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Environmentally Responsible Product Development: Information Flow, Objectives, and Metrics

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ABSTRACT

Environmentally responsible product development (ERPD), also known as environmentally benign manufacturing, considers both environmental impacts and economic objectives during the numerous and diverse activities of product development and manufacturing. There are many ways to minimize environmental impacts. Clearly, however, the greatest opportunity for ERPD occurs during the product design phases since the decisions that are made during these phases determine most of the product's environmental impact. This paper discusses studies of information flow and decision making in product development organizations. This research has yielded methods for improving environmental information processing and defining product environmental metrics.

1. INTRODUCTION

Environmentally responsible product development (ERPD), also known as environmentally benign manufacturing, considers both environmental impacts and economic objectives during the numerous and diverse activities of product development and manufacturing. ERPD seeks to develop energy-efficient and environmentally benign products. Throughout their life cycle, products generate environmental impacts from extracting and processing raw materials; during manufacturing, assembly, and distribution; due to their packaging, use, and maintenance; and at their end of their life. There are many ways to minimize these environmental impacts. Clearly, however, the greatest opportunity for ERPD occurs during the product design phases [1]. The decisions that are made during these phases determine most of the product's environmental impact. Although ERPD requires extra effort, it not only protects the environment but also reduces life-cycle costs by decreasing energy use, reducing raw material requirements, and avoiding pollution control [2].

Because environmental issues have become increasingly relevant to product design, product development organizations have spent a great deal of effort trying to adapt tools and practices that help their designers create products with a reduced environmental footprint. To date, most efforts have focused on tool development, particularly Design for Environment (DFE) and Life Cycle Assessment (LCA) tools. LCA is largely a descriptive tool that evaluates a range of environmental impacts associated with a product during its complete life cycle. DFE tools suggest product design improvements to help a designer reduce the environmental impacts and as such are prescriptive tools. Both LCA and DFE tools rely upon life cycle inventory (LCI) methods that calculate not only the materials found in the product but also determine the waste produced and the energy consumed during its life cycle (based on mass and energy balances).

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

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

We believe that product development organizations can improve their ERPD practices by applying the decision production system perspective [3]. This will lead to four types of benefits.

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

The current research project is an important first step to accomplish these goals (for more information about the project, see the project web site: http://www.isr.umd.edu/Labs/CIM/projects/premise/index.html). This research has studied ERPD at two manufacturing firms using the decision production system perspective. Although the decision production system perspective could be applied to study other types of design decision support methods, LCA and DFE tools are an interesting and distinctive domain to study because ERPD is a serious issue for manufacturers and our society and these sophisticated tools require a great deal of information and resources.

The remainder of this paper is organized as follows: Section 2 describes decision-making in product development organizations and related research. Section 3 discusses the decision production system perspective. Section 4 describes research into information flow for generating material disclosure statements. Section 5 discusses research into defining product-level environmental objectives. Section 6 concludes the paper.

2. DECISION-MAKING IN PRODUCT DEVELOPMENT ORGANIZATIONS

A *product development organization* includes the engineers, managers, and other personnel that make process and product engineering decisions as part of their designing activities. This organization brings new products to market. The group of involved decision-makers is not limited to those listed on the organization chart of the New Product Development hierarchy. Instead it includes participants from manufacturing facilities, suppliers, purchasing, marketing, and other groups who perform or provide input to designing activities. We view a product development organization as a network of people using information, making decisions, and generating information [3]. Thus, product development is an information flow governed by decision-makers who make decisions under time and budget constraints.

Because they realized that design decisions (though made early in the product life cycle) have an excessive impact on the profitability of a product over its entire life cycle, manufacturing firms and product development organizations have created and used concurrent engineering practices for many years [4]. Cross-functional product development teams and design for manufacturing guidelines, for example, avoid unnecessary manufacturing costs and expensive delays due to design iterations. Likewise, the greatest potential for reducing environmental impacts in a cost-effective way lies in improving product development.

Product development includes many different types of decision-making by engineers and managers. Some decisions are *design decisions* and others are *development decisions*. Design decisions determine the product form and specify the manufacturing processes to be used. Design decisions generate information about the product design itself and the requirements that it must satisfy. Development decisions, however, control the progress of the development process. They affect the resources, time, and technologies available to perform development activities. They define which activities should happen, their sequence, and who should perform them. That is, what will be done, when will it be done, and who will do it. Krishnan and Ulrich [5] provide a comprehensive survey of design decision-making.

