Integrating Environmental Concerns into the Design Process: The Gap between Theory and Practice

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***Abstract*—This paper focuses on the product design process and integration of environmental performance criteria during this critical stage. Specifically, we explore environmentally responsible manufacturing (ERM) as perceived and acted on by two critical groups within this design process. The first consists of the champions and supporters of ERM, who either formally or informally act as advocates of ERM within the organization. The second consists of the users of design for environment (DfE) tools and procedures. Typically, these people consist of product designers and design engineers. We study these two groups through in-depth interviews with managers and engineers in a sample of ten firms drawn from the "best-in-class" environmental leaders. We found that a large gap exists between the ERM supporters and the users of ERM tools in terms of expectations, perceptions and orientations toward ERM principles, practices and tools. To overcome some of the many obstacles preventing effective integration of environmental criteria into the design process, we conclude with a process map that proposes the following steps: 1) enlisting support of a corporate champion; 2) defining environmental goals; 3) selecting a pilot project; 4) setting product launch goals and evaluation system; 5) enlisting support of team members; 6) providing DfE tools and training; 7) monitoring the project; and 8) celebrating successes.**

***Index Terms*—Case studies, design for environment, environmentally responsible manufacturing.**

I. Introduction

WITHIN THE LAST decade, large corporations and small businesses alike have undergone unprecedented levels of change in response to global competition. Environmentally responsible manufacturing (ERM) is a relatively new concept of the 1990s, and is defined as: "*a system which integrates product and process design issues with issues of manufacturing production planning and control in such a manner as to identify, quantify, assess and manage the flow of environmental waste with the goal of reducing and ultimately minimizing its impact on the environment while also trying to maximize resource efficiency*" [48]. The business press (both academic and practitioner) validates the importance of ERM to business by publishing more books and articles on business and the environment every year [19], [30], [46], [55], [59], [71].

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Global manufacturing firms are paying more attention to their environmental performance for a number of reasons. A number of external forces also contribute to this need for change, including the following:

- Proponents of environmental responsibility claim that organizations can reduce their costs in the form of reduced waste management/disposal costs, reduced penalties and fines, reduced future liabilities, and lower regulatory driven costs [55], [56].
- Increasing governmental regulation.
- The advent of ISO 14 000 (with its emphasis on international standards for environmental compliance) [49].
- The potential for publicity (both good and bad).
- Increasing demands from customers for goods and services produced using environmentally friendly processes and designs.

Industry groups (e.g., chemical and electronic) and consumer groups (e.g., the Green Cross certification program and Canada's Eco Logo program) are also pressuring organizations to become environmentally responsible [66]. Product development managers are recognizing that markets will eventually reward ERM.

However, being environmentally responsible is not an easy task. The concept of ERM is surrounded by a number of obstacles. One obstacle is the confusion over what is meant by being "green" [70]. Second, government environmental standards and requirements are constantly changing, are not well-defined and, at times, are in conflict with one other. Third, managers believe that minimal compliance to regulations is sufficient, since the environment does not have a direct impact on competitive priorities. Some research points to the fact that environmental regulation is a costly deterrent to productivity [8], [34], [49], [53], [71]. Finally, managers are unsure how to deal with the obstacles introduced by ERM in an environment of increasing complexity.

In this paper, we begin by examining current theoretical foundations on the integration of environmental management into functional business processes. While prior theory provides some very broad guidelines, this body of work provides almost no direction for the practicing manager seeking to deploy environmental initiatives into current business processes. In Section III, we examine the implementation of ERM specifically within the product design process. Specifically, we focus our attention on two major categories of respondents: ERM supporters and product designers (users of design for environment (DfE) tools). By studying the different goals and objectives of each group, we can develop insights into the barriers to effective integration of environmental issues into the design process.

Interviews with these groups took place in a sample of ten firms drawn from a population consisting of advanced/leading edge ERM users. This research tests the following three propositions:

1. In ecologically sustainable organizations, designers are driven to explicitly consider environmental design decisions by corporate and new product development environmental objectives.
2. Ecologically sustainable organizations have ERM systems that explicitly measure and recognize environmental objectives at major points in the design process; these metrics carry at least the same weight as other design goals.
3. Ecologically sustainable organizations successfully integrate environmental issues into the design process by measuring environmental outcomes and integrating them into the strategic planning process; these outcomes form the basis for strategy and designer performance evaluation.

These three propositions were examined in an exploratory study, discussed in Sections IV and V of the paper. Based on our findings, we provide a preliminary model for technology managers to use in overcoming obstacles to ERM deployment within the design process. This model will require formal validation in future research.

II. Theoretical Foundations—Ecological Sustainability

A. Ecological Sustainability Paradigms

Generally speaking, little prior theory exists relating specifically to the role of new product designers and environmental initiatives. The primary theoretical paradigm in use is that of the "ecologically sustainable organization" and its role in "sustainable development." A recent content analysis of the literature describes "sustainable development" as:

> *A process of achieving human development in an inclusive, connected, equitable, prudent, and secure manner. Inclusiveness implies human development over time and space. Connectivity entails an embrace of ecological, social, and economic interdependence. Equity suggests intergenerational, intrageneration, and interspecies fairness. Prudence connotes duties of care and prevention: technologically, scientifically, and politically. Security demands safety from chronic threats and protection from harmful disruption* [25, p. 878].

While this definition is an interesting starting point, it provides relatively little guidance regarding integration of design activities with environmental initiatives. A somewhat more prescriptive, yet equally vague, theoretical contribution is made by Starik and Rands [65]. They adopt a systems approach to the ecologically sustainable paradigm, defined as the "ability of one or more entities, either individually or collectively, to exist and flourish (either unchanged or in evolved forms) for lengthy time-frames, in such a manner that the existence and flourishing of other collectivities of entities is permitted at related levels and in related systems" [65, p. 910]. Ecologically sustainable organizations (ESOs) are designed by selecting the organizational pattern of structure and process that matches the set of contingencies facing the firm, and developing structures and processes that are internally consistent [15]. In other words, they emphasize how organizations must become one with their environments, instead of being in conflict with it.

B. Integrating Environmental Concerns into Design

With respect to how such policies might influence designers, Starik and Rands [65] provide a few very broad guidelines.

- ESOs will include ecological sustainability considerations and criteria in job design, recruitment and selection, and training and development systems.
- ESOs will design their budgeting and reward systems, communication systems, organizational structures, and decision-making systems in order to empower individuals to engage in sustainability-oriented innovations.
- ESOs will be characterized by numerous cultural artifacts such as slogans, symbols, rituals and stories which serve to articulate and reinforce for their members the importance of ecologically sustainable performance.
- ESOs will adopt marketing and procurement policies emphasizing sustainable products, in part to create and enlarge markets for such products.
- ESOs will work to remove anti-sustainability subsidies, and/or to institute pro-sustainability subsidies.

While this vision of an ideal organization which promotes environmental concerns above other objectives is enlightening, the authors acknowledge that their framework provides relatively little direction in terms of implementing this vision. Allenby [3] also discusses the need to create a "science and engineering of sustainability," while Walker [70] calls for a "holistic approaches to sustainable design." All of these authors recognize the difficulties in creating a mix of financial and nonfinancial incentives to influence designers' sustainability-oriented behavior. They also note the lack of any theory providing guidance on organizational policies that reward compliance versus innovation.

Shrivastava [64] offers a set of more technical recommendations regarding how certain tools can help create more environmentally friendly designs. He notes that a total quality environmental management (TQEM) approach seeks to optimize the ecological performance of the entire corporate system. This includes applying lifecycle analysis (LCA) as a holistic approach to understanding the linkages between an organization and its natural environment. TQEM also encourages energy and natural resource conservation by reducing the use of energy and virgin materials through product redesign, making use of renewable materials, off-setting energy/resource consumption with replenishment, and developing ecologically sensitive purchasing policies and inventory–management systems. In illustrating these policies, Shrivastava [64] cites examples of organizations first mentioned by Makower [46], such as Tetrapak, Herman Miller, The Body Shop, and Loblaws. In effect, the author implies that implementing TQEM tools and techniques can be easily done, and merely requires a restructuring of the organizational policy manual.

C. Studies of the Actual Design Process

Our research and that of other field researchers points to the fact that tools such as lifecycle analysis (LCA), green purchasing, green product redesign, and other tools are not as widely used as these authors suggest. These tools commonly fall into the rubric of DfE tools. Research into DfE falls into one of three categories. The first category of research is case studies describing the success stories of companies recognized for environmentally friendly designs by the press (e.g., [18], [54], [58], [60]). The second category of research offer engineers and managers specific guidelines and advice for integrating environmental concerns into the product design process (e.g., [8], [12], [15], [49]). The third line of research develops and evaluates specific tools to be used when integrating environmental issues into the design process. These tools have two objectives:

1) to identify the true costs and benefits of DfE;
2) to identify the environmental and cost implications of alternative materials or process decisions [2], [28], [37].

This research largely concludes that DfE tools and methodologies are at a very early stage of development. For instance, Klassen and Breis [40, p. 24] concur that “the different lifecycle assessment methodologies under development in North America and Europe are only beginning to reach an initial consensus.” According to Gloria *et al.* [27] the concerns of poor data quality, data availability, high implementation costs, subjectivity, and a lack of standardization have sent tools such as LCA and impact and improvement analysis (IIA) into a state of flux. This is in part because DfE issues are very complex and the research foundation remains weak [27]. Barriers to the deployment of DfE tools span a range of organizational, technical and data issues. Engineers involved in ERM efforts report DfE tools do not exist, design personnel are not evaluated, and environmental aspects are considered on an ad hoc basis [37].

