Principal Investigator/Project Director: Jeffrey W. Herrmann

Institution: University of Maryland

Award Number: DMI0225863 **Program:** PREMISE

Project Title: PREMISE: Applying Decision Production Systems to Improve Environmentally Responsible Product Development

Applying Decision Production Systems to Improve Environmentally Responsible Product Development

Jeffrey W. Herrmann
Department of Mechanical Engineering and Institute for Systems Research
University of Maryland, College Park

Peter A. Sandborn
Department of Mechanical Engineering
University of Maryland, College Park

Linda C. Schmidt
Department of Mechanical Engineering and Institute for Systems Research
University of Maryland, College Park

1. Introduction

Environmentally responsible product development (ERPD), also known as environmentally benign manufacturing, considers both environmental impacts and economic objectives during the numerous and diverse activities of product development and manufacturing. ERPD seeks to develop energy-efficient and environmentally benign products. Throughout their life cycle, products generate environmental impacts from extracting and processing raw materials; during manufacturing, assembly, and distribution; due to their packaging, use, and maintenance; and at their end of their life. There are many ways to minimize these environmental impacts. Clearly, however, the greatest opportunity for ERPD occurs during the product design phases (Handfield *et al.*, 2001). The decisions that are made during these phases determine most of the product's environmental impact. Although ERPD requires extra effort, it not only protects the environment but also reduces life-cycle costs by decreasing energy use, reducing raw material requirements, and avoiding pollution control (Allen *et al.*, 2001).

Consequently, manufacturing companies have spent a great deal of effort developing tools to help designers create environmentally benign products. The two major classes of tools are life cycle assessment (LCA) and design for environment (DFE) tools. LCA provides a fundamental methodology that evaluates the environmental impact associated with a product during its complete life cycle. Design for environment (DFE) tools apply this approach through design decision support tools that help a designer reduce these impacts by improving the product design. DFE combines several design-related topics: disassembly, recovery, recycling, disposal, regulatory compliance, human health and safety impact, and hazardous material minimization. Because LCA is a central part of DFE, this paper discusses both classes of tools.

Many obstacles to the effective use of LCA and DFE tools have been noted. Two of the most significant obstacles are the difficulties acquiring the needed data and the challenges developing realistic, appropriate metrics of environmental impact. Consequently, LCA and DFE tools are, generally, not integrated with the other activities and tools used in the product development process. That is, there exists inconsistencies between the information flow and decision-making that exists in a product development organization and the information flow and decision-making that existing

LCA and DFE tools require to be effective. This conflict leads to tools that are expensive and time-consuming to use and tools that generate irrelevant information.

Two innovations are needed to improve the situation. First, product development organizations need powerful LCA and DFE tools that seamlessly fit the existing flow of information and decision-making. Second, to obtain these, product development organizations need methods to guide the development and implementation of particular tools (for specific decision-makers) and the rational and systematic deployment of LCA and DFE tools across the entire organization. Ultimately, this will reduce the time and cost of developing energy-efficient and environmentally benign products.

We believe that product development organizations can improve their ERPD practices by applying the decision production system perspective (Herrmann and Schmidt, 2002). This will lead to four types of benefits.

1. Product development organizations will better understand how decision-making and information flow affect their behavior, and they will be able to describe how they create information about environmental concerns and use this information in decision-making.
2. Product development organizations will be able to identify the inconsistencies between the information flow and decision-making in their organization and the information flow and decision-making that LCA and DFE tools require.
3. Product development organizations will design and implement more useful and effective LCA and DFE tools that seamlessly fit the decision production system and will deploy LCA and DFE tools in a more rational and systematic way across the entire organization.
4. Product development organizations will reduce the time and cost of developing energy-efficient and environmentally benign products by using effective LCA and DFE tools in a more coordinated manner.

The current research project is an important first step to accomplish these goals (for more information about the project, see the project web site: http://www.isr.umd.edu/Labs/CIM/projects/premise/index.html). This research will study ERPD using the decision production system perspective, elaborate and refine the concepts and their application, identify experienced and capable partners, and construct a long-term research plan. Although the decision production system perspective could be applied to study other types of design decision support methods, LCA and DFE tools are an interesting and distinctive domain to study because ERPD is a serious issue for manufacturers and our society and these sophisticated tools require a great deal of information and resources. The remainder of this paper gives relevant background and describes our approach to using decision production systems to improve ERPD.

