and higher media holding capacity. This suggested specifying that the media feeding subsystem be designed so it could be widened, and additional feeding trays added.

Other subsystems which might be effected by these changes in the media feeder were identified. The chassis needed to accommodate a number of different feeder configurations. The controller and computer software needed to be able to accommodate additional paper feeders. These specifications were included in the design criteria for the effected subsystems.

Next, the possibility of extending the product platform over several generations of products was investigated. The controller was identified as a subsystem highly susceptible to technological obsolescence. Requirements for an upgradeable processor and memory were included in the controller specifications.

Assessing the new architecture.

Modularity

Was this new architecture an improvement over the old one? One property of an architecture that will allow the most freedom for subsystem designers, and the fewest faults due to unforeseen interactions between subsystems, is low external cohesion, a measure of modularity. To assess the modularity of the rearchitected system, the functional model was mapped to the subsystem model, as shown in Figure 6-15.

The linkage between the functions and the subsystems was much less complex in the rearchitected system. The external coherence between subsystems was much lower

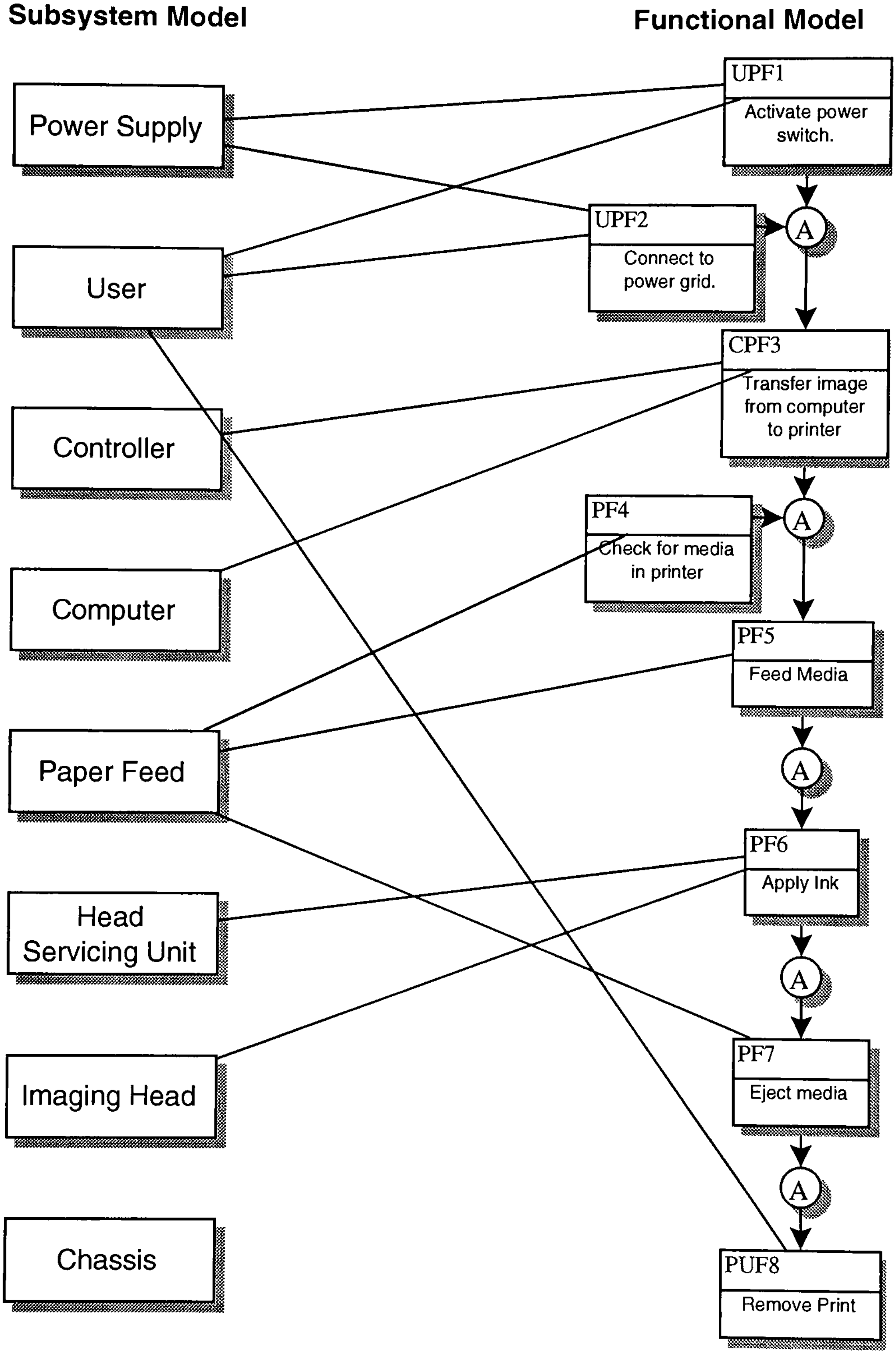


Figure 6-15. Mapping between the functional model and the subsystem model after rearchitecting the system

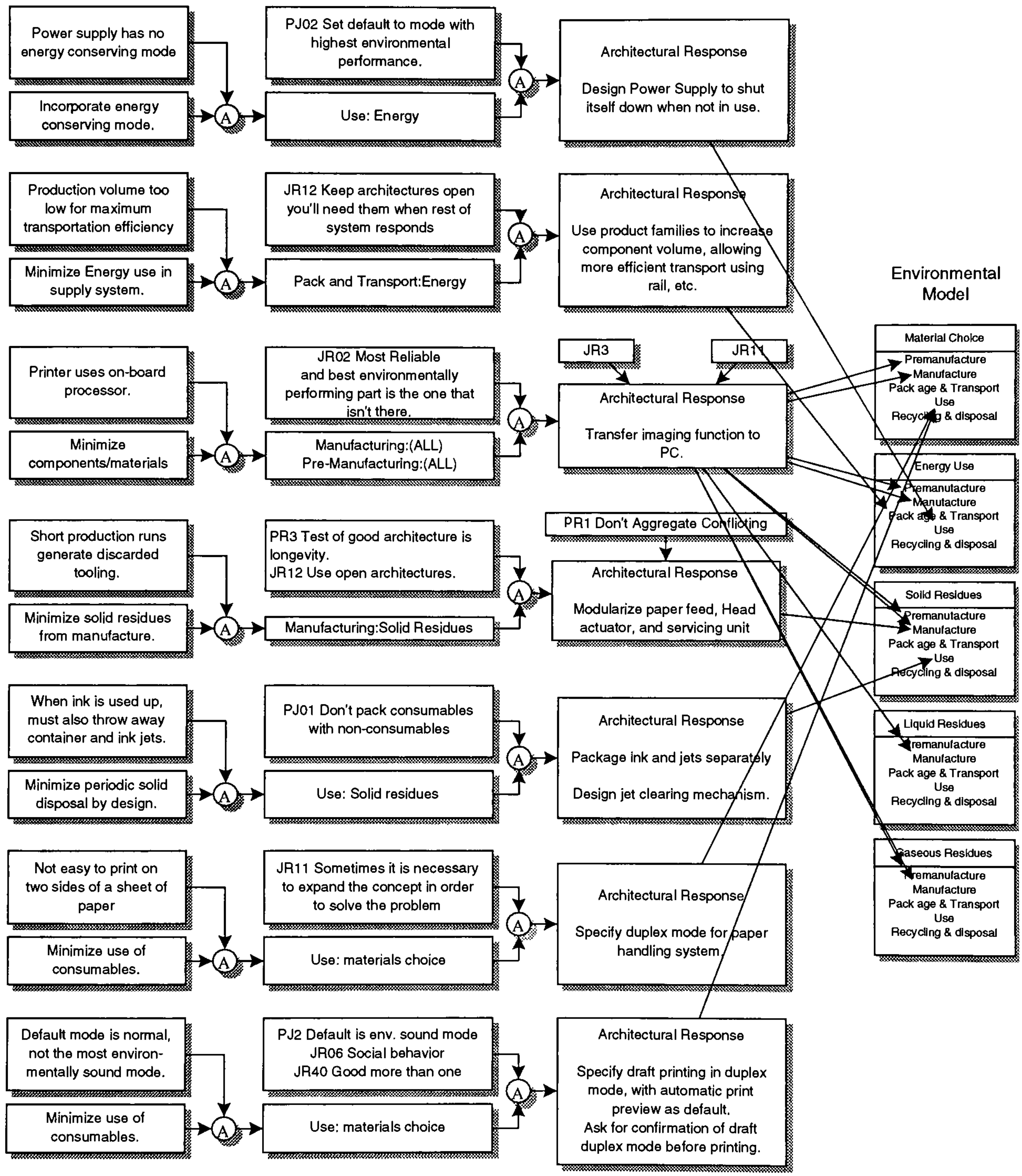


Figure 6-16. Map between environmental model and architectural responses.

since few functions used more than one subsystem of the printer. We can also see that we may want to integrate the print head cleaning subsystem and the print head

assembly into one subsystem since they share a function, and are not used for any other functions.

From this analysis, it appears that the modularity of the printer architecture has been substantially improved, enabling the implementation of some of the platform initiatives discussed earlier in the chapter.

Environmental Performance.