Handfield *et al.* [33] also found that very few companies considered to be “green” (including some of the companies mentioned by Shrivastava [64]) are truly proactive in nature, such that environmental concerns are integrated into everyday design processes. They found that once products are in the manufacturing stage, manufacturing and environmental engineers can do little more than minimize end-of-pipe waste, with a marginal effect on the total waste produced. Moreover, the use of DfE tools is sporadic, and when applied, is often done so as an afterthought and in an *ad hoc* manner. Nevertheless, environmental issues must be considered at the design phase since the amount of waste generated is a direct consequence of decisions made by designers [7], [13], [21], [22]. A lack of appropriate measures and tools for capturing the environmental impact of designs renders DfE a difficult process [2], [28], [44], [69].

On the other hand, recent research in the engineering literature suggests that a number of tools exist that, if implemented properly, can significantly improve the environmental impact of new designs. A recent engineering conference identified potential tools that range from relatively simple checklists/guidelines to more complex software-based decision-making tools [52]. However, another study discovered that the actual use of these tools is limited: 77 out of 81 firms had a corporate environmental program, but of these, only 30% had a corporate program for incorporating environmental concerns into design [43]. Further, only 20% had a formal process of design for the environment. Disturbingly, the researchers noted that designers almost never use environmental databases and design software, and that very few organizations had adopted environmental techniques such as LCA or full cost accounting.

More recently, an engineering conference on environmentally conscious design revealed that, although new tools and databases are being developed, the barriers remain significant and progress changing designers’ attitudes is slow [37], [63]. The greatest obstacle to ERM identified by researchers is the reaction of the designers to these various ERM-driven initiatives. As one team noted in their efforts to deploy a DfE software package, “The key to successful deployment of advanced technology products [DfE] is to have the right technology and to communicate effectively with the users about that technology” [37, p. 119]. Designers must be willing to embrace, accept, and actively use the tools, principles and systems of ERM on a day-to-day basis.

Developing this level of acceptance is not a foregone conclusion, since ERM must compete with other pressures and concerns. For example, with shorter product lifecycles, designers are now under pressure to ensure that their products work right the first time [73]. In addition, designers must produce products that are acceptable to customers (even if this means that less environmentally friendly materials are used). Finally, designers are under pressure to improve quality, reduce cost, and improve flexibility [70]. These strategic concerns are often reflected in the measurement systems used to assess and monitor the performance of designers; unfortunately, environmental measures are typically overlooked [12], [32], [37].

III. Propositions: Integrating Environmental Concerns into the Design Process

A. Disconnect Between Theory and Practice

Clearly, a disconnect exists between what environmental proponents and theorists believe firms are doing in design for the environment, and what designers are reporting. The term DfE means making environmental considerations an integral part of the design of a product, process, and/or technology [2]. The concept of DfE originated from industry’s effort to target specific environmental objectives for design engineers to incorporate when creating a new product. On a broader scale, ERM objectives can only be achieved when environmental issues are identified and resolved during the early stages of product design. Using DfE tools, problems can be identified, and changes made to reduce or eliminate environmental waste [2]. Once decisions are made in the design stage, the environmental effects of these decisions on the product throughout its entire lifecycle are largely fixed [13], [60].

Some anecdotal examples and case studies are provided where DfE has proven to be successful, but these are isolated and limited to a few companies in the electronics industry [24], [37], [45], [54], [62], [63]. In general, manufacturing processes are the greatest generators of environmental waste, yet the greatest opportunity for ERM practices occurs during the design stage. The literature on concurrent engineering

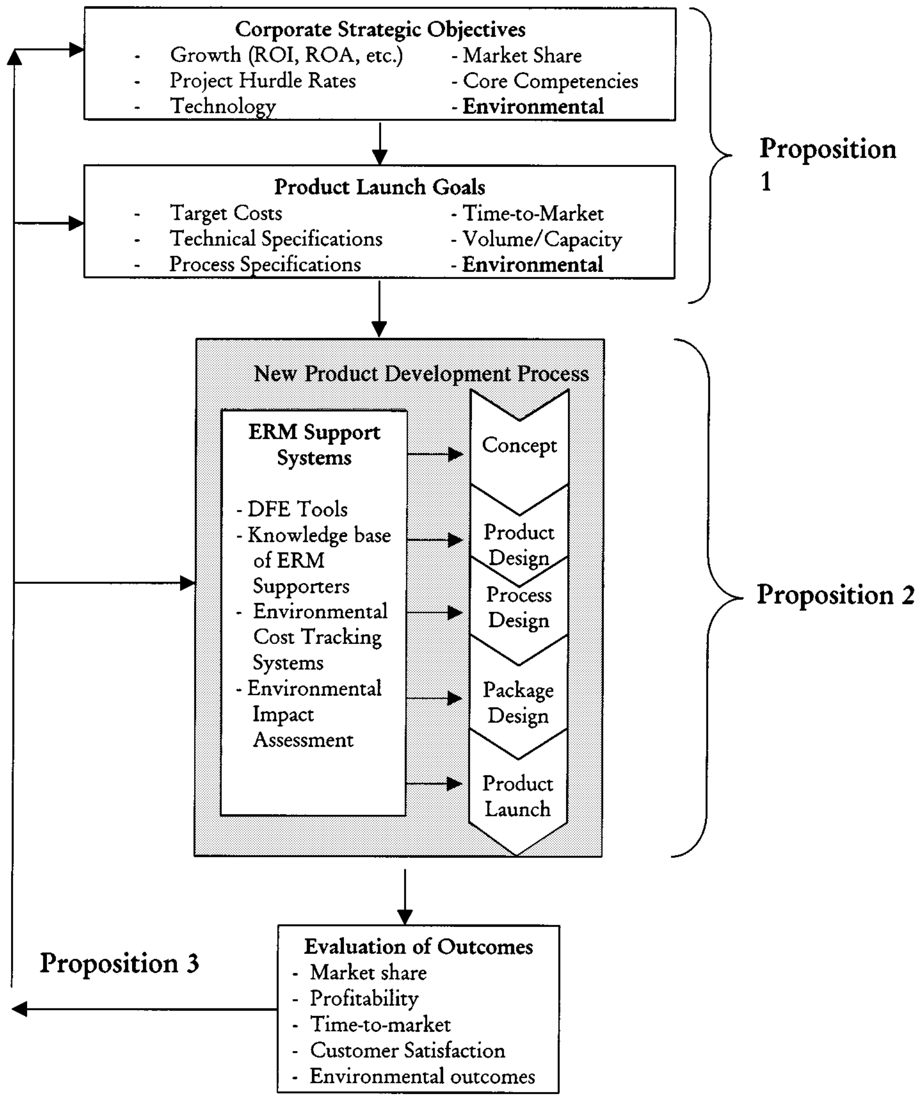

Fig. 1. Conceptual model of environmental role in the design process.

and design for manufacturing (DfM) discusses the working relationships required between process and design engineers at some length [23], [32], [42]. However, the effect of concurrent engineering and DfM on product and process environmental impacts is not explicitly addressed in this body of research.

We know that DfE tools and databases are available, but that designers are generally not using them. Hunt and Auster [36] discuss how a top level management commitment to an environmental program is not enough. To implement real change, managers must calculate the costs of poor environmental management must be calculated, and "sell" the need for good practices throughout the organization. This, in turn, requires a talented manager, and an organization restructured for visibility, accessibility, and effectiveness. As Karandikar *et al.* [37] point out, however, it is difficult to find someone to assume ownership of DfE efforts; in the absence of a corporate strategy, design and manufacturing engineers have not yet stepped up to their responsibility for making environmentally sound decisions.

To better understand the gap between theory and practice, we established a model that integrated an "ideal" set of theoretical relationships between the concepts of corporate ecological sustainability, ERM, and the product design process. This model is shown in Fig. 1, and serves as a starting point for the discussion of several important assumptions and premises regarding environmental design. These assumed theoretical relationships are presented by a set of three propositions that are drawn not only from our definition of ERM, but also from recent academic studies of environmental management and DfE. We then test these propositions based on a set of in-depth interviews with designers and environmental supporters in ten manufacturing organizations.

B. *Proposition 1—Corporate Environmental Objectives*

The ecological sustainability paradigm dictates that ESOs will design their budgeting and reward systems, communication systems, organizational structures, and decision-making systems in order to empower individuals to engage in sustainability-oriented innovations [65]. This view is embodied in the top portion of Fig. 1, which illustrates how environmental objectives are part of the strategic planning process. Corporate environmental objectives are then filtered down to the new product development planning process, where again, one expects to find specific environmental objectives established along with target costs, technical and process specifications, time-to-market, and volume/capacity goals [19], [21], [40].

The integration of product launch goals into the product design process is an important one. If environmental goals are not emphasized at the corporate level and communicated to product launch teams, then the path of least resistance is to simply discount them. Experience has shown that designers are not motivated to reduce waste unless organizational leaders provide the structure, goals, and incentives to do so. When environmental goals are not explicitly translated into product launch goals, the result is a remedial "end-of-pipe" solution. By delaying environmental goals, designers must try to later correct the environmental problems once they have created [33], [38]. This approach is relatively ineffective, because it fails to address the original source of the problem [8], [48]. Rather, it attacks the symptoms and does nothing to eliminate the problems from taking place again.

On the other hand, preventive solutions focus on dissolving problems before they arise [1]. By including environmental goals as a primary input into the design process, designers must recognize potential environmental problems early in the design stage (while it is still on paper). Early design decisions influence process decisions, material and component selection, the lifecycle attributes of the product (its production, use or disposal) [4], [13], [28], [45], [46], [60], [63].