2. Life Cycle Assessment and Design for Environment

Manufacturing companies have to be concerned about environmental issues at some level because of legislation (current or future) and litigation (current or potential). Other environmental drivers may include customer expectations, product differentiation, cost reduction, and stewardship. Specifically, both integrated circuit (IC) fabrication and printed wiring board (PWB) fabrication differ from other industries, including electronic assembly, in the importance of managing waste. The amount of waste generated during the fabrication of ICs and PWBs significantly exceeds the amount of material in the final fabricated chip or board, with a large portion of the waste considered hazardous. In conventionally fabricated PWBs, up to 5 times more waste than product (by weight, not including water) is generated during the board production process (MCC, 1993). Managing and disposing of this waste can represent up to 10% or more of the cost of a board (Sandborn and Murphy, 1998). Therefore, for the PWB fabricator, minimizing the waste stream does much more than create a perception of being an environmentally friendly company. It also contributes significantly to the company's bottom line.

Most electronics companies have adopted continuous improvement cultures and recognize the importance of being competitive. Most of the well-known quality elements (e.g., testability, manufacturability, and reliability) have clear-cut metrics. These metrics are typically parametric (i.e., they have independent and dependent variables) and are clearly tied to customer expectations and demands, and their impact on the product's cost can be quantified. More importantly the ability and critical nature of affecting these quality indicators at the product design level is appreciated and understood. This insight enables effective Design for X (DFX) activities. In general, the maturity of DFX activities progresses through three phases (Sandborn and Murphy, 1997): (1) problem articulation with few metrics, (2) formation of a concise metrology for measuring the magnitude of the problem on an application specific basis; and (3) linking the metrology to the product design cycle and mapping of the metrology to economic impacts.

However, for environmental impacts, there are few metrics, the metrics that do exist have simple values (go, or no-go), and the path to continuous improvement is not obvious. Consequently, the most common DFE tools are the simplest ones: checklists, design standards, design guides, and databases of chemicals and materials. (See also Mizuki, Sandborn, Pitts, 1996.) The successful transition of DFE methodologies to the second and third phases in this model depends on whether the methodology finds a practical location in the product development process where the data requirements of the methodology can be met and the outputs created by the methodology can be used. Similarly, Allen *et al.* (2001) observed that integrating DFE with other product development practices remains an important problem. Based on their survey, Handfield *et al.* (2001) note that, while many DFE tools exist, they are not used regularly and systematically, the necessary data are not available (or require too much effort to acquire), environmental issues are relevant only as constraints that must be satisfied at design reviews, and designers cannot make the tradeoffs between different environmental impacts.

LCA provides a fundamental methodology that evaluates the environmental impact associated with a product during its complete life cycle. Inventory LCA is a prerequisite for many DFE tools that calculate different environmental impacts based on this inventory. Though not as common at this time (as discussed above) more sophisticated DFE tools will suggest product design improvements to help a designer reduce the environmental impacts (Williams, 2000). (Hoffman, 1995, similarly states that LCA is a descriptive tool, while DFE describes prescriptive tools.)

Currently LCA has three main drawbacks:

1. LCA requires a large amount of data not only about the inputs and outputs of a firm's processes and operations but also about those of the suppliers (and their suppliers) and the customers. The firm needs information on materials and energy production and supply, the performance of the plant, and, most likely, on waste management. Even the most modest and "streamlined" LCA tools require a lot of background material. Much of this data is available in the public domain but comes from diffuse sources.

2. LCA is time-consuming. The firm needs to consider complex systems that require more effort every time they're considered. The firm needs to collect data from people for whom LCA is a very low priority. There is a lot of data processing and analysis to be performed. Some large companies effectively have internal consultancy teams to perform LCA, but smaller firms cannot afford these.