Was the environmental performance of the system actually improved? Figure 6-16 maps the changes we made to the architecture to the environmental model from Chapter 5. The corresponding areas of the target plot which are effected are highlighted

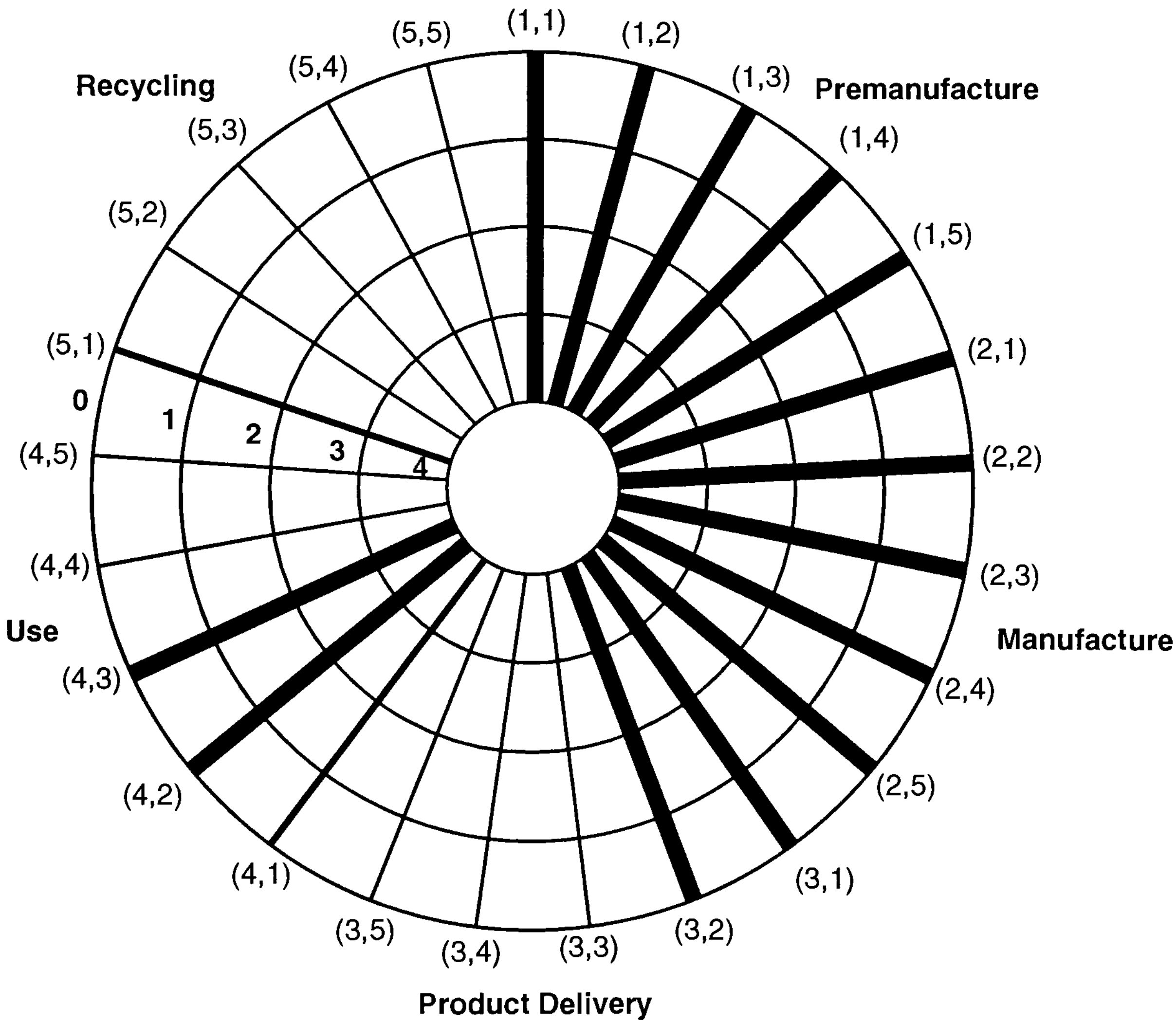


Figure 6-17. Areas of target plot effected by rearchitecting.

in Figure 6-17. The changes made to the current architecture affect about 56% of the SLCA stressors and life stages discussed in Chapter 4. The environmental performance of the printer clearly improved due to the rearchitecting of the system. Other environmental benefits may emerge due to the subsystem SLCA requirements the architect specifies for the subsystem design teams.

Chapter 7. Conclusions

Graedel and Allenby (1998, 20) write about the need to change the way industry addresses environmental problems. In the past, business has considered environmental issues as part of overhead, just another "cost of doing business". This has lead business to move operations to minimize this "cost" instead of looking at the roots of the problem. Graedel and Allenby stress the need to move past this old thinking, toward a more forward looking strategic approach.

By integrating concerns about environmental performance at every level of the product design and production process, production of a product which will not only be better for the natural environment, but will most likely also be less costly to produce and use is assured. As the central design professional whose domain includes the "big picture", the product architect is ideally positioned to ensure that environmental concerns are incorporated into every aspect of the product.

This connection between environmental performance and product architecture was confirmed by the 1099 links in Appendix B between Graedel's (1998) 91 SLCA environmental guidelines and about 70 architectural heuristics from Rechtin and Maier (1997) and other sources. These environmental guidelines and architecting heuristics are by no means a complete set, but give the reader a good place to start in building his or her own set of heuristics and guidelines. Some new architecting heuristics relating to achieving higher environmental performance are listed in Appendix D.

After establishing an environmental model based on Graedel's criteria (1998), a process was developed for rearchitecting a product, incorporating into the process Graedel's criteria for identifying environmental deficiencies, and a way to generate an architectural response to those environmental deficiencies. In addition to this method, several architectural platform strategies for improving the environmental performance of a product or product family were discussed.

These methods and strategies were applied to the DeskJet 540 case study, in which several environmental deficiencies in the existing product were identified, and architectural responses to those deficiencies were generated. After applying the architectural responses, the architecture radically changed. These architectural changes improved the environmental performance of the product in fourteen of the twenty five areas identified by Graedel, or 56%.

In addition to these improvements, there were other effects of environmental

architecting that are not so immediately apparent. These "secondary benefits" may be the result of the influence the architect of the product has over other parts of the design activity. The full impact of specifying that each subsystem be designed using a SLCA can't be measured without the subsystem teams finishing their design task. In fact, a true SLCA analysis of the impact of these changes can't be made unless we have more information about the manufacturing process of the existing system, and further develop the design. Neither of these phases of the product design are the concern of the architect per se.

By incorporating environmental considerations into the certification criteria, subsystem definitions, and critical interface definitions, the architect can exert extraordinary leverage on the resulting environmental performance of a product. By designing the environmental performance into the "bones" of the product, a high degree of environmental performance can be achieved while maintaining or exceeding current standards for profitability, performance, design cycle time, and cost reduction.

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Appendix A. Architectural Heuristics.

In the course of my research, I have collected heuristics and architecting principles which relate architecture to environmental performance. The list included in this appendix consists of heuristics from several sources. Those which I identified while studying the heuristics in Rechtin and Maier (1997) are denoted by a "JR" in their name. Those which I missed, but Paul Stiebitz identified are denoted by a "PR" in their name. The last class of heuristic were those thought up in the process of research, and they are denoted by a "PJ" or "H" in their name.

The heuristics have been abbreviated, and I recommend the reader consult the source of the heuristic for clarification if needed.

This list should in no way be thought of as complete. I have come across numerous others in the course of research which I chose not to include in the analysis and omit here for the sake of brevity.

The reader should consider this list a starting point on which they may build their own collection of heuristics.

Architecting Heuristics which Influence Environmental Performance

	Description1
H01	Shift fucntions from Hardware to Software.
H02	Make/Buy decision.
H03	Physical Interface
H04	Mass Customization
H05	Module Certification
H06	Share components across families
H07	Define Uniform Packaging interface within a family
H08	Certification Standards.
H09	Scoping /Goal Setting
H10	Defining the interface with external systems.
H11	General Interface
H12	Functional Model (Partitioning)
H13	Technology Model (Partitioning)
H14	Physical Model (Partitioning)

Appendix A. Architectural Heuristics.

	Description1
JR01	Efficiency is inversely proportional to universality.
JR02	The most reliable part is the one that isn't there because it isn't needed .
JR03	Don't confuse the functioning of the parts with that of the system.
JR04	Complex systems will develop and evolve within an overall architecture much more rapidly if there are stable intermediate forms than it there are not.
JR05	It's the perceptions, not the facts, that count.
JR06	If social cooperation is required, the way in which a system is implemented and introduced must be an integral part of its architecture.
JR07	If the politics don't fly. the hardware never will.
JR08	Ask early how you will evaluate the success of your efforts
JR09	Define how an acceptance criterion is to be certified at the same time the criterion is established.
JR10	Sometimes, but not always, the best way solve a difficult problem is to expand the problem itself.
JR11	Sometimes it is necessary to expand the concept in order to solve the problem.
JR12	Use open architectures, you will need them once the market starts to respond.
JR13	Don't make an architecture too smart for its own good.
JR14	By the first design review, performance, cost, and schedule have been predetermined.
JR15	Don't assume that the original statement of the problem is necessarily the best, or even the right, one.
JR16	The realities at the end of the conceptual phase are not the models but the acceptance criteria.
JR17	A model is not reality.
JR18	Don't believe nth order consequences of a first order model.
JR19	Constants aren't and variables don't.
JR20	The true value of a given service or product is determined by what one is willing to give up to obtain it.
JR21	Group elements which are strongly related to one another together, separate elements that are unrelated.
JR22	Subsystem interfaces should be drawn so that each subsystem can be implemented independently of the specific implementation of the subsystems to which it interfaces.
JR23	The greatest leverage in architecting is at the interfaces.
JR24	Since boundaries are inherently limiting, look for solutions outside of them.
JR25	The greatest dangers are at the interfaces.
JR26	The product and the process must match.
JR27	Contain excess energy as close to the source as possible.
JR28	Place barriers in the paths between energy sources and the elements the energy can damage.