Designers will adopt preventive approaches to environmental problems only when they are motivated to do so by corporate and product goals that specifically establish the need to "design-in" such criteria. In many organizations, there is a tendency to see environmentally responsible manufacturing as something that designers can decide to become involved in or not [15], [25], [64]. A fundamental flaw with this view is that every manufacturing and design decision and action has an impact on the environment. These decisions can be explicit (e.g., redesigning a process that produces less toxic material) or implicit (e.g., selecting a process that generates higher quality in less lead time and at lower costs). When we select that process, at that moment, we have also implicitly accepted the environmental effects attributable to that process.

Proposition 1: In ESOs, designers are driven to explicitly consider environmental design decisions by corporate and new product development (NPD) environmental objectives.

Although it may be viewed as controversial to equate the environment at the same level as other NPD metrics, several organizations have taken this step [46].

C. Proposition 2—Measuring Environmental Impacts

Taking a product design from concept to final product is a complex process involving large number of decisions. As shown in Fig. 1, designers often face a number of competing product launch objectives that have to be met, including the following [20], [23], [32]:

1) Target costs required for market entry;
2) Technical product specifications, including form, fit and function;
3) Process specifications, including process capability, manufacturing tolerances, etc.;
4) Time-to-market goals;
5) Volume and capacity goals.

Introducing environmental goals into the design process increases the degree of complexity by a factor of "n." Environmental targets force designers to confront a large set of possible tradeoffs and interactions with the above five criteria. Too often, the first five goals take precedence over environmental goals, as these have immediately observable effects in terms of profitability, customer requirements, and market share. In ecologically sustainable organizations, however, designers are expected to place at least the same weight on environmental targets as other performance targets. To enable success in this objective, ESOs also create an ERM system that provides support in measuring environmental outcomes and making tradeoff decisions throughout the product development process (see Fig. 1).

As shown in Fig. 1, effective environmentally responsible design processes must focus on the three Ps associated with design decisions after the Concept stage: product, process, and packaging. These involve:

1) product design (specifications, materials, environmental impact, end-of-life disposal/recycling/remanufacturing);
2) process (method of manufacture/assembly);
3) packaging (protective materials used in delivering components to the process or in delivering the product to the customer).

As such, effective ERM systems will ascertain the impact on environmental metrics made by different configurations of the product, process, and packaging design.

People typically associate environmentally responsible manufacturing (or the lack thereof) with the product and its use [18]. Designers often fail to understand the impact of their decisions on process and packaging issues. For instance, product design decisions can have a direct impact on the nature of the support facilities required to produce the product (e.g., tank farms, waste water treatment, etc). In many cases, some of the worst pollution comes from these support facilities.

ESOs employ integrated ERM systems that enable designers to identify the environmental impact of their decisions. ERM systems provide one or more of the followings types of resources to aid designers:

1) DfE tools provide insights regarding how products can be altered (e.g., by using new material) so as to reduce waste [9], [24], [52]. Tools that generate a set of "green scores" essentially quantify the environmental impacts of product design decisions [13], [37], [45], [52].
2) Decision support provided by experts on changing EPA regulations, new market requirements, problem suppliers, and cleaner process technologies enable designers to obtain early warnings of potential environmental problems/solutions [22], [33], [47], [54].
3) Environmental cost databases help assess the impact of design changes on product cost [10], [14], [19], [44], [49].

4) Environmental impact assessment systems containing historical design data and simulation studies provide insights into the lifecycle impact of design decisions. For instance, a set of tools and associated metrics in the electronics industry include [9], [45], [52], [63], [73]:
   - Disassembly/recycling analysis (disposal costs, revenue from recycled or reused parts, and disassembly times and costs);
   - Manufacturability analysis (proximity assessment, manual versus automatic assembly, aspect ratio, manufacturability scores);
   - Process flow analysis (optimization of overall system cost, quality, yield, and time);
   - Other performance tradeoff analysis (impact of technology, material, and design rule variations on the cost and performance of products).

To be effective, ERM systems have to be applied in every stage of product design, from "cradle to grave" [9]. Integrated ERM systems define environmental targets considered by designers along with traditional measures such as functionality, quality, time and cost. Once in production, ERM systems monitor environmental performance through interfaces with manufacturing planning and control systems. Finally, ERM systems should provide guidance on product and process end-of-lifecycles. Without this degree of integration, environmental issues are merely a series of externally imposed checks defining constraints that products and processes to be followed "after the fact."

Regardless of the nature of the manufacturing process found in different industries, integrated ERM systems provide meaningful metrics of environmental performance in product, processes, and packaging to aid designers in making better DfE decisions.

Proposition 2: ESOs have ERM systems that explicitly measure and recognize environmental objectives at major points in the design process; these metrics carry at least the same weight as other design goals (target cost, technical specifications, process specifications, time-to-market, and capacity)

Note that in the above proposition, both objective and subjective elements of the ERM system are relevant. Objective elements are the quantitative metrics of environmental performance provided by the system. Subjective elements are included through weights assigned to metrics determining their alignment with the corporate strategic planning process. Proposition 2 assumes both that objective environmental metrics are in use, and are weighted equally as important as cost, quality, time-to-market, etc.

D. Proposition 3—Measuring Environmental Outcomes

As the previous discussion indicates, no shortage of environmental tools or metrics exists to ascertain the impact of design decisions on product, process, or packaging. However, getting designers to use these tools is another matter altogether. At the root of this problem is a divergent set of perspectives held by two groups within most organizations: environmental supporters versus designers.

A common view held by designers is that the requirements to be environmentally responsible are imposed externally by the government and other similar regulatory bodies [18], [22], [33]. Since these requirements are driven by political and social considerations, it is difficult to justify any investments in ERM other than those dictated by the appropriate regulations. As a result, the only position that a firm can take with ERM is that of strict compliance—doing just what is needed to satisfy the regulations.

This position is echoed in other research by Angell and Klassen [4], who identified three organizational views of the environment:

1) constraint perspective (similar to the position of designers);
2) component perspective (focused on component-level issues);
3) integrated perspective (viewing the system as a whole).

They note that the latter perspective is necessary for improving practice in manufacturing strategy, quality, supply chain management, and technology management.

The "integrated" perspective of environmental management is more likely to be held by the second group of individuals we studied, the environmental supporters. These individuals view ERM as a set of sound business decisions [25], [55]. To enable the transition from a "compliance" view to an "integrated" view, environmental supporters often rely on the skills and motivation of a "policy entrepreneur." A policy entrepreneur is defined as a high-level champion willing to invest time, energy, money, reputation, etc., in the hope of future returns such as environmental policy changes and promotions [16]. In the context of socially responsible purchasing, Drumwright [16] showed that policy entrepreneurs exert both formal and informal power to bring environmental issues to the top of the corporate agenda. Policy entrepreneurs often bring a socially responsible vision into the organization, and then legitimize this vision through their ability to influence the organization's political agenda. This is achieved by translating the impact of ERM decisions into a rational framework familiar to corporate executives: a cost/benefit perspective. By evaluating the true costs and benefits associated with DfE decisions, policy entrepreneurs effectively make the decision to become environmentally responsible an obvious one [5], [19], [66].

Thus, the divergence between environmental supports and designers is resolved by integrating environmental criteria into metrics with direct cost and business implications. As shown in Fig. 1, designers can effectively utilize ERM system data in weighing the environmental cost implications of different design alternatives. In some cases, the resulting design decision may involve investing in a higher level of environmentally related activities than required by regulatory requirements. Examples include AT&T with CFC emissions, the Chemical Manufacturers' Association with "Responsible Care" and 3M with their "Pollution Prevention Pays" program. With a common ERM system linking their frames of reference, designers and environmental supporters would share a common and consistent objective: competitive advantage and corporate profit. While the theoretical model shown in Fig. 1 is appealing, a number of practical obstacles exist in deploying this vision.

Integrating environmental concerns into the design process is similar in many respects to the deployment of concurrent engineering for the first time. It requires the involvement of many people from different parts of the organization. No single person or function can identify all of the problems or issues pertaining to the environment. Instead, ERM involves people from different functional areas to uncover and assess environmental problems and to formulate appropriate solutions to these problems. ERM ultimately affects all of the functional areas of a business enterprise [40], [57], [72]. Participation is required from

- engineering (product, process/manufacturing and industrial);
- marketing (to assess market/customer response and demands);
- manufacturing;
- cost accounting (to assess the full costs of environmental problems);
- facilities/environmental engineering (to carry out cost estimates and to forward these estimates to cost accounting and finance);
- industrial facilities management (where to store waste);
- human resources (staffing and training);
- purchasing (acquisition and disposal of waste);
- legal (to assess the legal implications of new regulations and actions);
- support from middle and top management (to assess the strategic impacts of environmental performance) [5], [36], [68].

Having a separate and distinct department for environmental matters creates problems, because it makes it easy to "pigeonhole" environmental issues and ignore them. As shown in Fig. 1, however, an integrated ERM system enables cross-functional evaluation of environmental metrics being considered alongside other business outcomes such as market share, profitability, time-to-market, and customer satisfaction. The enabling role of ERM systems and metrics in ecologically sustainable organizations is captured in our final proposition.

Proposition 3: ESOs successfully integrate environmental issues into the design process by measuring environmental outcomes and integrating them into the strategic planning process. These outcomes form the basis for strategy and designer performance evaluation.

This proposition has been echoed before in prior research (e.g., [36], [61]). The research methodology used to develop the data and explore these propositions is described next.