3. LCA has a steep learning curve. Experience with conducting LCA brings many benefits. Not only do the veterans have some of the needed data, but also they are likely to have an idea as to where to find the rest of it. Crucially, they will be aware of some of the pitfalls (e.g., system boundary definition and allocation) that, although not insurmountable, are likely to be time-consuming for designers whose primary job responsibility is not LCA.

Because so many LCA and DFE tools exist, surveys and reports on their proper use have followed. Mizuki *et al.* (1996) and Williams (2000) discuss classification schemes for DFE and LCA tools. Sharma and Weitz (1995) review decision support tools used by Federal facilities and industry in decision-making, including environmental management. van Berkel *et al.* (1996) list the advantages, disadvantages, and possible applications of different types of DFE tools for the electronics industry. Eagan and Hawk (1996) describe how different types of DFE tools are useful for different types of products based on the products' market share and market growth rate. Sarkis *et al.* (1996) present a quantitative method for comparing different business practices (such as DFE and LCA) and helping an organization choose the best one for their regulatory environment. These are only general guidelines, however, and the challenge is to integrate DFE and LCA tools into the appropriate decision-making activities.

Published reports of DFE tools and systems (e.g., Chen *et al.*, 1996; Feldmann *et al*., 1999) do not address the needs of any particular decision-maker. Thus, there often seems to be a gap between the tool and the product development process, and it is not clear that the tool will support ERPD. Manufacturing companies need help integrating LCA and DFE with other engineering tools in the product development process (WTEC, 2000). Hoffman (1995) argues that DFE tools depend upon the information available. Since more information becomes available during the product development process, Hoffman discusses the different types of tools that are useful during different development activities. Moreover, the DFE tools used at one step can exploit the data generated by DFE tools used in a previous step of the development process.

3. Modeling Product Development Organizations

A *product development organization* includes the engineers, managers, and other personnel that make process and product engineering decisions as part of their designing activities. This organization brings new products to market. The group of involved decision-makers is not limited to those listed on the organization chart of the New Product Development hierarchy. Instead it includes participants from manufacturing facilities, suppliers, purchasing, marketing, and other groups who perform or provide input to designing activities. We view a product development organization as a network of people using information, making decisions, and generating information (Herrmann and Schmidt, 2002). Thus, product development is an information flow governed by decision-makers who make decisions under time and budget constraints.

It is difficult to model product development organizations due to their complex nature. The most common depictions are simple descriptions of product development teams and the various stages that product development projects typically follow. There exist many models of product development projects, including those used for project scheduling. Another widely known approach is the design structure matrix, which represents the activities in a product development project, their duration, the probabilities of repeating each, and the precedence constraints between them. This matrix can be used to determine the distribution of the project completion time. See, for example, Smith and Eppinger (2001), Carrascosa *et al.* (1998), and Yassine *et al.* (2000).

Reinertsen (1997) discusses methods that use sensitivity analysis to estimate how development expenses, unit costs, product performance, and development delays affect the profitability of a product development project. Both McGrath (1996) and Reinertsen (1997) discuss methods for managing a pipeline of product development projects. However, these methods and models do not address the complex nature of information flow and decision-making in product development organizations.

The most comprehensive approach (Adler *et al.,* 1995) uses capacity analysis and discrete event simulation to evaluate the performance of a product development organization. The organization is modeled as a queueing system. Jobs representing product development projects are processed by workstations representing groups within the organization. The models are used to evaluate resource utilization and project cycle times but do not address decision-making.

Using a more abstract model, Natter *et al.* (2001) represent a simple product development organization using two agents (one called marketing, one called production) that can learn but have limited knowledge and computational ability. The model uses neural networks to model each agent's learning and a life cycle model to predict the organization's profitability over time. Experimental results suggest how the organization structure, search techniques, incentive schemes, and other factors affect profitability.

4. Decision-Making in Product Development

Because they realized that design decisions (though made early in the product life cycle) have an excessive impact on the profitability of a product over its entire life cycle, manufacturing firms and product development organizations have created and used concurrent engineering practices for many years (Smith, 1997, provides a historical view). Cross-functional product development teams and design for manufacturing guidelines, for example, avoid unnecessary manufacturing costs and expensive delays due to design iterations. Likewise, the greatest potential for reducing environmental impacts in a cost-effective way lies in improving product development.