The design engineering community has focused much effort on understanding design as a decision-making activity. This work has yielded Decision-Based Design (DBD), a perspective that views design as a decision-making process involving values, uncertainty, and risk. (Details on DBD can be found online in the Decision-Based Design Workshop at http://dbd.eng.buffalo.edu/.) The research on DBD includes a wide variety of approaches. DBD researchers have primarily focused on making better design decisions (e.g., selecting the best design alternative). Because decision-making often involves multiple objectives, some DBD researchers have developed techniques for helping decision-makers make tradeoffs among competing objectives and methods that quantify and combine the multiple objectives into a single objective. The techniques of decision analysis, especially utility theory, are an important component. Thurston [6] gives an overview of DBD and discusses the role of utility theory in DBD. Research in this area continues. For an overview of rational decision-making, including subjective expected utility theory and prospect theory, see, for example, Hastie and Dawes [7].

Some research on DBD includes efforts to illustrate how engineering design should be done. That is, they claim that there is an alternative to the traditional decomposition of design. Specifically, researchers have developed approaches that integrate numerous design decisions and solve large optimization problems whose objective function is to maximize company profit [8, 9]. Because this simplifies the process, product development will take less time. Also, the integrated model includes all of the competing performance measures (including, possibly, environmental impacts) and maps them to more fundamental objectives (such as profitability and market share) that are important to the manager of the manufacturing firm. However, such integration remains a primarily academic exercise at this point.

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

3. DECISION PRODUCTION SYSTEMS

Based on our experience and careful study of product development organizations, we have developed a new paradigm for understanding product development. This paradigm views product development organizations as decision production systems. The following paragraphs briefly describe this perspective. For a more in-depth discussion, see Herrmann and Schmidt [3].