	Description1
JR29	Tally the defects, analyze them, trace them down to the sources, make corrections, keep a record of what happens afterwards, and keep repeating it.
JR30	The test system should always allow a part to pass or fail on it's own merit.
JR31	To be tested a system must be designed to be tested.
JR32	An element good enough for a small system is unlikely to be good enough in a more complex one.
JR33	The cost to find and fix an inadequate or failed part increases by an order of magnitude as it is successively incorporated into higher levels of the system.
JR34	The least expensive and most effective place to solve a problem is at it's source.
JR35	Knowing a failure has occurred is more important than the actual failure.
JR36	Recovery from a failure or flaw is not complete until a specific mechanism, and no other, has been shown to be the cause.
JR37	Quality can't be tested in, it has to be built in.
JR38	You can't achieve quality unless you specify it.
JR39	Next to interfaces, the greatest leverage in architecting is in aiding the recovery from, or exploitation of, deviations in system performance, cost, or schedule.
JR40	A good design has benefits in more than one area.
JR41	High confidence , not test completion, is the goal of a successful qualification.
JR42	Before ordering a test decide what you will do if it is (1) positive or if (2) it is negative. If both answers are the same, don't do the test.
JR43	Proven and state of art are mutually exclusive qualities.
JR44	The bitterness of poor performance remains long after the sweetness of low prices and prompt delivery are forgotten.
JR45	Before the war it's opinion, after the war it's too late!
JR46	The first quick analyses are often wrong.
JR47	If you don't understand the existing system, you can't be sure you're rearchitecting a better one.
JR48	When implementing a change, keep some elements constant to provide an anchor point for people to cling to.
JR49	Before the change it is your opinion, after the change it is your problem.
JR50	Given a change, if the anticipated actions don't occur, then there is probably an invisible barrier to be identified and overcome.
PJ1	Don't package consumables with non-consumables
PJ2	Make best environmentally performing mode the default mode.
PR1	Never aggregate sysems that have a conflict of interest; partition them to ensure checks and balances.
PR2	If a design is good, make sure that it stays sold (good).
PR3	The test of a good architecture is that it will last.

Appendix B. Environmental Links to Heuristics

		Rule	H01	H02	H03	H04	H05	H06	H07	H08	H09	H10	H11	H12	H13	H14	JR01	JR02	JR03	JR04
Premanufacture	Materials Choice	Minimize the use of materials In limited supply.															1	1		
		Design product to utilize recycled materials or components wherever possible.						1			1									
	Energy Use	Minimize the use of energy intensive virgin materials.									1						1	1		
		Minimize the the use of high density materials which will cost more to transport.									1						1	1		
		Minimize distance over which raw materials and components are transported.															1	1		
	Solid Residues	Minimize use of materials whose extraction and refining result in the production of large amounts of solid residues.									1						1	1		
		Minimize use of materials whose extraction and refining results in the production of toxic solids.									1						1	1		
		Totally reuse or recycle incoming packaging, or minimize its volume and weight .		1					1	1								1		
	Liquid Residues	Minimize the use of materials whose production results in toxic liquid residues.									1						1	1		
		Use refillable/reusable containers for incoming liquid materials.									1						1			
		Minimize use of incoming components which require cleaning with high volumes of liquids.								1	1						1	1		
	Gaseous Residues	Minimize the use of materials whose production Involves the generation of large amounts of gaseous residues.									1						1	1		

Appendix B. Environmental Links to Heuristics

		Rule	JR005	JR006	JR007	JR008	JR009	JR010	JR011	JR012	JR013	JR014	JR015	JR016	JR017	JR018	JR019	JR020	JR021	JR022	JR023	JR024
Premanufacture	Materials Choice	Minimize the use of materials in limited supply.				1	1	1						1	1			1				
		Design product to utilize recycled materials or components wherever possible.				1	1							1	1			1				
	Energy Use	Minimize the use of energy intensive virgin materials.				1	1	1						1	1			1				
		Minimize the the use of high density materials which will cost more to transport.				1	1	1						1	1			1				
		Minimize distance over which raw materials and components are transported.				1	1	1						1	1			1				1
	Solid Residues	Minimize use of materials whose extraction and refining result in the production of large amounts of solid residues.				1	1	1						1	1			1				
		Minimize use of materials whose extraction and refining results in the production of toxic solids.				1	1	1						1	1			1				
		Totally reuse or recycle incoming packaging, or minimize its volume and weight .				1	1	1						1	1			1				
	Liquid Residues	Minimize the use of materials whose production results in toxic liquid residues.				1	1	1						1	1			1				
		Use refillable/reusable containers for incoming liquid materials.				1	1	1					1	1	1			1				
		Minimize use of incoming components which require cleaning with high volumes of liquids.				1	1	1						1	1			1				
	Gaseous Residues	Minimize the use of materials whose production involves the generation of large amounts of gaseous residues.				1	1	1						1	1			1				

		Rule	JR25	JR26	JR27	JR28	JR29	JR30	JR31	JR32	JR33	JR34	JR35	JR36	JR37	JR38	JR39	JR40	JR41	JR42	JR43	JR44
Premanufacture	Materials Choice	Minimize the use of materials in limited supply.										1			1	1						
		Design product to utilize recycled materials or components wherever possible.										1			1	1						
	Energy Use	Minimize the use of energy intensive virgin materials.										1			1	1						
		Minimize the the use of high density materials which will cost more to transport.										1			1	1						
		Minimize distance over which raw materials and components are transported.		1		1						1			1	1						
	Solid Residues	Minimize use of materials whose extraction and refining result in the production of large amounts of solid residues.										1				1	1					
		Minimize use of materials whose extraction and refining results in the production of toxic solids.										1				1	1					
		Totally reuse or recycle incoming packaging, or minimize its volume and weight.										1				1	1					
	Liquid Residues	Minimize the use of materials whose production results in toxic liquid residues.										1				1	1					
		Use refillable/reusable containers for incoming liquid materials.										1				1	1					
		Minimize use of incoming components which require cleaning with high volumes of liquids.										1				1	1					
	Gaseous Residues	Minimize the use of materials whose production involves the generation of large amounts of gaseous residues.										1				1	1					

Appendix B. Environmental Links to Heuristics

		Rule	JR45	JR46	JR47	JR48	JR49	JR50	PJ1	PJ2	PR1	PR2	PR3	Stress Total
Premanufacture	Materials Choice	Minimize the use of materials in limited supply.												11
		Design product to utilize recycled materials or components wherever possible.												10
														0
														0
														0
														0
	Energy Use	Minimize the use of energy intensive virgin materials.												12
		Minimize the the use of high density materials which will cost more to transport.												12
		Minimize distance over which raw materials and components are transported.												14
														0
														0
														0
	Solid Residues	Minimize use of materials whose extraction and refining result in the production of large amounts of solid residues.												12
		Minimize use of materials whose extraction and refining results in the production of toxic solids.												12
		Totally reuse or recycle incoming packaging, or minimize its volume and weight .												13
														0
														0
														0
	Liquid Residues	Minimize the use of materials whose production results in toxic liquid residues.												12
		Use refillable/reusable containers for incoming liquid materials.							1					13
		Minimize use of incoming components which require cleaning with high volumes of liquids.												13
														0
														0
														0
	Gaseous Residues	Minimize the use of materials whose production involves the generation of large amounts of gaseous residues.												12
														0
														0
														0
														0
														0

		Rule	H01	H02	H03	H04	H05	H06	H07	H08	H09	H10	H11	H12	H13	H14	JR01	JR02	JR03	JR04
Product Manufacture	Materials Choice	Avoid manufacturing processes which use materials in restricted supply.															1			
		Avoid the use of toxic materials in manufacturing process.															1			
		Avoid the use of radioactive materials in manufacturing process.			1												1			
		Avoid the use of virgin materials in the manufacturing process.															1			
		Minimize chemical treatment of materials and components.															1			
	Energy Use	Minimize energy intensive processing steps.															1			
		Minimize energy intensive evaluation and testing.								1							1			
		Use co-generation, heat exchanges, and/or other techniques for utilizing otherwise wasted energy.									1									1
		Power down manufacturing facility when not in use.				1											1			
	Solid Residues	Minimize the amount of solid residues resulting from manufacture															1	1		
		Maximize the percentage of solid residues which are recycled.															1			
		Investigate the resale of all solid residues as feedstocks for other products or processes.									1									1
		Minimize the production of solid residues without resale value.									1						1			
	Liquid Residues	Investigate and implement minimization of the use of solvents and oils in manufacturing.									1									
		Investigate and implement sale of any liquid residues as feedstocks for other products or processes.									1									1
		Maximize the use of recycled liquids and the recycling of liquids in the process.									1						1			
	Gaseous Residues	Minimize the use of HCFCs in manufacture of product.									1						1			
		Minimize emmissions of greenhouse gases in production of product.									1						1			
		Investigate and implement the resale of gaseous residues for use in other processes or products.									1									1