Product development includes many different types of decision-making by engineers and managers. Some decisions are *design decisions* and others are *development decisions*. Design decisions determine the product form and specify the manufacturing processes to be used. Design decisions generate information about the product design itself and the requirements that it must satisfy. Development decisions, however, control the progress of the development process. They affect the resources, time, and technologies available to perform development activities. They define which activities should happen, their sequence, and who should perform them. That is, what will be done, when will it be done, and who will do it. Krishnan and Ulrich (2001) provide a comprehensive survey of design decision-making.

The design engineering community has focused much effort on understanding design as a decision-making activity. This work has yielded Decision-Based Design (DBD), a perspective that views design as a decision-making process involving values, uncertainty, and risk. (Details on DBD can be found online in the Decision-Based Design Workshop at http://dbd.eng.buffalo.edu/.) The research on DBD includes a wide variety of approaches. DBD researchers have primarily focused on making better design decisions (e.g., selecting the best design alternative). Because decision-making often involves multiple objectives, some DBD researchers have developed techniques for helping decision-makers make tradeoffs among competing objectives and methods that quantify and combine the multiple objectives into a single objective. The techniques of decision analysis, especially utility theory, are an important component. Thurston (2001) gives an overview of DBD and discusses the role of utility theory in DBD. Research in this area continues. For an overview of rational decision-making, including subjective expected utility theory and prospect theory, see, for example, Hastie and Dawes (2001).

Some research on DBD includes efforts to illustrate how engineering design should be done. That is, they claim that there is an alternative to the traditional decomposition of design. Specifically, researchers have developed approaches that integrate numerous design decisions and solve large optimization problems whose objective function is to maximize company profit (see, for instance, Hazelrigg, 1998; and Li and Azarm, 2001). Because this simplifies the process, product development will take less time. Also, the integrated model includes all of the competing performance measures (including, possibly, environmental impacts) and maps them to more fundamental objectives (such as profitability and market share) that are important to the manager of the manufacturing firm. However, such integration remains a primarily academic exercise at this point.

In practice, product development teams decompose the design problem, and design engineers and other members of the team must try to satisfy a variety of constraints and make tradeoffs between multiple competing objectives, including environmental concerns. Similar to other design decision support tools, LCA and DFE are created to provide data and perform calculations needed to assess environmental impact, which helps a designer reduce these impacts by improving the product design.

5. Decision Production Systems

Based on their experience and careful study of product development organizations, we have developed a new paradigm for understanding product development. This paradigm views product development organizations as decision production systems. The following paragraphs briefly describe this perspective. For a more in-depth discussion, see Herrmann and Schmidt (2002).

Traditional product development organizations follow a hierarchical organization structure. This structure is a natural and efficient way to make decisions. However, this hierarchy insulates design engineers from decision-making. Thus, design engineers have viewed their task as one of problem solving. They solve the problems that others give to them.

Although they may not realize it, design engineers are making decisions. Identifying the "best" product design commits the organization to this choice (though later steps may require a change of plans), and this decision generates information that other activities then use. When the design problem is extremely well formulated, the engineer makes a decision by solving an optimization problem. In other cases, the decision-making process is a collection of heuristics to generate solutions, evaluate them, and select the best one.

Under the pressure of time and budget constraints, however, product development organizations have found that information must flow through channels outside the organization chart and have implemented cross-functional teams and other concurrent engineering techniques.

Clearly, a product development organization is (independent of its formal structure) a network of people using information, making decisions, and generating information. Product development is an information flow governed by decision-makers who make both design decisions and development decisions under time and budget constraints. It is a decision production system.

The decision production system resembles a production system that has units dedicated to specific tasks. The information and decision-making flow for a typical new product development process is shown in Figure 1. In a decision production system, each unit is equipped to make decisions based on information received from other units and the internal processing of that information by members of the unit. For example, when Marketing receives a request for a sales forecast, they will assign the processing of that task to a member who will perform a study based on the history of similar products and information about competitors. It is likely that information exchange will occur between members of the units shown in parentheses at each step and from one unit to another.

