Decision Support Tools for Environmental Product and Process Management: Survey and Needs

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Abstract. Decisions that support Sustainable Product Development activities need to consider product information from a much broader perspective than is used for typical product decision-making. Collecting the necessary data for analysis within and across these functions and across geographical distributed suppliers is challenging. Various methodologies and tools exist for the analysis of environmental impact of chains or networks of processes in sustainable product development. In this state-of-the-art literature review, we classified the tools with four main categories: sustainable development concepts, environmentally conscious manufacturing, management and economics tools. Each category of methodologies has been grouped with specific tools and the characteristics, limitation and gaps between tools are discussed. Also the relationship between implementing tools within the environmental supply chain management (ESCM) is discussed. Our review indicates that better tools for SPD decision-making are required.


1. Introduction

Products create environmental impacts across many media. This includes upstream from final manufacture -- individual component material extraction, processing and manufacturing -- and downstream -- energy, use and waste management. These impacts are propagated to each component and material throughout the supply chain. Further, the costs associated with their impacts vary widely. Because the complexity, costs and benefits associated with upstream and downstream environmental impacts are poorly understood, they are rarely included in any design analysis or business decision-making. Sustainable product development (SPD) involves the life cycle of a product and shared responsibility for the life-cycle environmental impacts of the product. There are significant information-related challenges related to integrating environmental and product development assessments over the life cycle. It requires input from various staff functions — material, environmental, product design, manufacturing, engineering, and marketing — amongst others. Further these inputs must be integrated through the entire supply chain. Presently, however, little theory exists to explain what occurs in supply chains and in their management. A major part of supply chain management (SCM) is concerned with the sharing of responsibility for various aspects of performance such as: lead time, transaction cost, product quality, effective communication among suppliers, manufacturers, distributor and retailers. Environmental supply chain management (ESCM) defines its scope to the end user and beyond, to reuse, recycling, and disposal. However, environmental matters have not traditionally been highly valued in supply chain management. In order to analyze environmental impact over the ESCM, effective tools and methodologies should be integrated into ESCM. Decision-making in environmental management requires

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the assessment of a complex set of issues. A large number of tools have been developed in order to aid public or private sector environmental management strategies and operations. Each methodology has its own specific characteristics and is more or less suited to address particular environment-related issues. The choice of the methodologies and tools depends on: the scope of the decision problem, its definition in space and time, the availability of data on environmental impacts, and the uncertainty associated with the estimation of the costs and benefits (Wang and Johnson 1994). It is crucial to use the most appropriate tools for specific problem solving. Generally, no single tool can depict all sorts of problem shifting. Failure to use the appropriate combination of tools to support decision-making can result in the use of an incomplete or inappropriate analysis, and arrival at the wrong conclusion. In this paper, we provide a classification of methodologies and tools for sustainable product and process development and compare the characteristics of each tool with respect to their methodology. Also, we suggest the important relationship between tools and environmental supply chain management (ESCM).

2. Classification of Methods and Tools

Methods and tools for a sustainable product development process can be classified with four main categories: Sustainable Development Concepts, Environmentally Conscious Manufacturing tools, Environmentally Conscious Management tools, Environmentally Conscious Economic tools. Sustainable Development Concepts encompass life cycle thinking, design for environment, and cleaner technology. Tools, on the other hand, are operational methods supporting the concepts. Tools can be categorized according to their focus. First, the focus of Environmentally Conscious Manufacturing tools is on computational algorithms or checklists aimed at finding solutions that reduce the environmental impacts of product manufacturing. Second, the focus of Environmentally Conscious Management tools is on procedures to guide the best way to reach a decision on process management. Environmentally Conscious Management tools consist of decision procedures. Third, Environmentally Conscious Economic tools are used when integrating environmental product and process design into a business case. Because the complexity, costs and benefits associated with upstream and downstream environmental impacts are poorly understood, they are rarely included in business decision making process (Choi, Stuart et al. 2003). Because a company’s environmental performance is not only a measure of the impacts caused by the production processes, it is also a total measure of the environmental impacts caused by the products and the activities, the holistic perspective must be taken into consideration in order to improve its environmental performance. Finally, technical elements also can be distinguished as methods of obtaining data, data processing and of presenting information. A technical element may supply information to a variety of tools, and any one tool may require information from more than one technical element. The relationship between sustainable development concepts, environmentally conscious manufacturing, management, economic tools, technical elements, data and the decision process is indicated in Fig 1.