Appendix B. Environmental Links to Heuristics

		Rule	JR05	JR06	JR07	JR08	JR09	JR10	JR11	JR12	JR13	JR14	JR15	JR16	JR17	JR18	JR19	JR20	JR21	JR22	JR23	JR24
Product Manufacture	Materials Choice	Avoid manufacturing processes which use materials in restricted supply.	1			1	1							1	1			1				
		Avoid the use of toxic materials in manufacturing process.	1			1	1							1	1			1				
		Avoid the use of radioactive materials in manufacturing process.	1			1	1							1	1			1				
		Avoid the use of virgin materials in the manufacturing process.				1	1							1	1			1				
		Minimize chemical treatment of materials and components.				1	1							1	1			1				
	Energy Use	MInimize energy intensive processing steps.				1	1							1	1			1				
		Minimize energy intensive evaluation and testing.				1	1							1	1			1				
		Use co-generation, heat exchanges, and/or other techniques for utilizing otherwise wasted energy.		1	1	1	1	1	1				1	1	1			1			1	1
		Power down manufacturing facility when not in use.				1	1							1	1			1				
	Solid Residues	Minimize the amount of solid residues resulting from manufacture				1	1							1	1			1				
		Maximize the percentage of solid residues which are recycled.	1			1	1							1	1			1				
		Investigate the resale of all solid residues as feedstocks for other products or processes.	1	1	1	1	1	1	1					1	1			1				1
		Minimize the production of solid residues without resale value.	1			1	1							1	1			1				
	Liquid Residues	Investigate and implement minimization of the use of solvents and oils in manufacturing.				1	1							1	1			1				
		Investigate and implement sale of any liquid residues as feedstocks for other products or processes.	1	1	1	1	1	1	1				1	1	1			1				1
		Maximize the use of recycled liquids and the recycling of liquids in the process.	1			1	1							1	1			1				
	Gaseous Residues	Minimize the use of HCFCs in manufacture of product.				1	1							1	1			1				
		Minimize emmissions of greenhouse gases in production of product.				1	1							1	1			1				
		Investigate and implement the resale of gaseous residues for use in other processes or products.	1	1	1	1	1	1	1				1	1	1			1				1

		Rule	JR25	JR26	JR27	JR28	JR29	JR30	JR31	JR32	JR33	JR34	JR35	JR36	JR37	JR38	JR39	JR40	JR41	JR42	JR43	JR44
Product Manufacture	Materials Choice	Avoid manufacturing processes which use materials in restricted supply.										1				1						
		Avoid the use of toxic materials in manufacturing process.										1				1						
		Avoid the use of radioactive materials in manufacturing process.										1				1						
		Avoid the use of virgin materials in the manufacturing process.										1				1						
		Minimize chemical treatment of materials and components.										1				1						
	Energy Use	MInimize energy intensive processing steps.										1				1						
		Minimize energy intensive evaluation and testing.										1				1						
		Use co-generation, heat exchanges, and/or other techniques for utilizing otherwise wasted energy.										1				1						
		Power down manufacturing facility when not in use.										1				1						
	Solid Residues	Minimize the amount of solid residues resulting from manufacture		1								1				1						
		Maximize the percentage of solid residues which are recycled.										1				1						
		Investigate the resale of all solid residues as feedstocks for other products or processes.										1				1						
		Minimize the production of solid residues without resale value.		1								1				1						
	Liquid Residues	Investigate and implement minimization of the use of solvents and oils in manufacturing.										1				1						
		Investigate and implement sale of any liquid residues as feedstocks for other products or processes.										1				1						
		Maximize the use of recycled liquids and the recycling of liquids in the process.										1				1						
	Gaseous Residues	Minimize the use of HCFCs in manufacture of product.										1				1						
		Minimize emmissions of greenhouse gases in production of product.										1				1						
		Investigate and implement the resale of gasecus residues for use in other processes or products.										1				1						

Appendix B. Environmental Links to Heuristics

		Rule	JR45	JR46	JR47	JR48	JR49	JR50	PJ1	PJ2	PR1	PR2	PR3	Stress Total
Product Manufacture	Materials Choice	Avoid manufacturing processes which use materials in restricted supply.												9
		Avoid the use of toxic materials in manufacturing process.												9
		Avoid the use of radioactive materials in manufacturing process.												10
		Avoid the use of virgin materials in the manufacturing process.												8
		Minimize chemical treatment of materials and components.												8
														0
	Energy Use	Minimize energy intensive processing steps.												8
		Minimize energy intensive evaluation and testing.												9
		Use co-generation, heat exchanges, and/or other techniques for utilizing otherwise wasted energy.												16
		Power down manufacturing facility when not in use.												9
														0
														0
	Solid Residues	Minimize the amount of solid residues resulting from manufacture												10
		Maximize the percentage of solid residues which are recycled.												9
		Investigate the resale of all solid residues as feedstocks for other products or processes.												15
		Minimize the production of solid residues without resale value.												11
														0
														0
	Liquid Residues	Investigate and implement minimization of the use of solvents and oils in manufacturing.												8
		Investigate and implement sale of any liquid residues as feedstocks for other products or processes.												16
		Maximize the use of recycled liquids and the recycling of liquids in the process.												10
														0
														0
														0
	Gaseous Residues	Minimize the use of HCFCs in manufacture of product.												9
		Minimize emmissions of greenhouse gases in production of product.												9
		Investigate and implement the resale of gaseous residues for use in other processes or products.												16
														0
														0
														0

		Rule	H01	H02	H03	H04	H05	H06	H07	H08	H09	H10	H11	H12	H13	H14	JR01	JR02	JR03	JR04
Packaging and Transportation	Materials Choice	Minimize the number of different materials used in packaging.															1	1		
		Minimize the weight of the packaging.															1	1		
		Maximize recycled content of packaging.															1			
		Maximize recyclability and reusability of packaging, and label as such.									1						1			
		Use materials with a functioning recycling infrastructure in place.															1			
		Include a packaging engineer and product installation personel in product design.																		
	Energy Use	Avoid energy intensive packaging procedures.															1	1		
		Minimize energy use in component supply system and product distribution and installation.										1					1	1		
		Avoid energy intensive installation procedures.										1					1			
		Avoid or minimize long distance, energy intensive product transportation.									1						1	1		1
	Solid Residues	Maximize ease of separation of packaging into constituent materials.															1			
		Avoid use of materials which require special disposal when product is unpacked.															1	1		
		Minimize product packaging and weight.								1							1	1		
		Arrange to take back packaging for reuse and/or recycling							1								1			
	Liquid Residues	Use refillable or reusable containers for liquid products.									1						1			
		Design packaging operations which minimize the need for cleaning / maintenance procedures that generate large															1	1		
		Avoid requirements for unpacking or installation procedures which result in large amounts of liquid residues.															1	1		
	Gaseous Residues	Avoid release of pressurized gas during transport or installation.									1						1	1		
		Minimize gaseous emmissions from transport vehicles during distribution.									1						1	1		
		Minimize toxic gas emmissions if packaging material is to be incinerated.									1						1	1		

Appendix B. Environmental Links to Heuristics

		Rule	JR05	JR06	JR07	JR08	JR09	JR10	JR11	JR12	JR13	JR14	JR15	JR16	JR17	JR18	JR19	JR20	JR21	JR22	JR23	JR24
Packaging and Transportation	Materials Choice	Minimize the number of different materials used in packaging.				1	1	1						1	1			1				
		Minimize the weight of the packaging.				1	1	1						1	1			1				
		Maximize recycled content of packaging.				1	1	1						1	1			1				
		Maximize recyclability and reusebility of packaging, and label as such.	1			1	1	1						1	1			1				
		Use materials with a functioning recycling infrastructure in place.		1	1	1	1	1						1	1			1				
		Include a packaging engineer and product installation personel in product design.			1	1	1	1						1	1			1				1
	Energy Use	Avoid energy intensive packaging procedures.				1	1	1						1	1			1				
		Minimize energy use in component supply system and product distribution and installation.				1	1	1						1	1			1				
		Avoid energy intensive installation procedures.				1	1	1						1	1			1				
		Avoid or minimize long distance, energy intensive product transportation.		1		1	1	1						1	1			1				
	Solid Residues	Maximize ease of separation of packaging into constituent materials.				1	1	1						1	1			1			1	
		Avoid use of materials which require special disposal when product is unpacked.				1	1	1						1	1			1				
		Minimize product packaging and weight.				1	1	1						1	1			1				
		Arrange to take back packaging for reuse and/or recycling	1			1	1	1					1	1	1			1				1
	Liquid Residues	Use refillable or reuseble containers for liquid products.				1	1	1						1	1			1				
		Design packaging operations which minimize the need for cleaning / maintenance procedures that generate large				1	1	1						1	1			1				
		Avoid requirements for unpacking or installation procedures which result in large amounts of liquid residues.				1	1	1						1	1			1				
	Gaseous Residues	Avoid release of pressurized gas during transport or installation.				1	1	1						1	1			1				
		Minimize gaseous emmissions from transport vehicles during distribution.				1	1	1						1	1			1				
		Minimize toxic gas emmissions if packaging material is to be incinerated.	1			1	1	1						1	1			1				