IV. Research Methodology

Comparative literature reviews of research on environmental management confirm that DfE deployment is at an early stage of development [4], [12], [38], [39], [56], [67]. A key objective of our study was to develop insights into the critical success factors for integrating environmental issues into the design process. In instances where there does not exist a well-developed set of theories regarding a particular branch of knowledge, Eisenhardt [17] suggests theory building through case study research. Field-based data collection methods ensure that the important variables were identified. A case-based analysis involves defining the question, selecting cases, crafting instruments and protocols, analyzing data, shaping hypotheses, enfolding the literature and reaching closure using an intentionally small group of research sites.

A pitfall of qualitative case analysis is that theories are not parsimonious, or become entangled in the idiosyncratic details [17]. Further, it is difficult to draw deterministic inferences, and limitations in terms of the external validity of the study exist. These limitations are typically addressed in follow-up large sample studies or "before" and "after" quasi-experimental designs [11].

In the early stages of research, Eisenhardt [17] recommends developing a set of initial research questions that posit linkages between proposed key constructs. The research questions should also be related to a conceptual model for crafting research instruments and interview protocols [51]. In Fig. 1, we developed a set of relationships between the related areas of corporate strategic objectives, product launch goals, product development processes, and the evaluation of outcomes (summarized in Propositions 1, 2, and 3). While causality can never be shown in case studies, analysis of data collected from multiple sites help support the generalizability of the results.

The researchers relied primarily on the methods of qualitative data analysis developed by Miles and Huberman [51]. The approach consisted of anticipatory conceptual model development and simultaneous data collection, reduction, display, and conclusion testing. We visited multiple research sites to provide a broader taxonomy of environmental design strategies. A qualitative approach based on extensive interviews helped the researchers to envision the processes and barriers of integrating design and environmental objectives. Because this process is not well understood, and because many of the terms associated with this process and its goals are subject to confusion, a qualitative approach was better suited as compared to alternative quantitative approaches such as surveys [29], [51].

The approach consisted of five stages:

1) questionnaire design and testing;
2) identification of the sample;
3) identification of the respondents;
4) administration of the questionnaire;
5) analysis of the data.

A. Questionnaire Design and Testing

We designed the questionnaire around the three primary propositions discussed earlier. A copy of the questionnaire is shown in the Appendix. Eisenhardt [17] suggests that researchers develop a detailed interview protocol before visiting sites, and proceed with simultaneous data collection and analysis. Qualitative theory building is an iterative process involving data collection and analysis at one site followed by multiple replications [17], [51], [73]. Important issues raised in early cases are included in the protocol in subsequent replications. This ability to refine and improve the protocol between cases is a significant advantage of this type of research. The updating of the protocol after each visit is a foundation of grounded theory development [26].

We first developed a questionnaire designed to be used in telephone interviews. Related questions included the following:

1) background of the individual (length of time with the company, current and past responsibilities, description of the respondent's current position);
2) level of and predisposition of the respondent to environmental issues;
3) description of the current product design process;
4) the position of ERM in the current design process (how it was integrated, at what stages, who was involved, how long these changes had been in effect);
5) assessment of the current success of integrating ERM into the product design process;
6) identification of current obstacles and problems.

The questionnaire consisted of a mixture of open- and closed-ended questions. Due to concerns over the confounding influence of social desirability[1] (e.g., [6], [50]), we decided to use indirect questioning (i.e., "How would people within your department view the role of environmental concerns on the time it takes to design a new product?"). A panel of subject matter experts (in the areas of ERM, product design and questionnaire design) then evaluated the questionnaire for clarity and completeness. This panel included members of both the academic community (in the case of product design and questionnaire design issues) and the practitioner community (primarily for ERM-related issues).

We administered the questionnaire via a three-step process. In the first step, we faxed the questionnaire to the respondents (to allow the individual sufficient time in which to prepare their responses). Next, we gathered responses to the questions during a telephone interview. Finally, a series of open-ended questions were administered to the respondent at the conclusion of the telephone interview. These questions gathered information on the effectiveness of the ERM integration process and areas of future research.

B. Sample Identification

The sample for the study included a targeted population of organizations and individuals within those organizations. As Miles and Huberman point out, "Sampling involves not only decisions about which people to observe or interview, but also about settings, events, and social processes.... The conceptual framework and research questions determine the foci and boundaries within which samples are selected" [51, p. 37]. Bearing this advice in mind, the researchers initially set out to find a set of organizations that had experienced the process of integrating environmental concerns in the design process. Specifically, we sought to study design activities within firms identified as being advanced or "leading edge" adopters of environmental principles and practices within the product design process. Although this made sense, we soon discovered that this population is rather small, and spanned multiple industries. Moreover, very few organizations have made significant in-roads into successful design for the environment approaches. Ten organizations deemed to be "leading edge" were discovered by applying two or more of the following selection criteria.

- Mentioned in at least two cases as a "best practice" example in the environmental management literature (see [9], [28], [33], [35], [36], [41], [46], [60], [64]).
- Listed on the "Who Scores Best on the Environment" report in Fortune magazine [58].
- Identified as "leading-edge" in a Delphi study involving managers from General Motors, Ford, and the Defense Logistics Center[2]. These managers are members of the Manufacturing Research Consortium (MRC) at Michigan State University, East Lansing, MI, and are part of a group involved in a three-year project, jointly managed by the Colleges of Business and Engineering at Michigan State University, and supported actively by the project's three industry partners. This group is engaged in an NSF-funded study of how environmental issues are being integrated in product design planning and manufacturing[3]. These managers were also helpful in pre-testing the questionnaire.
- Was mentioned on more than one occasion by environmental experts and consultants interviewed during the course of the study.[4]

In this manner, a form of snowball or chain sampling was built into the questionnaire design [51]. Snowball sampling seeks to identify cases of interest from "people who know what cases are information rich" [51, p. 28]. At the end of each questionnaire interview, we asked respondents if they knew of any other firms considered to be advanced ERM users or successful in integrating environmental concerns into the design process. This question furthered the research in two ways. First, we determined the extent to which the sample was adequate. Second, we identified firms that may have been overlooked in our initial sampling plan.

We decided to focus our research on leading-edge companies for several reasons. First, by picking advanced adopters of

[1]Societal desirability describes a situation where, because of strong social values attached to certain actions, the respondents will alter their answers so that the results are socially correct, rather than being factual. Being environmentally responsible is a topic that falls into this category of social desirability.

[2]The managers present at this meeting included R. Williams, Principal Research Scientist at General Motors; W. Francis, Design Engineer at the Ford Motor Company; B. Bryant, Environmental Manager at the Ford Motor Company; P. Lawrence, Design Engineer at the Ford Motor Company; and R. Sroufe, Environmental Specialist at the Defense Logistics Center. D. Young, Purchasing Agent at the Ford Motor Company, was also consulted in framing this issue.

[3]This research project is NSF ORD#64852, "Environmentally Conscious Manufacturing: Integrating Environmental Issues into Product Design Planning, and Manufacturing." Principal Investigators: R. Lal Tummala (Engineering), S. Melnyk (Management), R. Calantone (Marketing), R. Handfield (Management), E. Goodman (Engineering), and K. Helferich (Materials and Logistics Management Program Director). Note that this study focuses on the manufacturing/design interface, but does not address supply chain issues.

[4]We began with the Industry Executive Assessment Team described in Footnote 2, who recommended certain "experts" in the field, which included both managers and consultants. We only accepted someone as a consultant when 1) they had shown that they had a knowledge of the field (this was ascertained through telephone interviews); 2) they had written about topics pertinent to the field; and, 3) they indicated that they would be willing to help in securing access to other firms. These experts were interviewed, and pointed to firms that we should include in the study. However, we only included a firm if at least three of the people involved had identified that firm as being worthy of study and had provided a "good" foundation based on its actions that would justify the inclusion of the firm in the sample.

TABLE I
COMPANY PROFILES

Company	1998 Sales (Million $)	Location	Criteria Used to Include in Sample				
			1. Mentioned in Literature	2. Fortune (1993) [49]	3. Expert Opinion	4. Delphi Study	5. "Snowball Sample"
Automotive 1	145, 348	Detroit, MI	X	X	X	X	
Automotive 2	178,174	Detroit, MI	X		X	X	X
Automotive 3	145,348	Detroit, MI	X	X	X	X	
Office Furniture 1	1,702	Zeeland, MI	X	X	X	X	X
Office Furniture 2	2,760	Grand Rapids, MI	X		X		X
Office Furniture 3	1,320	Holland, MI	X		X		X
Computers 1	31,169	Boston, MA	X	X	X	X	X
Computers 2	78,705	Somerset, NY	*X*	X		X	X
Pharmaceutical 1	6,893	Kalamazoo, MI			X		X
Pharmaceutical 2	6,599	Deerfield, IL	X	X	X		X
Consumer Products	30,147	Trenton, NJ	X	X	X	X	X

ERM-principles, we would interview people who had already attempted to integrate environmental metrics and policies into the design process. Each organization approached had already been through the process of establishing an environmental vision and emphasizing its importance, and had made initial attempts adopt metrics and policies into their design process. In addition, we could approach designers (who were in some cases forced to change their design procedures) and explore their perceptions regarding the impact of environmental concerns on the overall design process. Furthermore, by limiting our attention to advanced users, we would be dealing with firms and people who were actually designing products that incorporated environmental concerns. That is, these companies had attempted to implement some of the specific tools that quantified the associated environmental impacts of different design decisions. We also limited our attention to the product design process rather than process design. This was done because of feedback received during initial stages of this study (from experts and people knowledgeable in the ERM area) that the product design process was both better organized in most firms and a focal point of attention for many firms' ERM activities. For example, Ford, as part of its Ford 2000 program, announced that it will design cars which are more environmentally friendly.