2.1 Sustainable Product Development (SPD) Concept

Life Cycle Thinking: If the environmental concerns are broadened to include solid waste, materials and energy consumption, then traditional waste minimization approaches are too limited in scope. Additional conceptual frameworks and paradigms are needed. Life cycle thinking is a circular process that begins and ends with the use of raw materials in the most efficient way. Its approach is aimed at reducing the adverse environmental impact of a product throughout its existence from raw material to end of life (Fava 1993). Life cycle thinking forms the basis of a company’s environmental activities. The goal is to reduce adverse environmental effects during the product life cycles by managing their own operations and supplier network and by incorporating Design for Environment principles into every stage. Design for Environment may embrace design, the environmental performance of their suppliers, decision-making within the company itself and responsible end-of-life practices. (Calcott, Walls 2000)(Ishii 1998) (Rose, Beiter et.al 1998)

Life Cycle Management (LCM): Life Cycle Management (LCM) is a business toolbox involving product- and firm-based decision-making (Rowledge et al. 1999). It is complementary to existing management structures at the finance-technology environment interface. LCM aims at integrating environmental concerns into industrial and business operations by considering off-site, or supply chain, impacts and costs by quantifiable indicators. LCM seeks to increase the competitiveness between new and existing products by examining advantages and reduce business risks associated with the environmental and social aspects of a product throughout its life cycle (Kimura 1999). Therefore, LCM can be seen as a means of putting sustainable development to work within a firm, given its temporal and financial constraints (Hunkeler and Rebitzer 2001). LCM has been defined many different ways. In general, it is seen to consist of the integration of life cycle concepts (“life cycle thinking”) with other information systems and metrics for management decision-making in firms (Norris and Segal 2002). LCM is not currently conceived as the task of promoting sustainable consumption or sustainable development. Table 1 shows the focal
point and limitation of LCM together with Life Cycle Assessment (LCA) which is an environmentally conscious manufacturing tool (Hunkeler, Rebitzer et al. 2002). Table 2 provides a methodological comparison of LCM and LCA based on (Alting and Legarth 1995; Westkaemper, Alting et al. 2000) (Hata, Kato et al. 2000) (Kimura and Kato 2002).

Table 1 Comparison of focal point and limitation between LCM and LCA

<table>
<thead>
<tr>
<th>Concept</th>
<th>Focal point</th>
<th>Limitation</th>
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<tbody>
<tr>
<td>LCA</td>
<td>A specified unit of product-delivered function</td>
<td>• Purchased products are not the only nor always the best way to achieve a function</td>
</tr>
<tr>
<td></td>
<td>Choices by firms either among alternative products or alternative operations</td>
<td>• Need satisfaction, rather than function delivery, is the core objectives of sustainable development</td>
</tr>
<tr>
<td>LCM</td>
<td></td>
<td>Profit-seeking firms are important part for sustainable development, there are also other decision making perspectives which must be empowered with decision support</td>
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Table 2 Methodological Comparison of LCM and LCA

<table>
<thead>
<tr>
<th></th>
<th>LCM</th>
<th>LCA</th>
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<tbody>
<tr>
<td>Approach</td>
<td>More qualitative</td>
<td>Data intensive</td>
</tr>
<tr>
<td>Requirement</td>
<td>Product understanding</td>
<td>Measurement of Environmental Impact</td>
</tr>
<tr>
<td>Emphasis</td>
<td>Environmental, Health, Safety, Energy</td>
<td>Environmental, Energy</td>
</tr>
</tbody>
</table>
Design for Environment (DFE): Design for Environment is based on life-cycle thinking and involves design procedures that minimize material and energy consumption while maximizing the possibility for reuse and recycling. It is possible to focus on a specific stage of the product’s life such that the environmental impact is minimized in that stage as well as emphasizing the entire life of the product (Gungor and Gupta 1999). DFE is the systematic consideration of design performance with respect to environmental, health, and safety objectives over the full product and process life-cycle (Fiksel 1996). DFE improves the design of the product from an environmental perspective. It is a combination of several design-related topics, including disassembly, recovery, recycling, regulatory compliance, disposition, health and safety impact, and hazardous material minimization. Its key principles include use recyclable materials, use compatible materials, avoid contaminants, use simple fastening methods to join materials together, use clear material identification and marking, and ensure easy removal of component of product (Stuart and Sommerville, 1998). It takes place early in a product’s design or upgrade phase to ensure that the environmental consequences of a product’s life cycle are understood before manufacturing decisions are committed. The successful implementation of DFE calls for commitment from cross-functional interaction between design, manufacturing, marketing, sales, and accounting. DFE requires the coordination of several design- and data-based activities, such as environmental impact metrics; data and data management; design optimization, including cost assessments; and others. Metrics for measuring environmental performance and/or impact must be determined, information flow between departments needs to be supported, and an infrastructure to carry out DFE-based decisions must be established. Failure to address any of these aspects will likely limit the effectiveness and usefulness of DFE efforts (Mizuki, Sandborn et al. 1996; Rose, Beiter et al. 1999).