		Rule	JR25	JR26	JR27	JR28	JR29	JR30	JR31	JR32	JR33	JR34	JR35	JR36	JR37	JR38	JR39	JR40	JR41	JR42	JR43	JR44
Packaging and Transportation	Materials Choice	Minimize the number of different materials used in packaging.										1			1	1						
		Minimize the weight of the packaging.										1			1	1						
		Maximize recycled content of packaging.										1			1	1						
		Maximize recyclability and reusebility of packaging, and label as such.										1			1	1						
		Use materials with a functioning recycling infrastructure in place.										1			1	1						
		Include a packaging engineer and product installation parsonel in product design.		1								1			1	1						
	Energy Use	Avoid energy intensive packaging procedures.										1			1	1						
		Minimize energy use in component supply system and product distribution and installation.										1			1	1						
		Avoid energy intensive installation procedures.										1			1	1						
		Avoid or minimize long distance, energy intensive product transportation.										1			1	1						
	Solid Residues	Maximize ease of separation of packaging into constituent materials.										1			1	1						
		Avoid use of materials which require special disposal when product is unpacked.										1			1	1						
		Minimize product packaging and weight.										1			1	1						
		Arrange to take back packaging for reuse and/or recycling										1			1	1						
	Liquid Residues	Use refillable or reuseble containers for liquid products.										1			1	1						
		Design packaging operations which minimize the need for cleaning / maintenance procedures that generate large										1			1	1						
		Avoid requirements for unpacking or installation procedures which result in large amounts of liquid residues.										1			1	1						
	Gaseous Residues	Avoid release of pressurized gas during transport or installation.										1			1	1						
		Minimize gaseous emmissions from transport vehicles during distribution.										1			1	1						
		Minimize toxic gas emmissions if packaging material is to be incinerated.										1			1	1						

Appendix B. Environmental Links to Heuristics

		Rule	JR45	JR46	JR47	JR48	JR49	JR50	PJ1	PJ2	PR1	PR2	PR3	Stress Total
Packaging and Transportation	Materials Choice	Minimize the number of different materials used in packaging.												11
		Minimize the weight of the packaging.												11
		Maximize recycled content of packaging.												10
		Maximize recyclability and reusability of packaging, and label as such.												12
		Use materials with a functioning recycling infrastructure in place.												12
		Include a packaging engineer and product installation personel in product design.												12
	Energy Use	Avoid energy intensive packaging procedures.												11
		Minimize energy use in component supply system and product distribution and installation.												12
		Avoid energy intensive installation procedures.												11
		Avoid or minimize long distance, energy intensive product transportation.												14
														0
														0
	Solid Residues	Maximize ease of separation of packaging into constituent materials.												11
		Avoid use of materials which require special disposal when product is unpacked.												11
		Minimize product packaging and weight.												12
		Arrange to take back packaging for reuse and/or recycling												14
														0
														0
	Liquid Residues	Use refillable or reusable containers for liquid products.							1					12
		Design packaging operations which minimize the need for cleaning / maintenance procedures that generate large												11
		Avoid requirements for unpacking or installation procedures which result in large amounts of liquid residues.												11
														0
														0
														0
	Gaseous Residues	Avoid release of pressurized gas during transport or installation.												12
		Minimize gaseous emmissions from transport vehicles during distribution.												12
		Minimize toxic gas emmissions if packaging material is to be incinerated.												13
														0
														0
														0

		Rule	H01	H02	H03	H04	H05	H06	H07	H08	H09	H10	H11	H12	H13	H14	JR01	JR02	JR03	JR04
Product Use	Materials Choice	Minimize use of consumables.									1						1	1		
		Avoid one use designs.								1	1						1			
		Avoid materials which require environmentally inappropriate maintenance.									1						1			
		Avoid materials which may allow an unintentional release of toxic materials into the environment during use.									1						1			
		Maximize recycled content of consumables.									1						1			
	Energy Use	Minimize energy use of product over service life.									1	1					1			
		Minimize energy use during maintenance and repair.			1						1						1			
		Incorporate energy saving features (e.g. auto-powerdown, super-insulation)					1			1	1	1					1			
		Incorporate ability to monitor and display products energy use or efficiency while in use.								1	1		1				1		1	
	Solid Residues	Avoid or minimize periodic disposal of solid materials as part of design. (e.g. toner cartridges, batteries)								1	1						1	1		
		Investigate alternatives to solid consumables.									1	1		1				1		
		Investigate less environmentally harmful alternatives for intentional dissipative emissions.																		
	Liquid Residues	Avoid periodic disposal of liquid materials associated with use and/or maintenance of product.								1	1						1	1		
		Investigate alternatives to liquid consumables.									1	1						1		
		Investigate less environmentally harmful alternatives to designs which result in intentional dissipative emissions to									1									
		Incorporate appropriate measures to avoid unintentional dissipative liquid emissions during use or repair of the															1			
	Gaseous Residues	Avoid or minimize periodic emission of gaseous materials during use or maintenance of product.									1						1	1		
		Investigate and implement use of alternatives to gaseous consumables.									1	1						1		
		Investigate less environmentallty harmful alternatives to intentional dissipative emissions to air.									1	1								
		Incorporate appropriate preventative measures if there is a potential for unintentional dissipation of gaseous materials.									1	1					1			

Appendix B. Environmental Links to Heuristics

		Rule	JR05	JR06	JR07	JR08	JR09	JR10	JR11	JR12	JR13	JR14	JR15	JR16	JR17	JR18	JR19	JR20	JR21	JR22	JR23	JR24
Product Use	Materials Choice	Minimize use of consumables.	1			1	1							1	1			1				
		Avoid one use designs.	1			1	1							1	1			1	1			
		Avoid materials which require environmentally inappropriate maintenance.				1	1							1	1			1				
		Avoid materials which may allow an unintentional release of toxic materials into the environment during use.				1	1							1	1			1	1			
		Maximize recycled content of consumables.	1			1	1							1	1			1	1			
	Energy Use	Minimize energy use of product over service life.				1	1							1	1			1				
		Minimize energy use during maintenance and repair.				1	1							1	1			1	1			
		Incorporate energy saving features (e.g. auto-powerdown, super-insulation)				1	1							1	1			1				
		Incorporate ability to monitor and display products energy use or efficiency while in use.	1			1	1							1	1			1				
	Solid Residues	Avoid or minimize periodic disposal of solid materials as part of design. (e.g. toner cartridges, batteries)				1	1							1	1			1	1			
		Investigate alternatives to solid consumables.	1			1	1							1	1			1				1
		Investigate less environmentally harmful altematives for intentional dissipative emissions.	1			1	1							1	1			1				
	Liquid Residues	Avoid periodic disposal of liquid materials associated with use and/or maintenance of product.				1	1							1	1			1	1			
		Investigate alternatives to liquid consumables.	1			1	1							1	1			1				1
		Investigate less environmentally harmful altematives to designs which result in intentional dissipative emissions to	1			1	1							1	1			1				
		Incorporate appropriate measures to avoid unintentional dissipative liquid emissions during use or repair of the	1			1	1															
	Gaseous Residues	Avoid or minimize periodic emission of gaseous materials during use or maintenance of product.				1	1							1	1			1				
		Investigate and implement use of altematives to gasecus consumables.	1			1	1							1	1			1				1
		Investigate less environmentallty harmful altematives to intentional dissipative emissions to air.	1			1	1							1	1			1				
		Incorporate appropriate preventative measures if there is a potential for unintentional dissipation of gaseous materials.				1	1							1	1			1				

		Rule	JR25	JR26	JR27	JR28	JR29	JR30	JR31	JR32	JR33	JR34	JR35	JR36	JR37	JR38	JR39	JR40	JR41	JR42	JR43	JR44
Product Use	Materials Choice	Minimize use of consumables.										1			1	1						
		Avoid one use designs.										1			1	1						
		Avoid materials which require environmentally inappropriate maintenance.										1			1	1						
		Avoid materials which may allow an unintentional release of toxic materials into the environment during use.										1			1	1						
		Maximize recycled content of consumables.										1			1	1						
	Energy Use	Minimize energy use of product over service life.										1			1	1						
		Minimize energy use during maintenance and repair.										1			1	1						
		Incorporate energy saving features (e.g. auto-powerdown, super-insulation)										1			1	1						
		Incorporate ability to monitor and display products energy use or efficiency while in use.							1			1	1		1	1				1		
	Solid Residues	Avoid or minimize periodic disposal of solid materials as part of design. (e.g. toner cartridges, batteries)										1			1	1						
		Investigate alternatives to solid consumables.										1			1	1						
		Investigate less environmentally harmful altematives for intentional dissipative emissions.										1			1	1						
	Liquid Residues	Avoid periodic disposal of liquid materials associated with use and/or maintenance of product.										1			1	1						
		Investigate alternatives to liquid consumables.										1			1	1						
		Investigate less environmentally harmful altematives to designs which result in intentional dissipative emissions to										1			1	1						
		Incorporate appropriate measures to avoid unintentional dissipative liquid emissions during use or repair of the										1			1	1						
	Gaseous Residues	Avoid or minimize periodic emission of gaseous materials during use or maintenance of product.										1			1	1						
		Investigate and implement use of alternatives to gaseous consumables.										1			1	1						
		Investigate less environmentallty harmful altematives to intentional dissipative emissions to air.										1			1	1						
		Incorporate appropriate preventative measures if there is a potential for unintentional dissipation of gaseous materials.										1			1	1						