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

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

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

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

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

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

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

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

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

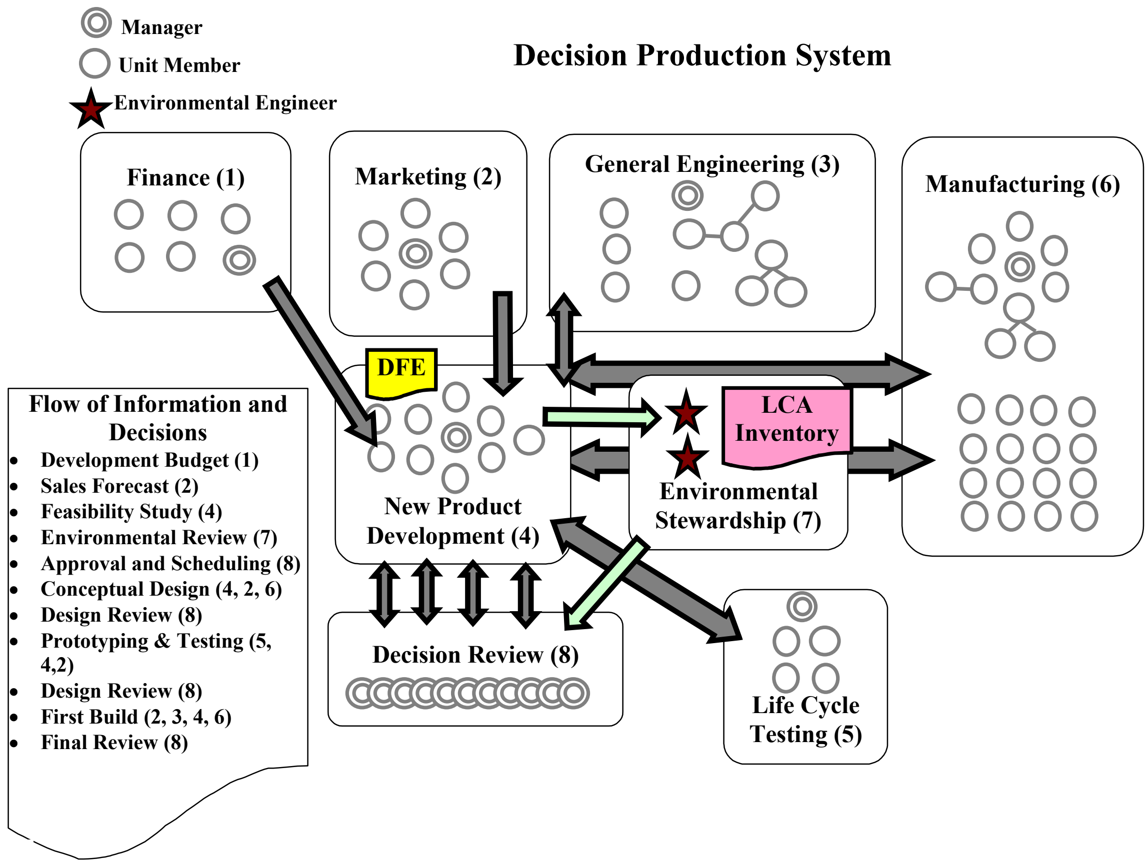

Figure 1. A product development organization with isolated environmental decision-making.

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

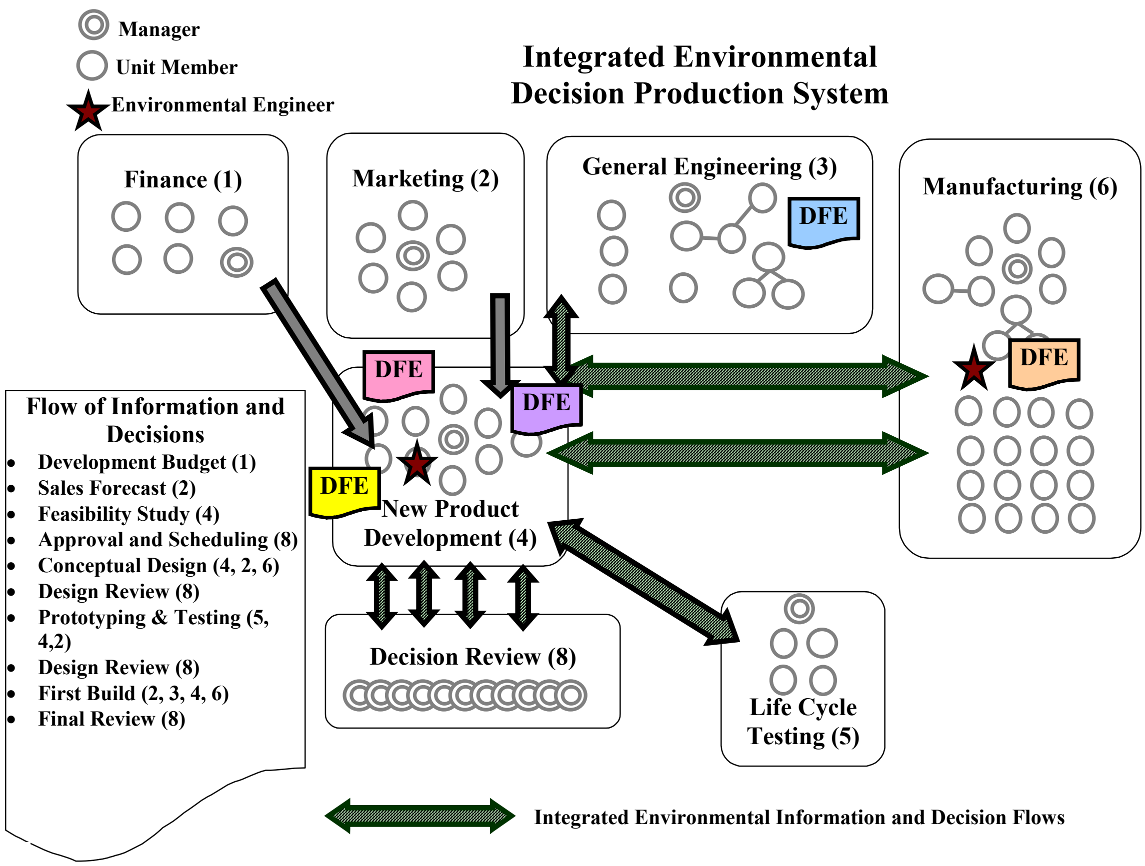

Figure 2. A product development organization with integrated environmental decision-making.