Extended Product Responsibility (EPR): EPR is an emerging principle for a new generation of pollution prevention policies that focus on product systems instead of production facilities. The principle of Extended Product Responsibility relies for its implementation upon the life-cycle concept to identify opportunities to prevent pollution and reduce resource and energy use in each stage of the product life cycle (or product chain) through changes in product design and process technology (Stoughton, Shapiro et al. 1999). EPR is the principle that the actors along the product chain share responsibility for the life-cycle environmental impacts of the whole product system, including upstream impacts inherent in the selection of materials for the products, impacts from the manufacturer’s production process itself, and downstream impacts from the use and disposal of the products. The greater the ability of the actor to influence the life-cycle impacts of the product system, the greater the degree of responsibility for addressing those impacts. Producers, for instance, accept their responsibility when they design their products to minimize the life-cycle environmental impacts and when they accept their share of the physical or economic responsibility for the environmental impacts that cannot be eliminated by design (Tojo 2001). The term EPR has gained greater acceptance in the United States because it implies shared responsibilities in the product chain, although often the producer is in the best position, both technically and economically, to influence the rest of the product chain in reducing life-cycle environmental impacts. There are three key attributes of EPR (Davis, Wilt et al. 1997)

- The extension or shifting of responsibility to a life-cycle stage or stages where responsibility currently does not exist or is not well-defined
- A product systems approach with a focus on creating feedback to product designers to design cleaner products
- Sharing of responsibility for the life-cycle environmental impacts of the product system among links in the product chain in such a way that there is a well-defined locus of responsibility, which may include more than one link.

End of Life (EoL) Management: It describes the approach or method associated with dealing with the product at the end-of-life. End-of-Life treatment includes the activities associated with recovering value from the product, through manual labor and/or machinery. The EoL system includes the activities associated with strategic planning and implementation ranging from the collection of products, treatment of those products and the associated impacts to society and environment (Rose, Beiter et al. 1999)(Ishii, K 1999). The following table defines end-of-life strategies.
based on the work of (Ishii 1995; Nilsson and Bjorkman 1999).

<table>
<thead>
<tr>
<th>Name</th>
<th>Definition</th>
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<tbody>
<tr>
<td>Reuse</td>
<td>Reuse is the second hand trading of product for use as originally designed</td>
</tr>
<tr>
<td>Service</td>
<td>Servicing the product is another way of extending the life of a durable product or component parts by repairing or rebuilding the product using service parts at the location where the product is being used. Remanufacturing is a process in which reasonably large quantities of similar products are brought into a central facility and disassembled. Parts from a specific product are not kept with the product but instead they are collected by part type, cleaned, inspected for possible repair and reuse. Remanufactured products are then reassembled on an assembly line using those recovered parts and new parts where necessary.</td>
</tr>
<tr>
<td>Remanufacture</td>
<td>Recycling reclaims material streams useful for application in products. Disassembly into material fractions increases the value of the materials recycled by removing material contaminants, hazardous materials, or high value components. The components are separated mostly by manual disassembly methods.</td>
</tr>
<tr>
<td>Recycling with disassembly</td>
<td>The purpose of shredding is to reduce material size to facilitate sorting. The shredded material is separated using methods based on magnetic, density or other properties of the materials.</td>
</tr>
<tr>
<td>Recycling w/o disassembly</td>
<td>This end-of-life strategy is to landfill or incinerate the product with or without energy recovery.</td>
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### Eco-Efficiency

In recent years a number of efforts to systematically address environmental effects of industrial processes and products have emerged under headings such as industrial ecology, cyclic economy, and sustainable production. These activities aim to improve materials use efficiency, close materials cycles, rely on inherently more benign substances and production methods, and reduce pollution over the entire life-cycle of a product or unit of service. Their goals are to avoid the shift of pollution from one environmental compartment to another, from one pollutant to another, from one place to another, or from this generation to the next. Table 4 lists The World Business Council for Sustainable Development (WBCSD)’s seven success factors for eco-efficiency towards which a company should strive.