Appendix B. Environmental Links to Heuristics

		Rule	JR 45	JR 46	JR 47	JR 48	JR 49	JR 50	PJ 1	PJ 2	PR 1	PR 2	PR 3	Stress Total
Product Use	Materials Choice	Minimize use of consumables.							1		1			14
		Avoid one use designs.							1					14
		Avoid materials which require environmentally inappropriate maintenance.												10
		Avoid materials which may allow an unintentional release of toxic materials into the environment during use.												11
		Maximize recycled content of consumables.												12
														0
	Energy Use	Minimize energy use of product over service life.												11
		Minimize energy use during maintenance and repair.												12
		Incorporate energy saving features (e.g. auto-powerdown, super-insulation)								1				14
		Incorporate ability to monitor and display products energy use or efficiency while in use.			1									18
														0
														0
	Solid Residues	Avoid or minimize periodic disposal of solid materials as part of design. (e.g. toner cartridges, batteries)							1					14
		Investigate alternatives to solid consumables.							1					15
		Investigate less environmentally harmful alternatives for intentional dissipative emissions.												9
														0
														0
														0
	Liquid Residues	Avoid periodic disposal of liquid materials associated with use and/or maintenance of product.												13
		Investigate alternatives to liquid consumables.												13
		Investigate less environmentally harmful alternatives to designs which result in intentional dissipative emissions to												10
		Incorporate appropriate measures to avoid unintentional dissipative liquid emissions during use or repair of the												7
														0
														0
	Gaseous Residues	Avoid or minimize periodic emission of gaseous materials during use or maintenance of product.												11
		Investigate and implement use of alternatives to gaseous consumables.												13
		Investigate less environmentallty harmful alternatives to intentional dissipative emissions to air.												11
		Incorporate appropriate preventative measures if there is a potential for unintentional dissipation of gaseous materials.												11
														0
														0

		Rule	H001	H002	H003	H004	H005	H006	H007	H008	H009	H010	H011	H012	H013	H014	JR01	JR02	JR03	JR04
Recycling and Disposal	Materials Choice	Choose materials with a plan for the desired recycling or disposal of the product.								1	1						1			
		Minimize the number of different materials used in manufacture.									1						1	1		
		Make different materials easy to identify and separate.								1	1		1				1			
		Avoid the use of batteries.								1			1				1	1		
		Avoid materials containing PCBs or PCTs.								1						1	1	1		
		Avoid polybrominated flame retardants or heavy metal-based additives in plastics.								1	1						1	1		
	Energy Use	Minimize the use of energy intensive process steps in disassembly by design.											1				1	1	1	
		Maximize the amount of high-level reuse of materials.			1			1									1			
		Minimize the energy Intensity of transportation for recycling by minimizing weight and volume as well as centrally	1								1						1	1		1
	Solid Residues	Minimize the use of chemical bonds or welds in deference to mechanical fasteners such as clips or hook and loop			1					1							1		1	
		Avoid joining dissimilar materials in ways which are difficult to reverse.								1							1		1	
		Use ISO marking to identify the content of all plastic components.								1										
		Try to establish dominant species of plastic parts which make up over 80% by weight of the plastics used.									1						1	1		
		Try to develop products which will be leased rather than sold.									1			1				1		
	Liquid Residues	Ensure that liquids contained in the product can be recovered at disassembly .								1							1		1	
		Minimize liquid residues generated during disassembly, recovery, and reuse.									1						1	1		
		Minimize the amount of liquid residues generated during materials reuse and recovery.									1						1	1		
	Gaseous Residues	Facilitate easy recovery of gases contained in product at disassembly.								1	1						1		1	
		Minimize gaseous residues generated during material recovery and reuse.									1						1	1		
		Choose plastics which can be incinerated without requiring sophisticated air pollution devices.								1	1						1			1

Appendix B. Environmental Links to Heuristics

		Rule	JR05	JR06	JR07	JR08	JR09	JR10	JR11	JR12	JR13	JR14	JR15	JR16	JR17	JR18	JR19	JR20	JR21	JR22	JR23	JR24
Recycling and Disposal	Materials Choice	Choose materials with a plan for the desired recycling or disposel of the product.				1	1	1					1	1	1			1	1	1		
		Minimize the number of different materials used in manufacture.				1	1	1						1	1			1				
		Make different materials easy to identify and separate.	1			1	1	1						1	1			1			1	
		Avoid the use of batteries.				1	1	1						1	1			1				
		Avoid materials containing PCBs or PCTs.	1			1	1	1						1	1			1				
		Avoid polybrominated flame retardants or heavy metal-besed additives in plastics.	1			1	1	1						1	1			1				
	Energy Use	Minimize the use of energy intensive process steps in disessembly by design.				1	1	1						1	1			1	1			
		Maximize the amount of high-level reuse of materials.	1		1	1	1	1		1	1		1	1	1			1	1	1		
		Minimize the energy intensity of transportation for recycling by minimizing weight and volume as well as centrally	1	1		1	1	1						1	1			1				
	Solid Residues	Minimize the use of chemical bonds or welds in deference to mechanical fasteners such as clips or hook and loop				1	1							1	1			1			1	
		Avoid joining dissimilar materials in ways which are difficult to reverse.				1	1							1	1			1			1	
		Use ISO marking to identify the content of all plastic components.	1			1	1							1	1			1				
		Try to establish dominant species of plastic parts which make up over 80% by weight of the plastics used.				1	1							1	1			1				
		Try to develop products which will be leased rather than sold.	1	1	1	1	1	1					1	1	1			1				
	Liquid Residues	Ensure that liquids contained in the product can be recovered at disessembly .		1		1	1							1	1			1				
		Minimize liquid residues generated during disessembly, recovery, and reuse.				1	1							1	1			1				
		Minimize the amount of liquid residues generated during materials reuse and recovery.				1	1							1	1			1				
	Gaseous Residues	Facilitate easy recovery of gases contained in product at disessembly.		1		1	1							1	1			1				
		Minimize gaseous residues generated during material recovery and reuse.				1	1							1	1			1				
		Choose plastics which can be incinerated without requiring sophisticated air pollution devices.				1	1	1						1	1			1				

		Rule	JR25	JR26	JR27	JR28	JR29	JR30	JR31	JR32	JR33	JR34	JR35	JR36	JR37	JR38	JR39	JR40	JR41	JR42	JR43	JR44
Recycling and Disposal	Materials Choice	Choose materials with a plan for the desired recycling or disposal of the product.										1			1	1						
		Minimize the number of different materials used in manufacture.										1			1	1						
		Make different materials easy to identify and separate.										1			1	1						
		Avoid the use of batteries.										1			1	1						
		Avoid materials containing PCBs or PCTs.										1			1	1						
		Avoid polybrominated flame retardants or heavy metal-based additives in plastics.										1			1	1						
	Energy Use	Minimize the use of energy intensive process steps in disessembly by design.										1			1	1						
		Maximize the amount of high-level reuse of materials.						1				1			1	1						
		Minimize the energy intensity of transportation for recycling by minimizing weight and volume as well as centrally			1							1			1	1						
	Solid Residues	Minimize the use of chemical bonds or welds in deference to mechanical fasteners such as clips or hook and loop										1			1	1						
		Avoid joining dissimilar materials in ways which are difficult to reverse.										1			1	1						
		Use ISO marking to identify the content of all plastic components.										1			1	1						
		Try to establish dominant species of plastic parts which make up over 80% by weight of the plastics used.										1			1	1						
		Try to develop products which will be leased rather than sold.	1		1							1			1	1						
	Liquid Residues	Ensure that liquids contained in the product can be recovered at disassembly .										1			1	1						
		Minimize liquid residues generated during disassembly, recovery, and reuse.										1			1	1						
		Minimize the amount of liquid residues generated during materials reuse and recovery.										1			1	1						
	Gaseous Residues	Facilitate easy recovery of gases contained in product at disassembly.										1			1	1						
		Minimize gaseous residues generated during material recovery and reuse.										1			1	1						
		Choose plastics which can be incinerated without requiring sophisticated air pollution devices.										1			1	1						