4. MATERIAL DISCLOSURE STATEMENTS

This section describes work studying material declaration statements (MDS), which are inventories of material content in a finished product [10, 11]. MDS generation is necessary to obtain prominent eco-labels such as Blue Angel, TCO '99, and Green PC, which contain requirements restricting the use of specific materials. Material content data is also useful for determining the end-of-life management for a product. The interest in final product material content is driven by actual or pending environmental legislation that forces manufacturers to take some level of life cycle responsibility for the materials that are present in the products they sell and support.

The challenges with MDS generation fall into two categories: (1) the logistics of identifying and obtaining the appropriate data from appropriate sources (a challenge which the work in this project addresses); and (2) fusing the information into a useable form, i.e., there is no universally agreed upon content at this time and further, there is not necessarily a common denominator inventory to collect. For example, some legislation governs only materials that are "intentionally added," while other regulations govern total material content. This problem makes MDS generation for an electronic system a significantly complex data fusion problem.

Generating an MDS is a complex information processing system and thus serves as an appropriate domain to use the decision production system approach. The research team has studied the MDS generation process at a printed circuit board manufacturer. This firm is being required to produce MDSs by many of its customers who are already complying with (or preparing to comply with) various types of worldwide environmental legislation. The information flow within the firm, its supply chain, and to its customers was modeled to create a representation that identifies the participants, the decision-making and information-processing activities, and the nature of the information flows. The model was used to determine the quality standards for MDSs, identify mismatches between available data and data needed to complete MDS, and identify other decision-making processes that use similar environmental information. To date, the research team has conducted interviews with the firm's engineering staff, reviewed forms and documents involved in the process, created representations of the process (see Figure 3), identified opportunities for improving the process, and compared these representations to other MDS processes.

The research team has discovered opportunities for improving the MDS generation process at the printed circuit board manufacturer. The team discovered that there are existing information processing systems in place already. These existing systems are the tooling creation process and the new chemical introduction process. MDS generation requires enhancing these systems. The new chemical introduction process can collect and store information about materials and components used to make printed circuit boards. The tool creation process can use data about the boards to be created along with this already-stored material data to calculate the MDS.