<table>
<thead>
<tr>
<th>Reduce</th>
<th>Increase/ enhance</th>
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<tbody>
<tr>
<td>• Material intensity of goods and services</td>
<td>• Material recyclability</td>
</tr>
<tr>
<td>• Energy intensity of goods and services</td>
<td>• Sustainable use of renewable resources</td>
</tr>
<tr>
<td>• Toxic dispersion</td>
<td>• Durability of products</td>
</tr>
<tr>
<td></td>
<td>• Service intensity of goods and services</td>
</tr>
</tbody>
</table>

The ecological efficiency of industrial production has become the focus of a range of innovative and promising research and implementation activities. Eco-efficiency promises to achieve a less polluted environment at lower costs than pollution control and ensure human well-being with less detrimental effects than adaptation and remediation (Hertwich 1997). Pollution Prevention (P2) and cleaner technology (CT) are examples of Eco-Efficiency. P2 focuses on process optimization, input substitution and better housekeeping measures. However, CT aims to develop new technologies that replace existing polluting technologies. Technological solutions have been prominent throughout environmental protection. The attempt to develop inherently clean technologies, in contrast to “end of pipe” technologies, has been called no-waste, cleaner, or environmentally responsive technologies, cleaner production, and zero-waste management (Hertwich 1997).

**Cleaner Technology (CT):** Cleaner technology for product development ranges from manufacturing technology of near-net shape manufacturing of parts to the technologies for the utilization of renewable resources. Cleaner Technology is a manufacturing process which by its nature or intrinsically reduces effluent and other waste production, maximizes product quality, maximizes raw materials and energy. Thus one technology is usually
compared to some other technology or process. Cleaner Technology may be thought of as a subset of Cleaner Production activities with a focus on the actual manufacturing process itself and considers the integration of better production systems to minimize environmental harm and maximize production efficiency from many or all inputs (Denmark Ministry of the Environment 1992). Production managers and other industry decision makers are often concerned with decisions regarding conflicting technology choices. In principle, choices should be made while considering the environment among the many other competing issues so as to select the cleanest technology, all other options being equivalent. Unfortunately in reality, choices are not so simple and a range of conflicting parameters may make selection of the most environmentally preferable option difficult (Ryding, Steen et al. 1993).

**Pollution Prevention (P2):** P2 focuses on reducing pollution from existing plants and processes. DFE and cleaner technology are sometimes subsumed under pollution prevention; The US Federal Pollution Prevention Act of 1990 specifically lists seven source reduction practices which are provided in Table 5. Governments, consultants and the new ISO 14000 environmental management standards promote environmental auditing as a means of identifying pollution prevention opportunities. In addition, pollution prevention offices often promote the adoption of cleaner technologies that have moved into the commercialization stage or inform clients about technologies and practices that have been successfully implemented somewhere else.

**Table 5 Seven source reduction practices in P2**

<table>
<thead>
<tr>
<th>Equipment modernization &amp; modification</th>
<th>Improved maintenance</th>
<th>Inventory control</th>
<th>Improved operation practices</th>
<th>Process &amp; product modification</th>
<th>Substitution of inputs</th>
<th>In-process recycling</th>
</tr>
</thead>
</table>

### 2.2 Environmentally Conscious Manufacturing Tools

Environmentally Conscious Manufacturing (ECM) involves producing products such that their overall negative environmental effects are minimized (Sarkis 1995). There are two key issues in ECM: understanding the life cycle of the product and its impact on the environment at each of its life stages and making better decisions during product design and manufacturing so that the environmental attributes of the product and manufacturing process are kept at a desired level. In addition, it is critical to understand the end-of-life stage of the product because one of the largest impacts on the environment may occur at this stage.

**Life Cycle Assessment (LCA):** LCA is a process to access and evaluate the environmental consequences of a product through extraction and acquisition of raw materials, production, transportation and distribution, use, remanufacturing, recycling and final disposal (Alting and Jorgensen 1993). LCA examines and quantifies the input/output of energy and materials and assesses the impact of the product on the environment. The scope of LCA involves tracking all the materials and energy flows of a product from the retrieval of its raw materials out of the environment to the disposal of the product back into the environment (Miettinen and Hamalaninen 1997). LCA usually facilitates the systematic collection, analysis and presentation of environmentally related data (Gungor and Gupta 1999). The product life cycle has been represented in various ways, but the most well-known and respected life cycle representation is that of Society of Environmental Toxicology and Chemistry (SETEC), shown in Figure 2.

![Fig. 2 Product Life Cycle according to SETAC (Ciambrone 1997)](image-url)
Industry may use LCA to support product development so that the overall environmental impact of the product is minimized. During conceptual design of each new product, LCA takes into account the qualitative and quantitative characteristics of the product life cycle (Wenzel, Hauschild et al. 2001) (Hauschild and Wenzel 1998). Designers are able to estimate the costs and benefits associated with the design attributes such as energy consumption or material requirement by using LCA. The main characteristics of LCA can be described as follows (Wrisberg and Gameson 1998):

- LCA is a study of different options to supply a given function. Thus, it links changes in products (goods and services) in the economy to impacts on the environment.
- LCA follows a cradle-to-grave approach: all processes connected with the function, from the extraction of resources until the final disposal of waste, are being considered. This approach may induce companies to look beyond their gates, or governments to detect unexpected side-effects of their policies.
- LCA is comprehensive with respect to the environmental interventions and environmental issues considered. In principle, all environmental issues or problems connected with the function are specified as resulting from extractions, emissions and other physical interventions.
- LCA may provide quantitative or qualitative results. With quantitative results, it is easier to identify problematical parts of the life-cycle and to specify what can be gained by alternative ways to fulfill the function.