Appendix B. Environmental Links to Heuristics

		Rule	JR45	JR46	JR47	JR48	JR49	JR50	PJ1	PJ2	PR1	PR2	PR3	Stress Total
Recycling and Disposal	Materials Choice	Choose materials with a plan for the desired recycling or disposal of the product.												15
		Minimize the number of different materials used in manufacture.									1			13
		Make different materials easy to identify and separate.									1			16
		Avoid the use of batteries.												13
		Avoid materials containing PCBs or PCTs.												14
		Avoid polybrominated flame retardants or heavy metal-based additives in plastics.												14
	Energy Use	Minimize the use of energy intensive process steps in disassembly by design.												14
		Maximize the amount of high-level reuse of materials.												20
		Minimize the energy intensity of transportation for recycling by minimizing weight and volume as well as centrally												17
														0
														0
														0
	Solid Residues	Minimize the use of chemical bonds or welds in deference to mechanical fasteners such as clips or hook and loop									1			14
		Avoid joining dissimilar materials in ways which are difficult to reverse.									1			13
		Use ISO marking to identify the content of all plastic components.												10
		Try to establish dominant species of plastic parts which make up over 80% by weight of the plastics used.									1			12
		Try to develop products which will be leased rather than sold.										1	1	20
														0
	Liquid Residues	Ensure that liquids contained in the product can be recovered at disassembly .												12
		Minimize liquid residues generated during disassembly, recovery, and reuse.												11
		Minimize the amount of liquid residues generated during materials reuse and recovery.												11
														0
														0
														0
	Gaseous Residues	Facilitate easy recovery of gases contained in product at disassembly.												13
		Minimize gaseous residues generated during material recovery and reuse.												11
		Choose plastics which can be incinerated without requiring sophisticated air pollution devices.												13
														0
														0
														0

Appendix C. Glossary of Terms

Architecture
Underlying Structure of Things (Rechtin 1992)

Architecting
The process by which a system is created, designed, and built. (Rechtin 1992)

Autocatalysis
catalysis of a reaction by one of its products. (Websters New Collegiate)

Boundary Conditions
The sum of a module's interfaces. Defines the function space and design parameters the module exists in. (Reinertsen 1996)

Catalysis
a modification and esp. increase in the rate of a chemical reaction induced by material unchanged chemically at the end of the reaction. (Websters New Collegiate)

Certification
Process by which client is assured that system will meet their requirements, and builder is assured they will be paid, if the system satisfies certain requirements. (McKendree 1994) *(Need to include environmental performance criteria in certification requirements -jjs)*

Chaotic system
See Fully Chaotic Systems and Weakly Chaotic Systems (Percivall 1994)

Closed system
One which does not exchange matter or energy with the environment. Entropy, the measure of disorder, remains constant or increasing.(Percivall 1994)

Cohesion
The measure of the functional association among the elements of a software component. (Sage and Lynch 1998)

Complexity Science
The study of the general behavior and resulting emergent structures of systems composed of a large number of interacting, autonomous components. (Percivall 1994)

Concurrent Design
Process of designing the modules of a system concurrently (as opposed to sequential design.) (Reinertsen 1996)

Concurrent Engineering
Design philosophy which seeks to maximize concurrency between product design and process design. Still uses traditional sequential model for product and process designs. (Reinertsen 1996)

COTS (Commercial off the shelf system)

System (usually used as a subsystem) which is available ready made from and internal or external manufacturer. (Sage and Lynch 1998)

Coupling

The degree of dependence between modules. Loosely coupled modules can change a great deal without forcing a redesign of the other modules. e.g. A power supply with 110W capacity is loosely coupled with the circuit that it supplies which only requires 50W of power. (Reinertsen 1996)

Coupling

The complexity of the interactions between software modules, external to each module. (Sage and Lynch 1998)

Developing an extended system

See extending a system (Sage and Lynch 1998)

Dissipative systems

see open, dissipative systems.(Percivall 1994)

Dynamic Interface

An interface whose terminal, connector, or media change over time. Can be state dependent or time-critical (Sage and Lynch 1998)

Economic Value to the Customer (EVC)

Assessment of product's total value in terms of its economic impact on the purchaser. Particularly useful when purchase process is essentially rational. More comprehensive than life-cycle costs. (Reinertsen 1996) *(would we want to think about environmental impacts too, maybe in TI total Impact or TVC total value to the customer -jjs)*

Edge of chaos

where the components of a system never quite lock into place, and yet never quite dissolve into turbulence, with emergent properties over a sustained time (Waldrop 1993).(Percivall 1994)

Engineering

The art and science associated with a process that leads to creation of cost-efficient technological solutions that fulfill human needs. *(Sharp contrast to Rechtin, who draws a distinction between the art and the science, the architect, and the engineer. -jjs)* (Sage and Lynch 1998)

Engineering Architecture

Adds detail to the principal elements of the reference architecture . Maps logical activity groupings into available or instantiable subsystems. comprised of three principle elements: The subsystem model, the interface model, and the Integrating mechanisms. (Sage and Lynch 1998)

Equilibrium

Systems at equilibrium are those that are stable to perturbations, retaining their existing structure.(Percivall 1994)

Evolutionary phase

Portion of a system's life in which it is an evolving system.(Percivall 1994)

Evolvability

see System Evolvability (Percivall 1994)

Evolving system

Systems in which complexity will increase until a critical state is reached. Further changes will cause the system state to go to a less than critical value. (Percivall 1994)

Extending a system

Modifying a system by adding to it without removing any functionality. (Sage and Lynch 1998)

External Interface

An interface with at least one terminal inside the element of focus, and at least one terminal outside the element of focus. (Sage and Lynch 1998)

Fully Chaotic Systems

systems characterized by a time scale beyond which it is impossible to make predictions.(Percivall 1994)

Functional Decomposition

breakdown of each function of the system into it's component functions, each having specified inputs and outputs. (Sage and Lynch 1998)

Functional Interface

The description of the role an interface will play in translating control, information, or energy between entities (Sage and Lynch 1998)

Grass roots development model

A bottom up design methodology that resembles a stochastic process. Chief disadvantage is that it can consume considerable time. Chief Advantage is that each evolutionary step frequently results in a system well suited to the special needs of a user or group of users. Contrast with System engineering approach (Percivall 1994)

Hardware to Hardware Interfaces

Physical interfaces that are real objects which tough the environment and the media. These interfaces can be described using physical laws. An example of a physical interface is the description of the operation of a diesel engine. (Sage and Lynch 1998)

Hardware to Software Interfaces

Some type of transducer changes electrical or electro-mechanical signals into binary form which can be read by software. Software application developers sometimes fail to recognize that hardware serves as the media in all software interfaces. Software is merely a logical command structure used by hardware to implement functions and services. (Sage and Lynch 1998)

Hard Point

Hard points are components that have reached design maturity in a system development effort, and whose interface can't be changed. The rest of the system must conform to the hard points. *(Can't teach a mature component new tricks -jjs) (Can the Environment be though of as a hard point? Do no harm? -jjs)* (Sage and Lynch 1998)

Heuristics

Empirical rules of thumb derived from experience and judgement, useful for attacking problems too complex to be solved by analytical techniques alone. (Rechtin 1992)

iCMM

Integrated Capability Maturity Model. Incorporates the features of several other Capability Maturity Models to help alleviate the quagmire developing over this alphabet soup. developed by the FAA, integrating the SW-CMM, SE-CMM and the SA-CMM

Implementation Architecture

Adds operational detail to the elements described in the reference and engineering architectures. describes the components, languages and protocols to be used. COTS products included in the design are specified. Design detail is specific enough to create actual code. Consists of four primary elements:

Inactive Perspective

Organization does not consider the need for integration at the level of:

methods and tools
product
process
systems management

Except perhaps in an intuitive and qualitative manner. (Sage and Lynch 1998)

Information Model

Model which represents the entire collection of objects, relationships, and information units that are involved in interactions between subsystems. (Sage and Lynch 1998)

Integrating Mechanism

These represent the mechanism of exchange used for each identified interface. (Sage and Lynch 1998)

Integration

The making of a whole entity by bringing all of the components of that entity together. (Sage and Lynch 1998)

Integration Perspective

Perspective taken in order to insure that the needs of the :

Customer
Systems engineering team
Existing or legacy systems.

are considered, or, in effect, integrated.
(also see Process Oriented Perspective)
(Sage and Lynch 1998)

Interactive Perspective

*(Integrate as you go. - jjs)*Organization will plan for integration and implement integration constructs as a system (could be a product, service, or process.) moves through various phases of the life-cycle process that produces it in order to detect problems as soon as they occur, diagnose their causes, and correct them through recycling *(rework? -jjs)*, feedback, and retrofit to that portion of the life-cycle process in which problems occur. (Sage and Lynch 1998)

Interface Constraints on the design of a subsystem.