Members from different units may make decisions concurrently. However, it is useful to view the "product" of the decision production system as the culmination of a number of decisions made within and among members of units. The decision production system view puts all decision-makers on the same level, because they are all working on the same virtual shop floor.

The decision production system perspective does not advocate one particular type of product development process. Instead, it looks at the organization in which the product development process exists and considers the decision-makers as a manufacturing system that can be viewed separately from the organization structure.

One advantage of viewing the decision production system in this way (both literally and conceptually) is the focus on information processing flows instead of personnel reporting relationships. The decision production system view is a meta model that can be used to help organization members understand the flows of decision-making in the same way as an organization chart describes administrative authority relationships.

For instance, Figure 1 shows the information flow and decision-making in a typical product development organization. The various arrows represent information that is exchanged between individuals in different units during the product development process. Note that the environmental information (represented by the pale arrows) is used only by the environmental engineers performing the environmental review (an LCA inventory, for example) and is isolated from the other activities. Likewise, a single designer is the only person using a DFE tool, and the resulting environmental information is not communicated to anyone else.

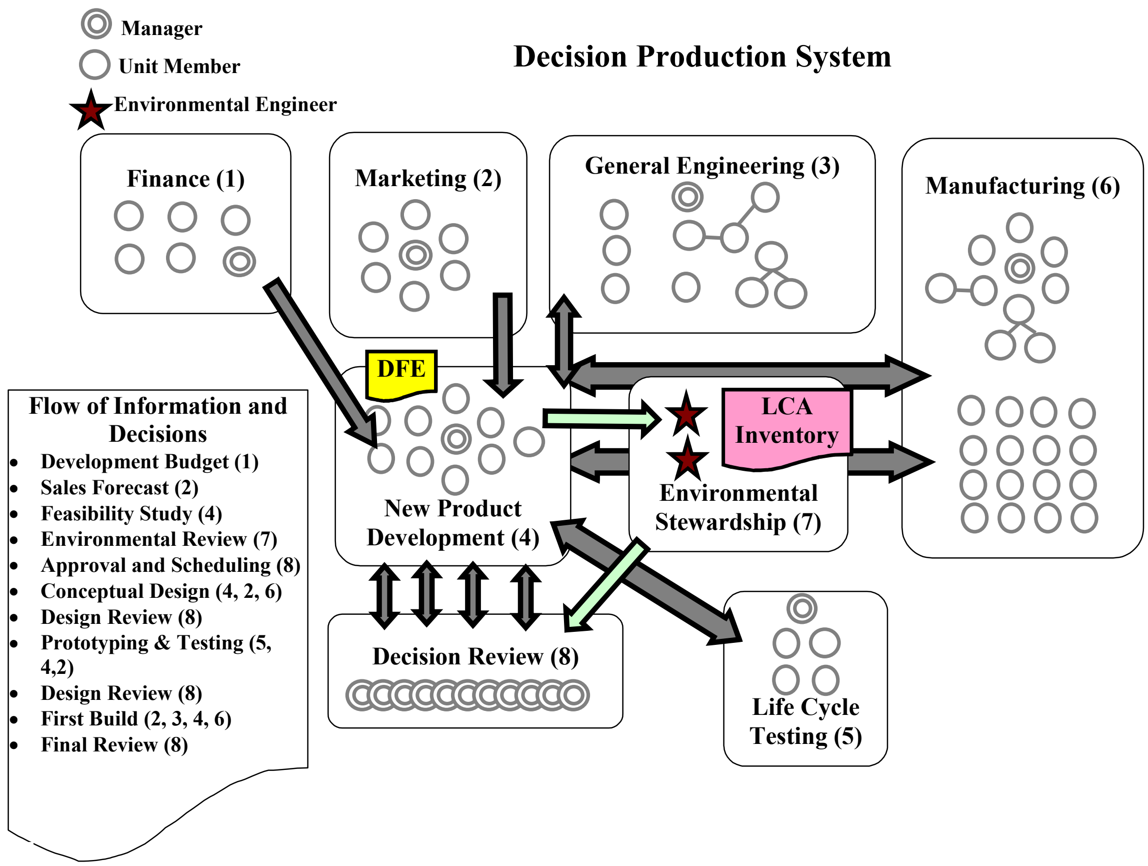

Figure 1. A product development organization with isolated environmental decision-making.