**Material Input per Service unit (MIPS):** The MIPS concept is a life cycle tool for analysing material inputs per service unit and it is the measurement for material and energy intensity from processes, products, infrastructure and services in our economical system. This concept uses a resource indicator to measure the environmental performance of a cradle-to-grave business activity. Calculations are made per unit of delivered “service” or function in the product during its entire life cycle -- manufacturing, transport, package, use, reuse, recycling, new manufacturing from recycled material, and final disposal as waste. By calculating material and energy flows and the number of products produced, it is possible to calculate the material intensity related to the function of a particular product (Ryan 2000). The whole material and energy input are indicated in kilogram or ton, measured from raw material extraction process from the environment until disposal of waste material to the environment. Thereby a picture of the environmental performance related to that product is achieved. The concept is based on the philosophy that a better utilization of materials and resources is needed to achieve sustainable development. Using this concept, one may analyze the entire working process including all inserted natural resources, material and energy in the process to produce a desired product or service (Spangenberg, Hinterberger et al. 1999). Thus, MIPS is a benchmark in the best tradition of economical principles to achieve a certain result with a minimum input (dematerialization) and to reach a maximum result with a certain input (resource productivity)(Cahyandito 2001). M.J. Welfens from the Wuppertal Institute for Climate, Environment and Energy in Germany has developed strategies to practice dematerialization. Strategies for dematerialization mean that resources are used in a more efficient way (Welfens 2000).

![Fig. 3 Strategies for Dematerialization (modified after (Welfens 2000))](image-url)
From the technical perspective, the use of the MIPS concept has the following advantages and disadvantages.

Advantages:
- Material and energy expenditures are measured in the same units. In doing so, contradictions in the ecological evaluations are avoided, and the evaluation becomes directionally stable.
- The MIPS Concept helps in the design of industrial products, in the planning of environmentally-friendly processes, facilities and infrastructures, as well as in the ecological assessment of services.
- The MIPS Concept can serve as the basis for a comprehensive ecological labeling strategy, and can be an aid in purchasing decisions and customer counseling.

Disadvantages:
- The MIPS Concept does not take into account the specific “surface-use” for industrial as well as for agricultural and forestry activities. This is of considerable importance as the amount of the earth’s surface available for our purposes is limited.
- The MIPS Concept does not take into account the specific environmental toxicity of material flows. The approach is not intended to supplant the quantification of Eco-toxicological dangers of materials in environmental policy, but rather to supplement it by stressing the material and energy intensity of economic services.
- The MIPS Concept makes no direct reference to questions of biodiversity. It seems fair to speculate that the chances for species survival are related to the intensity of soil and resource use. Therefore we cannot exclude the notion that the material intensity of a society’s economy has something to do with its contribution to species extinction.

**Material Flow Accounting/ Substance Flow Analysis (MFA/SFA):** Under the notion of sustainability, the focus moved from the output side of the production system to a complete understanding of the physical dimension of the economy. From this point, the economy was conceptualised as an activity, extracting materials from nature, transforming them, keeping them as society’s stock for a certain amount of time and, in the end of the production-consumption chain, disposing of them again in nature. It has been recognised that environmental problems can arise at every step in this process. Under the heading of Material Flow Accounting (MFA), empirical research has been stimulated by this new conceptualization of society’s environmental problem (Fischer-kowalski and Haberl 1993; Fischer-kowalski, W.Bruckner et al. 1999) (Ayres and Simonis 1997). The aim of MFA is to draw a complete picture of the physical dimension of the social system by capturing all material flows driven by these system activities. The total amount and the progress through the economy of these materials is ideally reported within an accounting framework provided by MFA methodology. Most influential empirical work has been done on economy-wide MFA concentrating on bulk material flow analysis. Within Material Flow Analysis, there are two approaches, material flow accounting (MFA) concentrating on material and Substance flow accounting (SFA) concentrating on chemical substances like carbon, nitrogen, lead, chlorine and so on. Despite these differences, both approaches result in rather similar methodological assumptions. Moreover, due to methodological correspondance, MFA can be linked to SFA rather easily. One basic idea of MFA should be the attempt to reach a full balance integrating the input and the output sides. This idea of a mass balance is one of the most powerful features of the MFA approach. In terms of policy, this approach allows for the development of integrated resource and waste/emission strategies. Balancing is also a methodological tool, as it provides a framework for consistency checks and estimation of data gap. For material balances the first law of thermodynamics, the “law of conservation of mass” applies, which is also a leading theoretical criteria for material accounting. The law of conservation of mass attributed to MFA results in the following equation:

\[
\text{The sum of material inputs into a system} = \text{the sum of outputs corrected by changes in stocks}
\]

This equation applies not only to the system as a whole but also to all its sub-systems to which we refer as components of the system (Schandl and Schulze 1997).