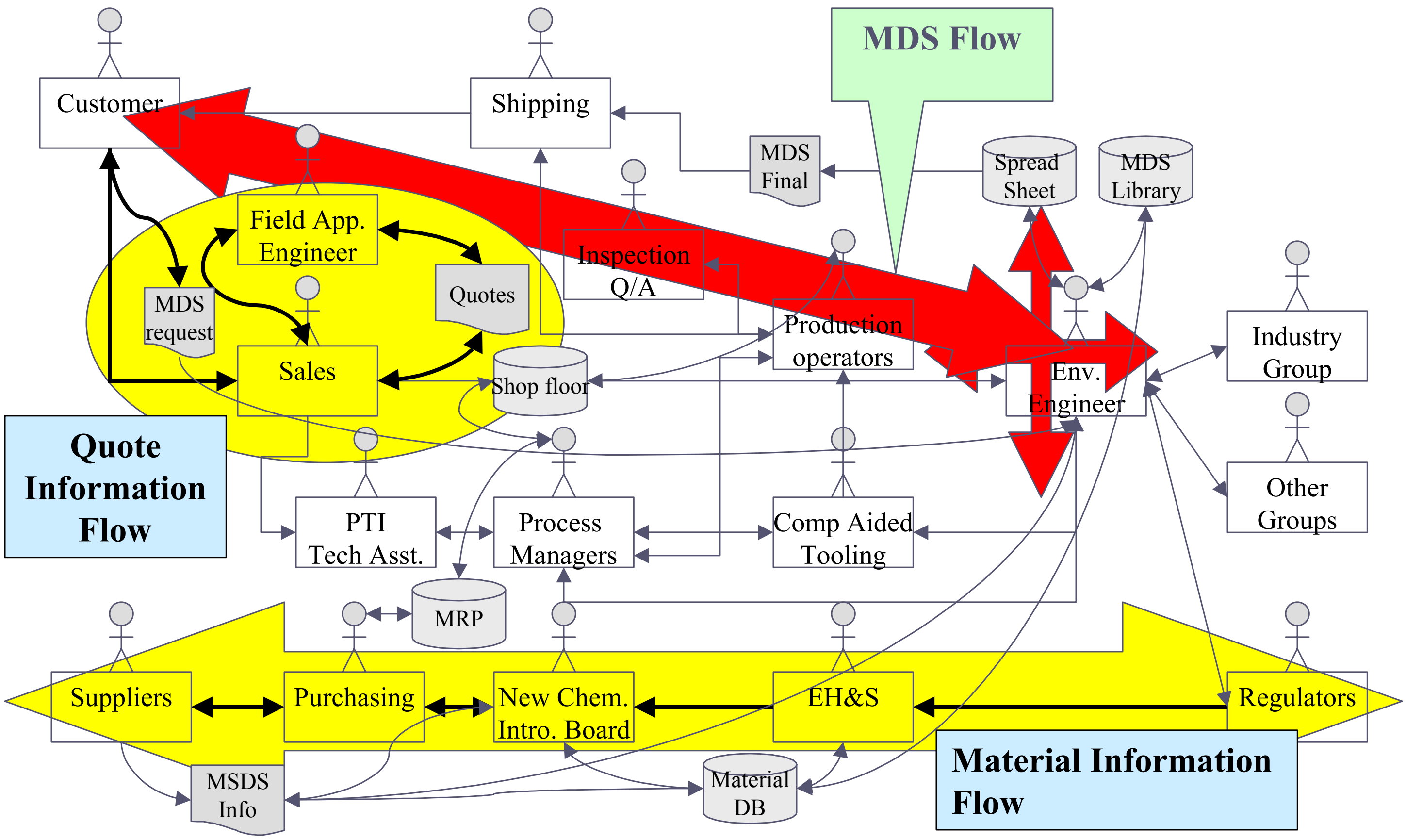

Figure 3. Decision Production System for Generating Material Disclosure Statements

The research team has compared the decision production system representation to other representations of MDS generation processes. A traditional process flowchart illustrates the specific processes used to create an MDS. The flowchart shows the different steps that must be performed and describes the conditions under which these steps are required. The flowchart does not explicitly describe the individuals who perform each step, the sources that provide data needed for each step, or the information that each step generates.

A database view of the process shows the multiple information systems that provide data needed for generating an MDS. This view also indicates where data flows from one system to another (and sometimes describes the data itself). This view does not describe the steps that need to be performed or the individuals who process the information.

A decision production system representation describes the steps that need to be performed (like a process flowchart), the individuals who perform each step, the sources that provide data needed for each step (like a database view), and the information that each step generates.

5. DESIGN FOR ENVIRONMENT METRICS

This section describes work that studied environmental objectives and product-level metrics at TM, a publicly traded firm that is a global manufacturer and distributor of quality power tools and accessories.

TM is interested in defining product-level environmental objectives that product development teams can use to evaluate the environmental performance of the products. There is, however, a huge range of metrics that various manufacturing firms and research teams have proposed [12]. To identify those that are most relevant to TM, the research team first identified TM's key environmental objectives. These were used to define relevant, useful product environment metrics.

5.1. Corporate Environmental Objectives

Based on discussions with TM staff and documents provided by TM, we identified six primary environmental objectives (listed below in no particular order):

1. demonstrating environmental awareness,
2. complying with environmental regulations,
3. addressing customer concerns,
4. mitigating environmental risks,
5. limiting financial liability, and
6. reporting environmental performance.

Demonstrating Environmental Awareness. TM seeks to demonstrate environmental awareness through a variety of actions: writing and printing pamphlets, creating an environmental policy and publishing it on their website, including information about recycled content on packaging, and having a Design for Environment program. In addition, TM belongs to environmental organizations such as the World Environmental Center.

Complying with Environmental Regulations. As a manufacturing corporation that produces and sells goods around the world, TM must comply with a variety of Federal, state, and European regulations. TM provides employees with training on handling hazardous wastes, which is required by the Resource Conservation and Recovery Act and the Hazardous Materials Transportation Act [13].

The Occupational Safety & Health Administration (OHSA) limits exposure of certain chemicals to workers in the workforce. In addition, the Environmental Protection Agency (EPA) sets limits on how much of certain chemicals can be released into the environment [14].

Addressing Customer Concerns. TM's large retail customers are concerned about the environmental impacts of the products they sell. Among these customer concerns are: the production of magnesium (climate change), an increase in recyclability and recycled content in packaging, the use of cadmium in batteries, and the use of lead in printed wiring boards and the charger cord. More specifically, Lowe's requires that TM's products be free of lead-based paint.