6. An Example of Decision Production Systems

Consider the following example in which a product development organization seeks to improve its ERPD practices. A manufacturing firm seeks to develop multiple LCA methods for different phases of the product development process (as proposed by Hoffman, 1995). The LCA tool for concept development will ask questions that force the product development team to consider environmental impacts and life cycle requirements. Using the more precise design information that is available, the LCA tools for detail design will give a designer feedback on the environmental score of each component or subsystem (relative to the best possible combination of materials and processes). Finally, the product development team can use a traditional LCA after prototypes have been manufactured and the team has detailed information about the product and manufacturing processes.

However, the firm must answer a number of questions. Which persons should use which tools? What data do the tools require? Are these data available to the persons using the tools? Which metrics will the tools evaluate? Can the new activities leverage existing communication channels or will they require new patterns of communication? Developing a general methodology that can help the firm find good solutions is a difficult and important challenge.

The firm can use the decision production system perspective to guide the development and implementation of the LCA tools. First, the firm can model, analyze, and understand the information flow and decision-making in the product development organization, including the environmental information. The LCA system can tap these sources of information either by including those personnel in the system or by establishing access to the information generated. Moreover, this will identify gaps between the required data and the available data. The firm can then find resources to generate the required data or modify the design of the LCA tools. Second, understanding the production development organization's behavior (information flow and decision-making) will identify which personnel and groups should use which LCA tools because they have (or can get) the needed data and they make the relevant decisions. For instance, asking an environmental steward to perform LCA for subsystem design will lead to many time-consuming iterations between the steward and the designer (or design team) responsible for that subsystem. Including the environmental steward in the LCA for concept development may be a more effective way to use the person's time and to use a wide range of relevant data in the right place at the right time. Moreover, this will identify the people at suppliers, recycling firms, government agencies, and other outside organizations who have valuable information or make important decisions. The LCA system should include these people or their knowledge somewhere. Finally, the decision production system perspective will help guide the design of environmental information systems by identifying which information needs to flow from one person or database to another person or database to provide input for decision-making.

7. Studying Decision Production Systems

The current research project consists of two tasks: 1. Constructing a long-term collaborative research agenda that guides a research program using the decision production system perspective to improve ERPD, particularly by integrating LCA and DFE tools into other product development activities. 2. Conducting an exploratory study to describe the flow of information related to LCA and DFE in the product development activities of an electronics manufacturing company.

In the second task, the research project will conduct an exploratory study of information flow and decision-making in the product development organization of an electronics manufacturer. This task will have three steps: (1) study the decision-making activities and create a data flow model, (2) identify the environmental elements of the data flow model, and (3) analyze the model for external and internal inconsistencies. We are collaborating with Merix Corporation in Forest Grove, Oregon, a manufacturer of high technology printed circuit boards.

The exploratory study will describe the flow of information related to LCA and DFE in the process engineering activities at Merix. The project team will look at how Merix creates material disclosure statements requested by Merix's customers and the data collection and other activities that accompany this process. The study will examine the information flow and decision-making that occur in the process design and planning activities associated with completing customer orders. The study will identify changes that improve these activities and create conceptual models to represent these changes.

For instance, Figure 2 depicts the revised information flow and decision-making that results from moving environmental engineers into other units, systematically deploying a variety of DFE tools across the organization, and integrating environmental impacts and metrics into the other information generated and used by new product development decision-makers. (This degree of integration is missing in the decision production system shown in Figure 1.)