Through this process we identified ten firms spanning the following industries: office furniture (3); automotive and automotive suppliers (3); computers (2); prescription drugs (1); and, consumer products (1). Although in diverse industries, these organizations have a common link: they have all made significant in-roads into improving their design process to include environmental concerns. By selecting a sample using a variety of independent selection criteria in a relatively small population, it is reasonable to believe that the sample is not biased in nature. Table I provides a brief profile of these ten organizations, including their 1998 sales, location, and the related selection criteria.

C. *Identification of Respondents*

Having identified the sample firms, we next proceeded with the task of identifying two groups of respondents from each firm (with the unit of analysis being the design process). Our intent was to identify at least one ERM supporter/champion and at least one designer actively involved in the product design process and who had used some DfE tools (e.g., lifecycle assessment, product check sheets). An ERM supporter is any person charged with the task of supporting ERM activities and encouraging the acceptance and use of ERM tools, systems and perspectives. Supporters were in some cases identified by designers because of their championing of ERM issues during strategic planning meetings [16]. We identified ERM supporters through their:

1) departmental identification (e.g., belonged to a group such as Employee Safety and Environmental Affairs);
2) job description (e.g., job title was head of the environmental affairs department or facilities engineering or management group);

3) user identification (e.g., a designer or manager within the organization identified the "resident expert" on environmental issues).

Some of the job titles associated with these individuals included: "Environmental Manager," "Environmental Specialist," "Manager of Corporate Environmental, Health, and Safety," "Director of Facilities Management," or "Director of Environmental Compliance and Safety."

The second group of interviewees consisted of designers with experience in DfE tools in product design or packaging design. We identified at least one ERM supporter and one designer in every firm. If a targeted respondent decided not to participate, they were asked to identify a replacement.

D. Administering the Questionnaire

We administered the questionnaires over a speaker phone using a two-person interviewing team. In each case, one of the researchers posed the questions and led the discussion while the other recorded the data and developed follow-up questions to clarify unclear responses. The interviews with each individual took place separately.

E. Analysis of the Data

The data analysis included both within-case and between-case analysis. Within-case analysis examined design issues in a single context, while across-case analysis served as a form of replication to test the constructs of interest in different settings [73]. Several actions were taken to control for the affects of the researchers' *a priori* beliefs regarding why ERM issues were or were not embraced. First, the primary researcher wrote up the interview notes prior to coding. The secondary researcher, who was also present for the interview, reviewed these notes. Finally, a third researcher reviewed the notes. The group of researchers then met and reviewed the notes together to ensure that responses were not misinterpreted.

Miles and Huberman [51] note that the acts of coding and data reduction are actually forms of data analysis. In other words, the act of coding could lead to confirmation bias problems in future cases. Therefore, we limited coding for within case analysis to categorizing the individual case on previously identified constructs and identifying interesting new issues to pursue at future interviews. This method helped in opening the research to alternative explanations raised in future replications, by avoiding comparisons and model building early in the research.

Between-case analysis consisted of looking for patterns of firms' experiences with ERM issues in the product design process across leading edge organizations. To reduce the amount of data and to display the data in a meaningful fashion [51], [73], we formed a number of categories based on the research propositions. The concepts that interviewees identified as being related to ERM were also compiled (i.e., focus on measurement). Through a process of combination, renaming, and redefining, the responses were refined to reflect the most frequently noted reasons for ERM.

All responses were reviewed and analyzed using a simple form of content analysis. The goal was to identify similarities and differences either externally (e.g., between designers working at different companies) and internally (e.g., between designers and ERM supporters). We analyzed responses to identify major concerns and obstacles affecting the implementation of ERM systems and tools.

V. Summary of Findings

To simplify the presentation of the findings, they will be summarized by proposition. The propositions derived from the environmental literature are repeated as a "Theory" statement, then immediately followed by a statement of "Practice," (reflecting the findings from our ten case studies.) The gap between theory and practice is then discussed in more detail. Tables II and III augment this discussion and summarize the major company responses to each set of propositions.

A. Proposition 1

1) Theory: In ESOs, designers are driven to explicitly consider environmental design decisions by corporate and new product development (NPD) environmental objectives.

2) Practice: Integration of environmental issues into the design process is primarily limited to the use of checkpoints and exit requirements.

In describing their product design processes, nearly all of the designers described a process that was sequential and linear in structure. That is, they began with product concept and proceeded through a number of stages (typically four or five, as shown in Fig. 1). While cross-functional groups were present at each stage, the ERM supporters played a limited role. The first column of Table II describes the primary approach used to integrate environmental criteria into the design decision at each organization.

The responses in this column are a far cry from the "environmentally aware organizations" described in the press. Although top management in these corporations often had a formal environmental policy for shareholders and the public, the impact of this policy on product launch objectives was limited. The role of ERM was limited to company education and awareness programs. ERM supporters served as "consultants" to make designers aware of the cost and benefits of ERM. They also tried to inform designers about the different classes of materials (i.e., materials not to be used at all because of environmental problems, materials which should be avoided whenever possible). For instance, Automotive 2 developed a published document, (that unfortunately was not effectively used by designers), while Office Furniture 1 offered training in lifecycle analysis and DfE tools. Too often, however, no formal process existed to ensure that top management environmental directives were disseminated at the product launch level. In four of the ESOs identified as "best-in-class," no formal measurement of environmental criteria even existed in the design goals.

In some of the firms, ERM supporters influenced exit requirements encountered at the end of each stage in the product design process. As a product design finishes with one stage, it often must pass a checkpoint. At this checkpoint, the design is subjected to an evaluation (typically using "yes/no" questions). Issues raised at this checkpoint must be addressed and resolved before the design is allowed to proceed to the next step. It is

TABLE II
RESPONSES TO INTERVIEWS—PROPOSITIONS 1 AND 2

Company	Proposition 1: Designers explicitly consider environmental design decisions.	Proposition 2: ERM systems explicitly measure and recognize environmental objectives at major points in the design process.	Proposition 2: Environmental criteria carry as much weight as other criteria. (D=Designer, S = Environmental Supporter)
Automotive 1	❑ Alternative materials introduced at product concept stage. ❑ Major assessments are done in the plastics area (LCA), emissions, and climate control (cooling products, hoses, lubricants, antifreeze, etc.), but many areas have no explicit environmental objectives.	❑ Smaller, lighter components ❑ Source reduction (solvents, soldering, adhesives) ❑ Emissions ❑ Dollar value of EPA fines compared to other major automotive manufacturers	❑ D: "It is tougher and tougher to find the low-hanging fruit, in terms of environ mental initiatives which also save money. CFC elimination saved a lot of money. There are not many other areas left." ❑ S: "We are making progress. Top management has emphasized that the environment is important, but to date, it's been a lot of "fluff"".
Automotive 2	❑ The division developed a joint published document that outlines specific environmental concerns for design and development. No one is aware of the impact of this document, nor how it is being used.	❑ Environmental issues defined largely as a "checklist" of issues that must be reviewed – no verification occurs. ❑ Focus on reducing significant fines and remediation costs associated with VOC's, hazardous waste, etc.	❑ D: "It is difficult to substitute materials once the vehicle is in production." ❑ S: "My input (environmental engineer) into decisions is limited to the plant level, since most decisions are made at the design stage. Basically, I am asked to help only when there is a problem."
Automotive 3	❑ Primary issues include disassembly of plastic parts, but is often superseded by customer requirements. ❑ Marketing emphasizes that customers do not want used parts in their new vehicles.	❑ Scrap reduction ❑ Recycling of metal and copper, leads, brass, etc.	❑ D: "Any time you have to meet a government regulation after innovation stage, it costs too much money. It is difficult to make disassembly easier, as such issues are superseded by manufacturability, reliability, and avoidance of liability." ❑ S: "We have used QFD tools to integrate environmental concerns in the past - the question is, can we integrate future regulations into current innovations?"
Office Furniture 1	❑ Company has a history of top management support for the environment. ❑ Some training in LCA and DfE tools has taken place. However, the software and data requirements for these tools are not readily available and provide an additional level of complexity. Consequently, tools are not used."	❑ Pounds of waste recycled ❑ Reduction in tons of waste dumped ❑ Amount of energy co-generated ❑ Some initial attempts to translate above measures into cost savings measure	❑ D: "LCA is great in theory, but horrible in practice. I took a seminar on it, but have never used it in design. I simply have too many other issues to deal with on a day-to-day basis." ❑ S: "We have integrated environmental criteria into all of our processes."
Office Furniture 2	❑ When new projects begin, the environmental department leads the teams through a discussion of environmental issues. No answers are supplied; they just discuss the concerns. The design team must	❑ Pounds of waste recycled ❑ Reduction in tons of waste dumped ❑ Amount of formaldehyde and ODS in products	❑ D: "Whenever possible, we will try to meet the environmental supporters' requests to use appropriate types of wood and reduce weight. We do not pay a lot of attention to anything else." ❑ S: "Designers do their best to do what is

here that environmental issues are most often formally found. As long as the design does not violate an environmental regulation, the design passes the checkpoint.

Because of its placement at checkpoints (after certain decisions had been made), designers viewed environmental issues as constraints; they had to pass these minimum requirements before proceeding to the next stage. Angell and Klassen [4] encountered this view as well in their managerial interviews. None of the designers viewed ERM as an opportunity (i.e., a positive) when viewed within the context of a specific design. However, some mentioned that on occasion environmental issues represented an opportunity for being more creative.