**Check Lists (CL):** Check-lists are qualitative tools that give guidance to design, environmental management, and setting eco-labelling criteria. CL used for a particular purpose, such as check lists for design, may be general or customized for a specific sector or company. CL consider various different aspects such as recyclability or minimizing harmful substances (Behrendt, Jasch et al. 1997). Box 1 shows guidelines and design principles. Planners, designers and engineers are confronted with the question as to how to put these principles into action. They are easy to integrate into the normal planning and design process. In every design step it is easy to check if all
relevant criteria have been taken into account.

| Achieving environmental efficiency / optimal function | Saving resources |
| Use of renewable and sufficiently available resources | Increasing product durability |
| Design for product reuse | Design for material recycling |
| Design for disassembly | Minimizing harmful substances |
| Environmentally friendly production | Minimizing environmental impact of product in Use |
| Use | Implementing environmentally friendly logistics |
| Using environmentally friendly packaging | |
| Environmentally friendly disposal of nonrecyclable materials | |

**Box 1. Environmental Product Design Criteria and Principles**

### 2.3 Environmentally Conscious Economic Tools

The economic counterpart of Decision Making is known under several names, as Life Cycle Costing (LCC), Total Cost Assessment (or Accounting) (TCA), Cost Benefit Analysis (CBA), and Economic Input-Output Analysis (EIOA) (Klopffer 2000). With the exception of product take-back or producer’s responsibility of payment of the waste collection, costs involved in the use of products and in waste removal, or recycling generally do not show up. The main difference between conventional cost accounting and LCC or TCA consists in accounting for "hidden" or "less tangible" costs, including costs for environmental protection (Norris and Segal 2002). These costs are included in conventional cost accounting, mostly in the form of overhead, but they are not attributed clearly to a specific product system. Clear attribution to a product system is important for assessment in order to estimate the true costs (LCC) or true environmental interventions (LCA) of the product (system) of alternatives.

**Life Cycle Costing (LCC):** A company cannot afford to make product design decisions on strictly an LCA basis, without regard to economics and product performance. For an economic assessment, a decision maker has to address all the costs and benefits for which actors and participants in a product’s life-cycle are accountable. This investigation of economic impact is called Life-Cycle Costing. Basically, LCC is an assessment of the costs in each stage of the life-cycle of a product. The different cost factors (such as capital, labor, material, energy, and disposal) are investigated on the basis of current and/or future costs. LCC and LCA have major methodological differences despite the similarity of their names. LCA evaluates the relative environmental performance of alternative product systems for meeting the same end-use function from a broad, societal perspective. However, LCC evaluates the relative cost-effectiveness of alternative investments and business decisions, which is related to the usage phase in LCA, from the perspective of an economic decision maker such as a manufacturing firm or a consumer (Choi and Ramani 2003). Even if LCA and LCC are extensive methods in accessing environmental and economic respectively, each method has some limitations and absences of important concepts for the application in real business situation.

<table>
<thead>
<tr>
<th>Focal point</th>
<th>Limitation</th>
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<tbody>
<tr>
<td>LCA</td>
<td>Relative environmental performance of alternative product systems from a broad, societal perspective</td>
</tr>
<tr>
<td></td>
<td>No integration of costs and revenue streams which are not necessarily proportional to physical flows</td>
</tr>
<tr>
<td></td>
<td>No cash flow related to investment in product and process changes</td>
</tr>
<tr>
<td></td>
<td>No information of the timing of cash flow (cost/benefits)</td>
</tr>
<tr>
<td>LCC</td>
<td>Relative cost-effectiveness of alternative investments and business decision</td>
</tr>
<tr>
<td></td>
<td>No physical flows information; only considers the flows into or from LCC lifetime processes</td>
</tr>
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</table>