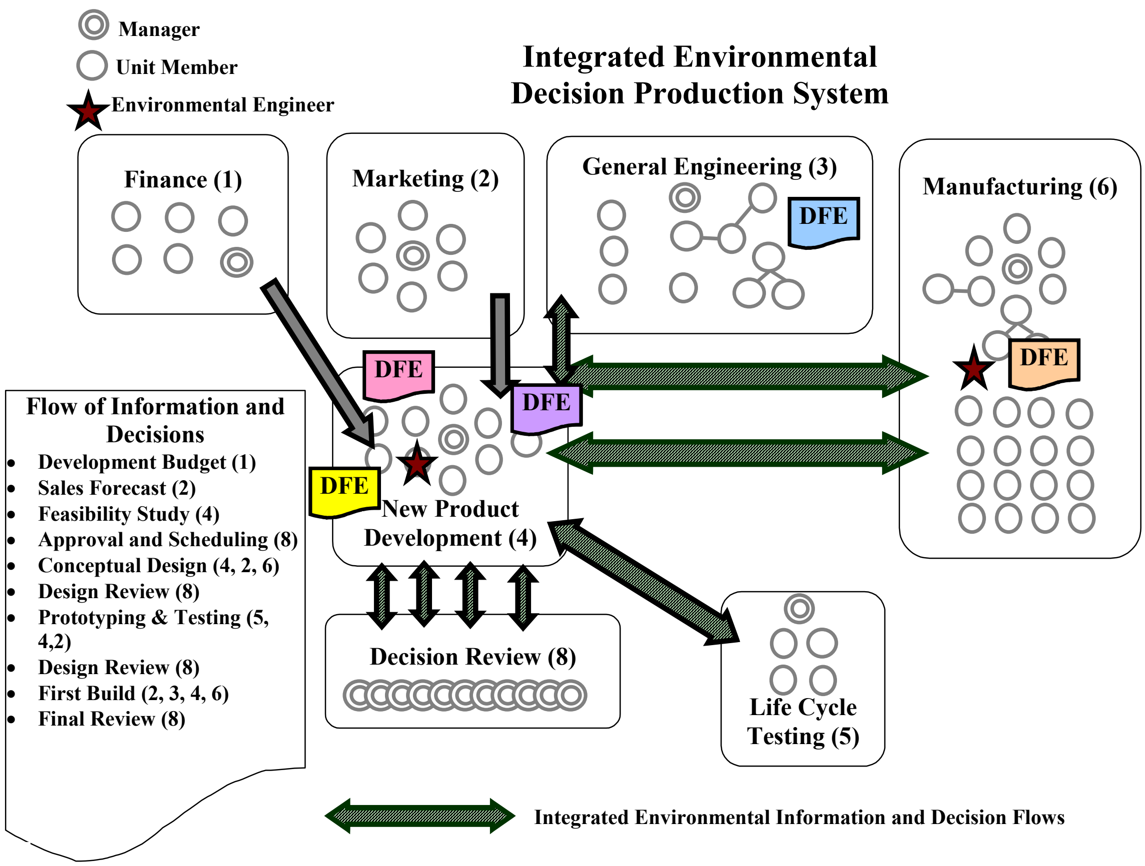

Figure 2. A product development organization with integrated environmental decision-making.

8. Summary and Conclusions

The current research project begins a new research program on information flow and decision-making in ERPD. The ultimate goal of the research is to help organizations reduce the time and cost of developing energy-efficient and environmentally benign products. The research will describe how a product development organization creates information about environmental concerns and uses this information in decision-making. The research will provide models to represent information flow and decision-making and systematic methods to analyze this behavior. Our approach uses a novel, systems-level paradigm to develop new insights into the behavior of product development organizations. Unlike many existing approaches, this perspective examines the entire organization, not just individual product development projects.

This research program will develop a sophisticated methodology for developing and implementing ERPD practices such as LCA and DFE tools. This methodology will be a significant advance. Current approaches for developing LCA and DFE tools do not consider the behavior of the product development organization that will use the tools. Thus, although many tools exist, the tools do not provide the data that an actual decision-maker needs to compare various product or process alternatives that are under consideration. Consequently, simple guidelines or checklists are the only useful DFE tools in practice at this time. This research program will lead to more powerful tools that are customized address the decision-maker's specific environment.

This would transform the development of LCA and DFE tools methods from the two current extremes (either simple checklists or sophisticated, scientific models) to tools that fit the product development organizations that want to use them. This is similar to the drive to mass customization of consumer products. The research will enable mass customization of DFE tools that are intelligent and quantitative but are practical, cost-effective, and feasible without unnecessary reengineering of the product development process.

ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation under grant DMI-0225863. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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