Interface definition includes physical attachment points, test points, cooling requirements, mass and moment of inertia, altitude limits -- *anything that constrains the design of other subsystems*. The sum of the interfaces for the module are the boundary conditions for that design task. (Reinertsen 1996)

Interface

The interface is the point at which independent systems or components meet and act or communicate with each other. (Sage and Lynch 1998)

Interface Model

Describes the interactions between subsystems, represents sets of input-output connections specified by the functional decomposition (Sage and Lynch 1998)

Internal Interface

An interface residing inside the element of focus. (Sage and Lynch 1998)

IPD-CMM

Integrated Product Development Capability Maturity Model. recently merged with the iCMM (Sage and Lynch 1998)

Islands of change

Functionally isolated pieces of the system which are constantly changing. Changes in activities of one island do not propagate through the frozen core of stability to the other islands.(Percivall 1994)

Life-Cycle Costs

The cost of a product over it's life-cycle. Does not include secondary impacts on the rest of the company due to it. e.g. hatch design may increase maintenance costs. (Reinertsen 1996)

Low-Contribution Subsystems

Subsystems which make little difference to customer value (EVC). (Reinertsen 1996)

Make/Buy Decisions

decision the system architect makes about which components of the system to make and which to buy from another vendor. (Reinertsen 1996)

Market-Requirements Document

Part of the process that defines the system's outer parameter by specifying the market needs that a product needs to satisfy. Leads to the Technical Product Specification. (Reinertsen 1996) *(This is a key stage to maximizing the environmental performance of the system. -jjs)*

Maturity Model

A maturity model is a way of assessing where your process (and organization) are in respect to what your ultimate process objectives are. In other words, it is a way of tracking the evolution of a process or organization toward the enlightened holy land that is your objective. (JJS gleaned from Sage and Lynch)

Metastable

having or characterized by only a slight margin of stability (a metastable compound) (Webster's New Collegiate)

Modularity

Dividing something into modules in such a way that it allows reuse of modules in more than one product. Modules in a flexible architecture have loose coupling to rest of system. (Reinertsen 1996)

Open, dissipative systems

Those which develop order while operating far from equilibrium.(Percivall 1994)

Operational Architecture

Description of activities, operational elements, and information flows required to support operations. (Sage and Lynch 1998)

Partitioning Heuristic

From Rechtin (1991):

> Choose elements so that they are as independent as possible, that is, elements with low external complexity and high internal complexity. *(Makes for easier reuse, reman. -jjs)*
>
> For distributed systems, choose a configuration in which local activity is high speed and global activity is low speed. *(In a physical system like a city, this would yield higher environmental performance and speed since the heuristics drastically reduces the amount of speed*distance~energy consumed -jjs)*
>
> Choose a configuration with minimal communications between the subsystems. (used in Aerospace applications) *(Enhances reusability and recyclability -jjs)*
>
> Don't partition by slicing through regions where high rates of information exchange are required (used in computer applications.) *(Enhance recyclability and reusability -jjs)*

(McKendree 1994)

P-CMM

SEI People Capability Maturity Model applies many of the same principles of the SW CMM to development and management of work forces.

Proactive Perspective

*(look before you leap - jjs)*Proactive systems integration efforts are those designed to predict the potential for errors, and enable the synthesis of an appropriate life-cycle process that is sufficiently mature such that systems integration error potential is minimized. (Sage and Lynch 1998)

Process Oriented Perspective
Perspective taken in an effort to insure a product line that is cost-effective and trustworthy. (also see integration perspective) (Sage and Lynch 1998)

Product Development process
The process by which any system should be brought about. Consists of Five Phases.

1. Conception.
2. Building.
3. Testing.
4. Certification.
5. Operation.

(Rechtin 1992)

Product Integration
The integration of subsystems and components that give systems their superiority over a set of elements that do not work together without integration. (Sage and Lynch 1998)

Reactive Perspective
Organization will attempt to integrate only after it has detected a performance problem, or failure. Once the cause of the problem id diagnosed, they will often eliminate, the symptoms affecting integration. (Sage and Lynch 1998)

Reference architecture
Obtained by mapping the system onto logical groupings of activities that are to be performed. Obtained through functional decomposition, followed by the development of a system model and an information model. (Sage and Lynch 1998)

Rework
When portions of a design need to be changed after their design phase is over because they do not meet marketing or technical requirements. (Reinertsen 1996)

Robust Interface
More Tolerant of changing requirements (Reinertsen 1996)

RTD&E
research, development, test, and evaluation focus of systems engineer to insure all needed technologies are available, and at a sufficient state of maturity. (Sage and Lynch 1998)

SA-CMM
Software Acquisition Capability Maturity Model. This model is developed for companies which outsource software development to other companies, and is used to evaluate the capabilities of the company developing software, integrating the outsourced pieces. (Sage and Lynch 1998)

Satisficing

finding at least one solution which is satisfactory (as opposed to optimizing) (McKendree 1994) *(Make sure that environmental performance is part of satisfactory. -jjs)*

Scope
How large the project under development is. This would include how much of the functionality is new, how much is being out-sourced, etc. (Reinertsen 1996)

SE CMM
Systems Engineering Capability Maturity Model. (Sage and Lynch 1998)

Self-Organization
the emergence of new, metastable entities or structures that, at a component level, are not just non-existent, but even meaningless. (Percivall 1994)

Sequential Design
The old school method of design where each phase of the design follows after the other. e.g. Design the circuit, then measure the load, then design the power supply for that load, then design the case to fit the circuit and power supply. (Reinertsen 1996)

Software Interfaces
Can be functional, informational or environmental. Examples include user interfaces, protocols for interprocess and network communications. Two key concepts in the Software interface are coupling and cohesion. (Sage and Lynch 1998)

Subsystem Model
Describes the subsystems that will be considered as black boxes (Sage and Lynch 1998)

Surface Issues of Strategic Importance
Technical issue that seems to drive system. e.g. If subsystem is required to do an order of magnitude or less than what it can do, may allow systems architecting to consider a totally different system design. When these issues are found by systems and subsystems engineers, need to tell architect. (McKendree 1994) *(Industrial Ecology moves environmental issues from overhead to strategic. -jjs)*

Surface Problems
Some issues which come up during development are not amenable to analysis by systems engineering. Probably indicate a mismatch requiring an adjustment in the architecture. Systems Engineering should inform Systems architecting of these situations as soon as possible. (McKendree 1994)

SW CMM
Software Capability Maturity Model. (Sage and Lynch 1998)

System
A collection of different things related in such a way as to produce a result greater than what its parts, separately, could produce. (Rechtin 1992)

System Architect
Person who creates the conceptual model of the system, translating the clients desires into a technical description the builder can understand. As an agent of

the client, the system architect must assure that system integrity is assured throughout the program phases, and that design certifications is meaningful and passable. (McKendree 1994) *(Need to find ways of specifying unquantifiable design criteria such as environmental performance in such a way that the system engineer can apply tools to maximize it. Some sort of scoring system that will result in maximizing environmental performance-jjs)*

System Architecture

Description of system components and their interconnections required for supporting critical operational functions. (Sage and Lynch 1998)

System Boundaries

Line drawn by system architect to define what factors are considered to interact with the system (or subsystem) being designed. (Reinertsen 1996)

System Concept

A model of the system that will address the client's needs and desires while using an acceptable portion of the client's resources. Initially may leave a great number of details to be designed, but will form a structure within which the details can be resolved. (McKendree 1994)

Not necessarily complete description covering all the key points in the concept, so that the remaining specifications can be derived. Principal output of systems architecting to engineering. (McKendree 1994) *(Needs to include criteria for maximizing environmental performance. -jjs)*

System Engineer

Team member given precise, well defined functions to achieve, and develops all the detailed specifications, down to the subsystems and components. Must also address every subsystem interface. Contrast with System Architect.(McKendree 1994) *(Will have few tools to deal with the unquantifiable like environmental performance. -jjs)*

System Engineering

Process based effort that is comprised of a number of activities that:

Assist in the definition of a system that will be trustworthy, high quality, and cost-effective in meeting user needs;

Transform the resulting set of requirements and specifications into a system through various development efforts; and

>Provide for deployment of the system in an operational environment.

(Sage and Lynch 1998)

System engineering development model

A top down design methodology. Chief disadvantages are tends to produce systems that lack flexibility needed for long life-cycles. chief advantages are its efficiency in terms of development time and cost. Contrast with grass roots approach. (Percivall 1994)

System Evolvability

a trait of a system that allows the system to be easily modified due to changes in the environment. (Percivall 1994)

System Model

Model describing the assignment of functions to the subsystems and identifies and characterizes the subsystem types. (Sage and Lynch 1998)

Technical Architecture

Set of rules defining the interactions and interdependencies of system parts and elements used to ensure that that compatible systems satisfy a set of requirements. Information is provided regarding information types, content, and the nature and timing of information movement. (Sage and Lynch 1998)

Technical Product Specification

The translation of the market-requirements document into parameters that serve as targets for the design team, specifying the outer boundaries of the system. These are used in the sequential engineering process, and never go deeper to define what the partitioning of the subsystems is. (Reinertsen 1996)

Waterfall Model

Development model based on:

1. The top-down flow of requirements and design development
2. Followed by detailed design and implementation
3. Followed by several upward integration steps.

In this model, a fixed set of requirements are determined at the outset of the project, from which the design follows. The project proceeds through well defined "phases" in which the project can be said to be in at any given time.b(Percivall 1994)

Weakly Chaotic Systems

systems which lack a time scale beyond which it is impossible to make predictions, and are thus, in the long term, predictable, even if they are not predictable in the short term.(Percivall 1994)

Wholism

The sense of the system, how it hangs together, creating a single entity. (McKendree 1994) *(Part of that system is it's environmental interfaces. Need to define the whole as including the outside environment. -jjs)*

Appendix D.
New Environmental Heuristics.

Some heuristics for improving environmental performance, found by the author.

- The higher on the architectural hierarchy a portion of a system can be reused, the higher the environmental performance of the system.
- The more modular an architecture is, the higher the environmental performance of a system.
- If a module or product is broken down into modules by the service life of the components, it will have higher environmental performance.
    - Architectures with minimal commingling of product and consumables will have higher environmental performance.
- If a module or product is broken down into modules by dominant technologies, it will have higher environmental performance.
- The more operational support required for high environmental performance, the lower the chance that environmental performance will be obtained in reality.
- The customer will be most pleased at the edge of chaos.