**Total Cost Accounting (TCA):** Total Cost Accounting (TCA) was introduced in the late 1980s with the introduction of clean production. The method typically focuses on in-company assessments of cleaner production investments. TCA can be described as a normal, long-term oriented cost accounting method, which pays special attention to hidden, less tangible, and liability costs. Liability costs are fines due to liability for items such as future clean-up, health care and property damage. Less tangible costs are consumer acceptance, corporate image and external relations. The TCA method also focuses on the risks and hidden costs associated with a product or activity.
In this method, also the economic benefits of pollution control measures are included, whereas in conventional accounting only the costs of pollution prevention would be taken into account. This inclusion of positive trade-offs clearly indicates life cycle thinking. The term "life cycle", however, is often defined in another way in the economic sciences, namely as the sequence product development - production - marketing/sale - end of economic product live (Norris and Segal 2002), this economic "life cycle" may be even shorter in some products than the physical life cycle ("cradle-to-grave") used in LCA. In a further step, even the external costs due to environmental damages connected with the products may be included. These costs are not incurred to the company, but rather to society or even to future generations. Since damages connected to the interventions caused by a product system is not clear, the quantification of these costs is difficult.

**Cost Benefit Analysis (CBA):** Cost-benefit analysis is an economic tool for supporting decisions on larger investments from a social point of view. Its domain of application includes regulatory and technology choices. It has been developed as a tool to remediate a number of shortcomings of a purely market oriented analysis of costs and benefits. CBA repairs some of the deficiencies cause by the market imperfections such as external effects and collective goods which are not expressed in market prices. For example, costs of emissions collection versus costs of emission damages (Boardman 2001). The main focus in the development of cost-benefit analysis is on how to evaluate unpriced effects. As in market choices, individual’s preferences can be expressed in monetary terms. The overall evaluation then is in one single category: money, providing a comparable yardstick for the decision maker (Hanley and Spash 1993).

**Economic Input/Output (EIO) Analysis:** Production of most typical products and materials requires a large number of diverse inputs, which in turn use many other inputs in their production. Often there are interdependencies in inputs, which have to be modeled. Attempting to trace all the direct and indirect inputs and associated environmental burdens all the way to ultimate raw material extraction becomes unpractical. In order to keep the analysis tractable, most LCAs limit the scope of analysis only to the major inputs at each stage, leading to problems of subjective boundary definition and comparability across studies. Moreover, data on input requirements and emissions for even such truncated LCAs have to be collected from a large number of different suppliers leading to high cost, time, and issues of data confidentiality and verifiability. To address the problem of subjective boundary definition in conventional LCA, Economic input-output life-cycle assessment (EIO-LCA) has been introduced by Lave (Lave, L et al. 1995). EIO-LCA takes a top-down approach and treats the whole economy as the boundary of analysis. Another strength of EIO-LCA approach is that economy-wide interdependencies in inputs are modeled as a set of linear simultaneous equations. EIO-LCA leads to a consistent boundary definition. However, it is still subject to several well-recognized limitations (Joshi 2000).

Limitation:

1. Current EIO-LCA is appropriate for comparing aggregate, disparate products that are well approximated by their commodity sectors, but not for comparing heterogeneous products within a commodity sector, or products that differ significantly from representative output of the sector, or completely new products
2. EIO-LCA captures the upstream environmental burdens associated with raw materials acquisition and manufacturing stages, but not those associated with product use and end-of-life options

2.4 **Environmentally Conscious Management Tools**

**Environmental Management System (EMS):** The LCA approach is widely recognized as a useful framework and attempts are underway to integrate life-cycle thinking into business decisions (Joshi 2000). A major international initiative in this direction is the series of environmental management standards proposed by the International Standards Organization, widely known as ISO14000. Standards being developed for inclusion under ISO 14000 include principles and guidelines for conduction of LCA for product evaluation. EMS is that part of the overall management system which includes the organizational structure, responsibilities, practice, procedures, processes and resources for determining and implementing the environmental policy. An EMS includes procedures for understanding environmental aspects, setting objectives and targets, establishing programs to achieve those objectives and targets, and reviewing performance versus those objectives and targets.

**Eco-Labeling (EL):** Eco-labeling is a voluntary method of environmental performance certification and labeling that is practiced around the world. An "Eco-label" is a label which identifies overall environmental preference of a product or service within a specific product/service category based on life cycle considerations. An Eco-label is awarded by an impartial third-party in relation to certain products or services that are independently determined to
meet environmental leadership criteria. Eco-labels are used to provide information about the environmental impact of a product. In environmental claims, it is important that verification is properly conducted (EU 1997).