Mitigating Environmental Risks. An activity's environmental risk is the potential that the activity will adversely affect living organisms through its effluents, emissions, wastes, accidental chemical releases, energy use, and resource consumption [15]. Environmental risk is measured using one or more environmental indicators, including Primary Energy Demand, Global Warming Potential (GWP), Photochemical Oxidant Potential (POCP), Acidification Potential (AP), Human Toxicity Potential (HTP), Aquatic EcoToxicity Potential (AETP), Terrestric EcoToxicity Potential (TETP), Eutrophication Potential (EP), and Ozone Depletion Potential (ODP). TM has indicated that it seeks to reduce its contribution to GWP and AP. TM can do this by reducing the amount of greenhouse gases (e.g., carbon dioxide and methane) and the amount of sulfur dioxide produced.

Reducing Financial Liability. There are different categories of financial liability related to environmental impacts. The Environmental Protection Agency (EPA) defines the term *environmental liability* as "a legal obligation to make a future expenditure due to the past or ongoing manufacture, use, release, or threatened release of a particular substance, or other activities that adversely affect the environment." They define the term *potential environmental liability* by placing the word "potential" before the word "legal" in the same definition for environmental liability. The EPA notes the difference between the terms by stating, "A 'potential environmental liability' differs from an ‘environmental liability’ because an organization has an opportunity to prevent the liability from occurring by altering its own practices or adopting new practices in order to avoid or reduce adverse environmental impact.” There are different types of environmental liabilities [16]:

- Compliance obligations are the costs of coming into compliance with laws and regulations.
- Remediation obligations are the costs of cleaning up pollution posing a risk to human health and the environment.
- Fines and penalties are the costs of being non-compliant.
- Compensation obligations are the costs of compensating “damages” suffered by individuals, their property, and businesses due to use or release of toxic substances or other pollutants.
- Punitive damages are the costs of environmental negligence.
- Natural resource damages are the costs of compensating damages to federal, state, local, foreign, or tribal land.

Reporting environmental performance. TM reports environmental performance to many different organizations, including customers, financial organizations, non-government organizations, and government agencies.

5.2. Product Environmental Metrics

This section describes product-level environmental metrics that product development teams can evaluate during the product development process. These metrics were chosen because they relate directly to a particular product (they are not plant or corporate metrics). In addition, the measures concern attributes that are relevant to TM’s primary environmental objectives (described above).

There are eight product-level environmental metrics:

1. Hazardous material use
2. Non-hazardous material use
3. Recycled material content of the product
4. Recycled material content of packaging
5. Recyclability of the product
6. Recyclability of packaging
7. Energy consumption during use
8. Application of DFE approach

Hazardous Material Use. This measures the mass of each hazardous material contained in the product. A material is considered hazardous if it is banned, restricted or being watched with respect to regulations or customers.

Non-Hazardous Material Use. This measures the mass of each non-hazardous material contained in the product. A material is considered non-hazardous if it is not banned, restricted or being watched with respect to regulations or customers.

Recycled Material Content of Product. This fraction (expressed as a percentage) is the mass of recycled material in a product divided by the total mass of the product. Calculating this requires understanding the amount of recycled material in the materials that are used in products.

There are two primary types of recycled material. The first type (“post-industrial”) is material that is recycled after use in a manufacturing facility. The second type (“post-consumer”) is material that is recycled after use by the consumer. It is common to find measures of recycled content that include both types of recycled material and measures of recycled content that include just the second type of recycled material. TM must decide which measure they wish to use.

Recycled Material Content of Packaging. This fraction (expressed as a percentage) is the mass of recycled material in the packaging of a product divided by the total mass of the packaging.

Recyclability of the Product. This measures the degree to which each component and subassembly in the product is recyclable. There exist recyclability ratings that are based on the technical feasibility of recycling the material and existing markets for remanufacturing a part [17]. The recyclability of a complex assembly (such as a power tool) requires evaluating the recyclability of each component.

Recyclability of Packaging. This measures the recyclability of the materials used for packaging. It is measured in the same way as the recyclability of the products.

Energy consumption during use. This measure is important for products (such as compressors, generators, and battery chargers) that consumer a great deal of energy during the use phase of their life cycle.

Application of DFE approach. This binary measure (yes or no) is the answer to the following question: did the product development team follow the DFE approach during the product development process? Following the DFE approach requires the team to review the DFE guidelines and evaluate the product-level environmental metrics.

6. SUMMARY AND CONCLUSIONS

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

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