TABLE II (*Continued.*)
RESPONSES TO INTERVIEWS—PROPOSITIONS 1 AND 2

	find a solution. The designer is not told what he or she can or cannot use(no formalized check list).		right for the environment."
Office Furniture 3	❑ Environmental staff leads and serves as consultants to design and other departments. ❑ The environmental function has created a white paper to guide the design staff in environmental concerns in design. No formal assessment of its impact.	❑ Pounds of waste recycled ❑ Reduction in tons of waste dumped ❑ Amount of energy co-generated	❑ D: "Our design teams are cross-functional and have ownership of manufacturing, product quality and environmental quality in processes, design and customer expectations. However, the environment is often the last concern." ❑ S: "We are as good as anyone in the industry."
Computers 1	❑ Environmental criteria are not objectively measured during design, so little effect is evident.	❑ Production waste (volume of water used) ❑ Use of material that are recyclable. ❑ Use of recycled materials in new products.	❑ D: "The 'tyranny of the product launch' dictates that cost, cycle time, quality, and functionality are the primary objectives. The environment is a residual objective." ❑ S: "We talk a pretty good game, but don't do much about the environment."
Computers 2	❑ Environmental criteria are not objectively measured during design, so little effect is evident.	❑ Production waste (volume of water used) ❑ Use of material that are recyclable. ❑ Use of recycled materials in new products.	❑ D: "If you can't objectively define and measure environmental criteria, how do you expect me to improve it?" ❑ S: "If I help designers do a good job in designing an environmentally responsible product, who will know or care."
Pharmaceutical 1	❑ Primary tasks are to design products and schedule production – designers measured on environmental outcomes "after the fact".	❑ Tons of waste dumped in landfills	❑ D: "Because of the FDA and EPA, government auditors won't let us make a mistake." ❑ S: "Everyone knows that the regulations must be met."
Pharmaceutical 2	❑ Highly regulated industry means that as long as the EPA is happy, you are doing a good job.	❑ Tons of waste dumped in landfills ❑ Some metrics used for publicity purposes, but actual calculation of metrics were not revealed.	❑ D: "We recognize that we need to go from end of pipe to a process orientation." ❑ S: "Many of the chemicals being disposed of can still be used. We are not taking advantage of this opportunity."
Consumer Products	❑ Designers given feedback on product compliance with EPA regulations once product has been produced.	❑ Process waste generated to water, air, and landfill	❑ D: "There are few tools to link the impact of design decisions on waste output." ❑ S: "We recognize that lower waste will result in lower priced products and good public exposure."

An interesting feature of the typical design process was its strong sequential structure. That is, once designers completed and passed the exit requirements for a stage, they did not want to revisit decisions made in that stage. If an ERM supporter identified a problem that required a designer to revisit a previous stage, the typical response was to note it down and to remedy the situation in the next product design revision. Unfortunately, such "post-mortem notes" were often misplaced and were rarely acted upon. While the ERM supporters recognized the appropriateness of an iterative approach to product design, the designers did not want to deal with such a process. Designers often noted that the use of cross-functional teams made it difficult to reach a consensus at each step in the design process. With an iterative process, team member agreements would have to be reforged—something that the designers were not excited about doing.

B. Proposition 2

1) Theory: ESOs have ERM systems that explicitly measure and recognize environmental objectives at major points in the design process; these metrics carry at least the same weight as

TABLE III
COMPANY RESPONSES TO PROPOSITION 3

Company	P3: ESOs successfully integrate environmental issues into the design process by measuring environmental outcomes and integrating them into the strategic planning process	
	Representative Comments from Environmental Supporters:	**Representative Comments from Designers:**
Automotive 1	❑ "Conventional metrics are used to measure environmental criteria, including cost, cycle time, cost performance (5 M's), as well as all emissions, solid waste, etc. - however, these are not tied into individual products. This makes it difficult to justify at the design stage." ❑ "Vehicles last longer today than they ever have before. Technology is changing so quickly that cars quickly become obsolete - the useful life of the vehicle far outlasts their actual product life cycle."	❑ "Customers will not reward you if you are environmentally friendly, but will punish you if you are not." ❑ "How do I measure whether a product is green or not?"
Automotive 2	❑ "Our corporate office is not effective in helping our cause - they often ask the environmental engineer to provide reports, but never provide help with problem solving." ❑ "Environmental input involves looking for compliance with environmental laws, as there is little support from top management."	❑ "The environmental manager's nickname at the plant level is "Mother Nature", and she is typically viewed as a 'cop'." ❑ "We only meet with her when there is a problem. There is also little support, since resource generation is just not important in the secondary markets."
Automotive 3	❑ "Manufacturing does not look beyond the customer's front door, which is where we deliver the product. There are no easy methods in design. Designers should be concerned with end of life, but these responsibilities are not designed in. Reliability and durability can no longer be associated with the length of a car's useful life, because of changes in technology."	❑ "Time is the biggest enemy. If I was left alone, I could design a product to meet specifications which is also environmentally responsible. Unfortunately, I have a final design deadline in the new product development cycle. Between now and that deadline, a vice president will walk in the door and say the headlights are "frowning"! That will require a whole new redesign, and environmental considerations will be thrown out the window. What started as a design with 80% regrinds will become a product using 100% virgin plastic."
Office Furniture 1	❑ "There are tradeoffs between functionality and environmental criteria. For example, customers want a kidney shaped tables, which results in more wood scrap than a square table."	❑ "The environment is a fad. It will go away like everything else, and we'll be able to spend more time on other things."
Office Furniture 2	❑ "If we identify an environmental opportunity, it is typically put aside because changing the design will delay the product launch. The response is, maybe we'll look at it in the next product revision."	❑ "As long as we are not violating EPA requirements, environmental issues are not relevant."
Office Furniture 3	❑ "Environmental problems are viewed as the responsibility of the environmental management group. That is why they are there. Designers view their job as designing products, not worrying about the environment."	❑ "If I design a product that is environmentally responsible but costs more, I get penalized. If I bring costs down but reduce environmental performance, I am rewarded."
Computers 1	❑ "The result of poor decisions in design is higher environmental costs. However, once you assign environmental costs to overhead, it disappears! Overhead includes all costs that we cannot assign responsibility for."	❑ "We are unable to boil down environmental performance to a number."

other design goals (target cost, technical specifications, process specifications, time-to-market, and capacity).

2) Practice: The primary measures of ERM-related activities are material-related; these criteria carry considerably less weight than cost and time-to-market.

As pointed out by Melnyk and Smith [48], the goal of making products more environmentally responsible can be achieved by focusing on the material used in a product, the processes used to make these products and the interactions between material and process. In our study, we focused primarily on product design and the materials selected. As illustrated by measures and definitions shown in the second column of Table II, supporters urged designers to select and use environmentally friendly materials (i.e., incorporating remanufactured or recycled content).

TABLE III (*Continued.*)
COMPANY RESPONSES TO PROPOSITION 3

Computers 2	❑ "Environmental issues are a constraint, not an opportunity."	❑ "The only time we check with the environmental group is at major checkpoints in the design process. They are only involved at each checkpoint to tell us if we are doing anything that is not legal. Once they provide us with this information, we modify the design subject to those constraints."
Pharmaceutical 1	❑ "We are dumping good chemicals, and need to change the process."	❑ "Government auditors are present at every stage of our process. The entire process must be documented in detail to meet their requirements. Any changes in the process are time consuming and expensive, since the process must then be re-certified by the government again."
Pharmaceutical 2	❑ Before environmental considerations become important to designers, we need to work on education, develop awareness, and sell the benefits."	❑ "The actual metrics we are using to demonstrate to the public our environmental performance are actually rather 'flaky'. They are not what they seem to be. What we do and what we report to the public are not the same thing."
Consumer Products	❑ "The time from when a product is designed and the time it is produced is too long to be able to effectively link problems and causes. There is no feedback between the design and execution systems. We do not know if high environmental waste is due to design, human error, scheduling, or other factors."	❑ "We recognize that decisions made in design cause shop floor problems. However, we are unable to identify changes in the product design and resulting process that would improve environmental performance."

The most common tactic used was substitution (i.e., the replacement of a less environmentally friendly material by one that was more environmentally friendly).

To help the designers identify potential ERM-related problems, ERM supporters focused their activities on publishing and distributing various lists of materials. These lists included materials that were not to be used under any circumstances, substitutes for these materials, and lists of materials that should be avoided when possible. In addition, ERM supporters tried to educate designers about the various categories of materials and available alternatives.

When focusing on materials, the ERM supporters tried to help the designers become aware of material choice issues when dealing with all items and at the lowest levels in the bill of materials. However, almost all of the measures shown in Table II are "output related." That is, they represent measures at the end of pipe, and designers were often unable to link their decisions with these final measures. Examples of some of these measures include emissions, value of fines levied by the EPA, hazardous waste generated, pounds of waste dumped, etc. Designers primarily employed end-of-pipe due to another gap identified in the study: Conventional DfE tools are poorly understood and rarely used.