**Eco-Design**: Eco-design is the systematic application of environmental life cycle considerations at the product design stage. The aim of eco-design is to avoid or minimize significant environmental impacts at all stages of the life cycle of a product, from sourcing of raw materials and purchased components, design and manufacture, to distribution, use and end-of-life disposal (Stevels 1997). Where such impacts occur in the company’s supply chain rather than within the company’s own manufacturing or other operations, or in use and disposal by customers, then Supply Chain Management (SCM) should become one of the key tasks in implementing and managing eco-design. There are growing pressures and incentives for suppliers of electronic and electrical components, materials and assemblies to consider eco-design. The advantages of eco-design are listed in Table 6.

<table>
<thead>
<tr>
<th>Table 6 Advantages of Eco-design implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Market Advantages</td>
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<tr>
<td>• Many corporate customers are implementing environmental management systems, especially ISO 14001, and increasingly imposing environmental requirements on their suppliers</td>
</tr>
<tr>
<td>• Eco-labelling schemes require information from suppliers</td>
</tr>
<tr>
<td>• Eco-design offers opportunities to &quot;add value&quot; to customers by reducing their energy and waste costs</td>
</tr>
<tr>
<td>Other Advantages</td>
</tr>
<tr>
<td>• Potential cost savings by reducing materials, waste and energy</td>
</tr>
<tr>
<td>• Potential to exceed environmental regulation, especially relating to toxic and hazardous substances</td>
</tr>
</tbody>
</table>

In order to make eco-design operational it is necessary to establish guidelines and design criteria as described in Box 1 and to incorporate them into the development of new products and production procedures.

### 3. Relationship between Tools and Environmental Supply Chain

Environmental supply chain management (ESCM) defines its scope to the end user and beyond, to reuse, recycling, and disposal. However, environmental matters have not traditionally been highly valued in supply chain management. In order to analyze environmental impact over the ESCM, effective tools and methodologies should be integrated into ESCM. ESCM is the incorporation of environmental considerations into purchasing decisions and supplier management practices. It is essential to determine where environmental impacts occur. ESCM will become one of the key tasks in implementing and managing environmentally conscious tools if impacts occur in the company’s supply chain rather than within the company’s own manufacturing or supplier operations, or in use and disposal by customers. This is especially true in service and other organizations at the end of the supply chain. Such organizations typically do not have product design functions or carry out design except to the degree that they plan and design facilities and operations. They typically do not manufacture anything but buy in the products and materials they require. Consequently, most of the environmental impacts of their activities are in their supply chains. ESCM is likely to be an important element or outcome of an eco-design process seeking to reduce the bought-in environmental impacts of the many input materials and components. As such companies increasingly contract out manufacturing activities, design activities and product impacts may shift relatively to earlier points in the supply chain. ESCM is therefore becoming increasingly important as an issue. Environmentally Conscious Tools and ESCM are likely to be most effective if considered and carried out, not as separate exercises or as technical activities alone, but as part of an environmental management approach covering the company as a whole. Life Cycle Assessment (LCA), a technique for gathering data and improving the environmental performance of a product, is a candidate for ESCM integration. However, because of the complex interactions along and between the supply chains, it is clear that no single tool will suffice to give a complete analysis of the environmental impacts of providing the services.

### 4. Conclusion

In this paper, we presented a review of the state-of-art tools and methodologies on environmentally conscious manufacturing and management for sustainable product development. The reviewed work is presented by category. Some general conclusions from our review are as follows:

- Environmental issues are gaining popularity among society, governments and industry due to negative
environmental developments.

- Manufacturing of environmentally conscious product is crucial in order to minimize the materials use. This can be achieved by studying the life cycle of the product from its design stage to its retirement stage and incorporating this information into engineering design and production.
- A large number of tools have been developed in order to aid public or private sector environmental management strategies and operations.
- It is crucial to use the most appropriate tools for specific problem solving. Generally, no single tool can depict all sorts of problem shifting. Failure of using the appropriate combination of tools for supporting decision-making can result in the use of an incomplete or inappropriate analysis, and arrival at the wrong conclusion.
- The application of traditional tools is limited due to the objectives, constraints, and gaps between tools. Our review on the current state of the research indicates that better systematic tools for Sustainable Product Development (SPD) decision-making are required.
- Because traditional tools all focus on a common topic, there is a need for a clear characterization of them. This characterization will enable a sound linking of these tools to specific questions, thus preventing inappropriate use of them. It will also contribute to a consistent and productive methodology development and may lead to good guidance for the development of databases.
- Therefore, it is necessary to develop qualitative and quantitative decision tools by these clear characterization for successful implementation of Sustainable Product Development (SPD).
- Environmental Supply Chain Management (ESCM) is one of the key tasks in implementing and managing environmentally conscious tools if impacts occur in the company’s supply chain rather than within the company’s own manufacturing or other operations, or in use and disposal by customers. Developing methodologies for mapping the environmental impact along the extended supply is challenging.

References