One of the questions asked focused on the extent to which designers were familiar with such DfE-oriented tools as lifecycle analysis, risk assessment, and the AT&T environmental rating matrix [28]. A second follow-on question focused on the extent to which the designers used these tools when designing products. While many designers recognized one or more of the tools, none expressed comfort with or confidence in their ability to effectively and correctly use these tools. As shown in the third column of Table II, several reasons were cited. The first was that the designers felt that their commitment to ERM was limited to intent or desire. While designers all recognized that it was important to avoid using hazardous materials whenever possible, these "low-hanging fruit" (Automotive 1) were viewed as the only major opportunity to be environmentally friendly. Second, many designers had difficulty in either understanding or in applying the tools to their tasks. For instance, the designer at Automotive 3 felt that QFD was too complicated to use with government regulations, while the designer at Office Furniture 1 felt that lifecycle analysis was "great in theory but horrible in practice." In some cases, the tools served to only muddy the waters even further. One designer described the following dilemma:

You have two ways of building a part. One option is based on metal. Metal is heavy (thus, it consumes more resources). It also creates waste during the actual manufacturing process (in form of sludge). However, it can be recycled when it reaches the end of its product life. In contrast, we make the product out of graphite. This part is lighter (which means it uses less energy in use). In addition, it can be molded rather than machined (again resulting in less waste). However, when it reaches the end of its life, it must be disposed of in a land fill since it cannot be recycled. Which of these two options results in the greener product?

Designers perceived such tradeoffs as a major barrier to becoming environmentally friendly. In general, designers felt that the tools were too difficult to use, too time-consuming, and that their outputs did not justify the costs in terms of time and effort. Not surprisingly, environmental supporters at these companies felt frustrated by their efforts to prioritize environmental criteria. The limitations of existing ERM systems to measure and evaluate environmental criteria effectively meant that setting objectives was very problematic. Many of the designers felt that the tools distracted them from their major task—that of designing products. When "push came to shove," environmental criteria were all too often superseded by the "tyranny of the product launch, where cost, cycle time, quality, and functionality are primary objectives, and the environment is a residual objective" (Computers 1).

C. Proposition 3

1) Theory: ESOs successfully integrate environmental issues into the design process by measuring environmental outcomes and integrating them into the strategic planning process; these outcomes form the basis for strategy and designer performance evaluation.

2) Practice: ERM activities are evaluated primarily in terms of recyclability. Environmental performance is often the least important criteria in evaluating the success of the product launch.

As Hall [31] has pointed out, designers interested in designing environmentally responsible products have a large number of options available to them. The most important of these options include:

- redesign;
- substitution;
- reducing material use;
- recycling;
- rebuilding;
- remanufacturing;
- reuse;
- internal consumption;
- waste segregation;
- spreading of risk.

However, the most commonly identified outcome measure of performance we discovered in our sample was recyclability and material substitution[5]. The reason cited for this orientation was that it was the only criteria under the direct control of the designer. Recyclability was also frequently measured and publicly reported (especially in the case of the auto-related designers). Finally, it was the only measure on which both the designers and ERM supporters could agree.

While theoretical statements in the ESO literature suggests that designers and supporters work closely together to design products that have a minimal impact on the environment, we found that a large gap separates these two groups. The nature of this gap is manifested in designer evaluation systems. When the researchers began the study, they expected some degree of agreement to exist between the views and positions of the ERM supporters and the product designers. After all, we were dealing with firms that had experience in the integration of environmental issues into the design process. However, this initial position was not supported by the interviews.

ERM supporters shared a very similar view of ERM and product design. The comments from these supporters shown in Table III indicate that they believed that everyone was basically favorably disposed to being environmentally responsible. If people were not, it was because:

1) they had not been adequately informed and educated about ERM;
2) the designers were not aware of the true costs and benefits associated with ERM-related actions;
3) the designers had not been given the right measures pertaining to ERM;
4) the designers lacked access to the "right" set of tools for making ERM-related decisions.

As a result, ERM supporters had a common agenda.

1) Educate users about ERM.
2) Document and communicate costs and benefits associated with ERM actions.
3) Develop better ERM-related metrics.
4) Promote the use of existing tools and develop new tools.

The comments in Table III suggest that designers had a very different view of the design process than supporters. Many designers, while recognizing the need to become more environmentally responsible, had some misgivings about the ultimate effectiveness of their attempts to incorporate environmental concerns into product designs. In most cases, designing environmentally friendly products had no rewards associated with the activity, but plenty of pitfalls. Several reasons were cited for this gap.

- Some designers saw ERM as a marketing fad bound to become less important in the future.
- Several designers faced tradeoffs between environmental concerns and marketing priorities, which were always resolved in favor of the latter. For example, a furniture designer described his problems in designing a desk that was ergonomic and attractive to the customer. Square or rectangular desks typically resulted in the lowest amount of wood scrap. However, marketing informed product design that customers wanted ergonomic kidney-shaped designs. Kidney-shaped desks required that the wood tops be cut round, resulting in more wood scrap. Such a design, thus, ran counter to the avowed environmental goals of the firm. In the end, customers who were willing to pay for kidney-shaped desks won the battle.
- The designers saw their primary job as one of designing products (ERM was not part of their job descriptions, and was the job of the environmental manager).
- Designing environmentally responsible products would adversely affect corporate performance as measured in terms of cost, lead time, quality and flexibility.
- The designers were not measured on their ability to design environmentally responsible products, but rather on their ability to design new products with certain cost, quality, and lead time parameters ("If I do a good job in designing an environmentally responsible product, who will know or care?").
- Designing environmentally responsible products was time-consuming and required additional work.
- The designers were not comfortable with the ERM tools. Some expressed concern that the tools required them to learn new approaches and software systems that were not currently available. They simply did not have the time to go through this training.

The resulting gap between the designers and the ERM supporters is important because we see how it led to frustration and friction between the two groups, (since each group seemed to

[5]Another important metric used in the automotive industry is engine emissions. However, engines were not the focus of the product design decisions discussed within these organizations.

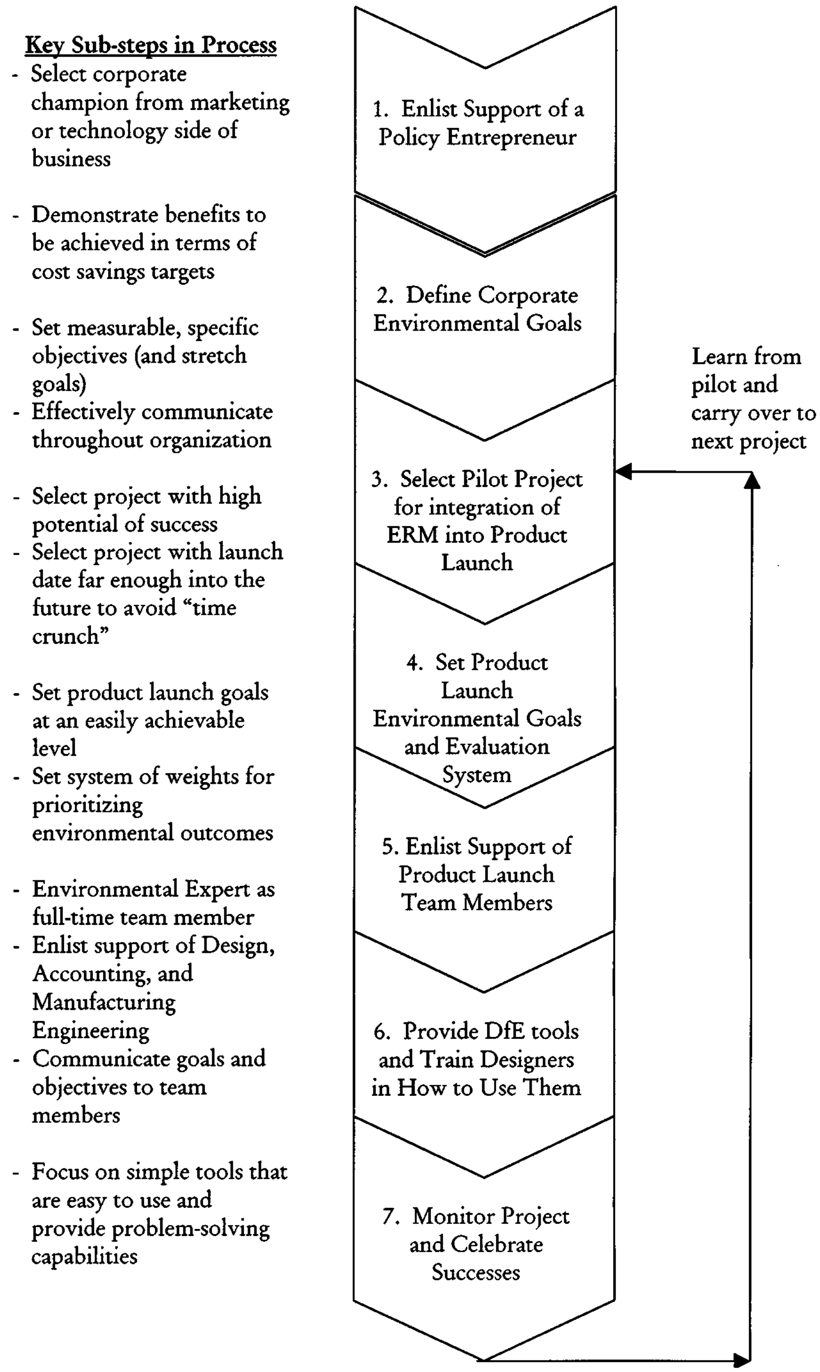

Fig. 2. Process Map: Integrating environmental criteria into the design process.

assume that the other party viewed ERM issues in the same way that they did). Developing new tools would do very little to address the performance measurement concerns raised by the designers.

The researchers were left at the end of the analysis section with the impression that unless this gap was closed, the future acceptance of ERM by designers will continue to be limited and the future growth of DfE methodologies constrained.

VI. Conclusion

Our observations help us to identify a process model that may provide guidance to engineering and technology managers in deploying ERM within the design process. Next we describe the steps in this process, and conclude with a description of limitations to the study and future research needs.

A. Process Map for Integrating Environmental Criteria into the Design Process

Fig. 2 provides a "process model" that project managers or environmental supporters can follow, in terms of how to address the types of problems discovered in this study and resolve them. These steps are described next.

1) **Enlist support of a policy entrepreneur**. A corporate director or vice president who can champion the cause of an environmental supporter is instrumental in helping to drive the initiative. Many of the environmental supporters in our study lacked meaningful support from their corporate headquarters. Further, a top level manager from the marketing or technology side of the business can help gain the support of others below him/her in the organization and bolster resources to make the initiative successful. Finally, a champion should also be willing to go to other functional directors, especially accounting and manufacturing, as their support will be instrumental in later stages of the project.
2) **Define corporate environmental goals**. As previously discussed, the lack of a precise, meaningful and easy to apply definition of green was a major stumbling block. Too often, corporate environmental objectives are stated in terms that are "fluff," without any tangible or measurable outcomes, (e.g., "making our world a better place to live in" [58]). On the other hand, one company we encountered had meaningful, measurable goals, in terms of pounds of recycled nonhazardous waste, reduction of packaging, amount of CFCs and heavy metals, etc. These types of goals are specific and measurable, and provide a standard against which to measure progress. Eventually, stretch goals should be set and benchmarked against other companies in the industry.
3) **Select pilot project for integration of ERM into product launch**. Initially, environmental supporters should identify a project that has a high probability of success in terms of meeting environmental goals. At the same time, the team should recognize the tension between market time pressures and the time to integrate environmental issues into design. This is important, as success generally breeds success. A problem that arose in many of the case studies was a poor history of using DfE tools in the past. This type of history is difficult to overcome, and designers need to be able to feel that they have met the objectives set out for them. If competing but mutually impossible goals are set forth, the effort will undoubtedly fail.
4) **Set product launch environmental goals and evaluation system**. Performance measurement played an important role in all of the organizations we studied. It became essentially an obstacle because few systems measured and rewarded good performance on the environmental design. As a result, the designers either tended to ignore this dimension of product development or to downgrade its importance (and hence the amount of time devoted to this dimension). However, if specific environmental goals are set from the beginning, they become part of the product design team's objectives from the very beginning. In addition, the evaluation of performance should contain specific weights for evaluating the outcomes from the project, tied into the design team's individual compensation and evaluation systems. As we noted earlier in Proposition 2, environmental metrics should carry at least an equal weight as other new product objectives. For instance, a weighted score for the design project might be:
   a) Achieving 10% target cost reduction = 25% importance;
   b) Achieving time-to-market deadline = 25%;
   c) Achieving function and fit requirements = 25%;
   d) Achieving 10% waste reduction = 25%.
5) **Enlist support of product launch team members**. All of the processes studied in the paper shared one important trait: they were strongly sequential in structure. Environmental concerns, when introduced, took the form of checkpoints or exit requirements. As a result, when problems pertaining to environmental concerns were identified, the usual practice was for the designers to make the minimum level of change necessary to meet the objections raised. In this case, environmental concerns effectively represented performance floors and constraints. However, introducing environmental concerns into a setting where true concurrence and multfunctional design teams are present from the outset may result in a very different behavior. Research is needed to study such environments in order to determine if the structure of the design process has an impact on how team members view environmental concerns. Two important team members that will play a role are accounting/finance and manufacturing engineers. One of the major concerns repeatedly raised involved worries over whether doing a better job with respect to environmental waste reduction/elimination would have a negative, positive or neutral impact on cost, lead time, quality or flexibility (the elements of value). Accounting team members can help the team understand the cost implications of choosing different materials and processes that are environmentally friendly. In many cases, this will also require the help of a manufacturing engineer. By creating a process map of the inflows and outflows from a manufacturing process and the interaction of different materials used in the product design, the team should be able to track the cost implications of environmental decisions before they are made. These types of cost impact assessments may require some "nontraditional accounting" procedures, involving the unbundling of environmental costs buried in overhead statements. For further guidelines on environmental cost accounting, see [14], [19].
6) **Provide DfE tools and train designers in how to use them**. Designers need a standard that they can quickly and easily apply in assessing different alternatives and in evaluating various tradeoffs. It is not enough to rely on the use of lifecycle analysis. In our cases, designers viewed lifecycle analysis as a very difficult, expensive and time-consuming tool to use. Designers in most cases do not have the time to wait and carry out such an analysis. It is better to train team members in less comprehensive tools such as process flow analysis, disassembly/recycling analysis, and manufacturability analysis [2], [4], [52].
7) **Monitor project and celebrate successes**. The project may require a careful eye on the part of the environmental supporter, as it is easy to get off track. The project

objectives must be kept in sight at all times. Teams must carry out post-mortems at project completion to identify the successes, lessons learned from project failures, and fruitful avenues for further investigation in future projects. Teams should also post these post-mortem reports on company websites, so as to disseminate the lessons learned for future project teams. In any case, communicate team results to the rest of the organization to celebrate the environmental successes and objectives reached.

B. Limitations of the Study and Future Research

In this study, we explored the orientation and perceptions of two critical parties involved in the product design process: the ERM supporters and the product designers. Our study clearly has some limitations. In reviewing the findings and results reported in this study, it is not known whether the issues and concerns raised in this study are limited to the participants, or whether they suggest a broader set of concerns. To make such a determination requires replication in different settings and industries (either domestic or internationally) and the development of a larger sample. These observations are based on a limited sample. As a result, no attempt to generalize beyond the sample is made. However, these findings helped us to develop a set of suggestions for how to better integrate environmental issues into the design process, as shown in Fig. 2.

The research design also included firms from a limited number of "environmental experts," and utilized a form of "snowball sampling." It is possible that with a different set of organizations in the sample, we would discover a different set of obstacles and practices. Future research using a broader sample is needed to address this limitation.

The process model shown in Fig. 2 is a beginning, but requires further validation through empirical study. A large-scale quantitative-based survey study might be able to determine the effect of the different variables mentioned in this model on environmental project goal attainment. Some of the important variables included in such a study might be:

1) presence of a policy entrepreneur;
2) participation of team members;
3) difficulty of goals established at the outset;
4) involvement of nondesign team members in the project;
5) use of tools in the team setting.

As can be seen, this study has shown that while answers in this field of study exist, there are even more questions present. However, given the increasing importance of this field, researchers must begin to address these issues. In addressing these questions, we must recognize the importance of beginning with design. It is at this stage that all of the critical decisions are made and the basic traits of the product (in terms of manufacturing needs, components and use) are established.

APPENDIX
QUESTIONNAIRE

To be administered either by fax or internet or by phone. These questions were asked of both ERM supporters and designers.

The following are the questions that will be discussed during the interview. If you wish, you may answer any question in the space provided.

GENERAL QUESTIONS

Name

Position

Years in position

Description of position

Responsibilities with respect to design issues

DESCRIPTION OF THE DESIGN PROCESS

Describe the design process for a specific but representative product. Be sure to clearly identify the major stages in the design process. To help you in this process, please feel free to use one of three approaches: list the steps or draw a flow chart or use the following line which represents the total time span for the start of the design process until its completion (when the product hits the market).

In describing this general design process, please identify a specific product for which this process would be appropriate.

What groups/functions are typically involved in the design process? Indicate the points at which each becomes involved on the preceding diagram.

What design tools/aids are used in the design process?

How long does the design process take for the typical part/product?

How do you evaluate the overall effectiveness of the design process?

ERM AND THE DESIGN PROCESS

To what extent are environmental issues considered during the design process?

[Design = all activities involved in taking the product from concept to product launch]

What environmental issues do you consider within the design process? Why were they selected?

To what extent are environmental issues considered during the development process?

[Development = all activities involved in identifying, refining and formulating the product concept]

What environmental issues do you consider within the development process? Why were they selected?

Returning to the diagram/chart/list of steps previously used and using a different color pen, indicate how/where the environmental issues are introduced during the design process (i.e., at what specific points in the process)?

Historically, in what year did you begin serious consideration of environmental issues in the design process? Why? What triggered this concern?

What tools/aids/incentives are used to facilitate the consideration of these environmental concerns in the design process?

[Tools = Lifecycle Assessment, spreadsheets, integrative diagrams, process charts]

What disposal/waste management options (e.g., recycle, reduce, reuse, use for cogeneration of power) are considered during the design process?

How is the impact of these options evaluated during the design process?

How is the impact of these options evaluated during the development process?

Who (i.e., what group/function), if any, is given the primary responsibility for monitoring the environmental issues during the design process?

After the design process?

How is the effectiveness of any changes in design which are related to environmental evaluated? If possible, please provide specific examples of measures or scales used.

If you use specific metrics, please identify the types of metrics used in measuring the effectiveness of the environmental initiatives? Is it possible for us to have a copy of these metrics?

What future opportunities or improvements do you foresee being introduced into the process?

In looking back over your experiences, what problems/obstacles did you encounter in introducing environmental issues into the design process?

How did you overcome these problems/obstacles?

OTHER ISSUES TO BE CONSIDERED

Is there any one in the firm involved in the design process with whom I should talk? Why? Who? Contact.

In addition, is there anyone in the firm who is familiar with the benefit/cost evaluation and assessment as it pertains to environmental issues. What is that person's name? Can I contact them?

Are there any other firms that you know of who are doing a good job of designing and/or building for the environment? Do you have a contact and telephone number?

Any other comments that you wish to make?

Thank you for your time. As soon as the study is done, a summary of the results will be sent to you.

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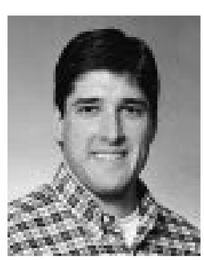

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