Progress on Internet-Based Educational Material Development for Electronic Products and Systems Cost Analysis

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Abstract

The objective of this project is to build internet-based educational materials that address the economic impact of electronic packaging technology, specifically the process of predicting the manufacturing and life cycle cost of electronic systems during their design and development process.

This paper reports progress on: 1) the development and dissemination of web-based instructional materials for use in cost analysis courses and as supplemental materials for a broad cross-section of other courses in the electronics and electronic packaging areas; and 2) the expansion of the elements within the course that address life cycle costs, particularly the concepts of life cycle assessment (LCA) and design for environment (DFE).

Six internet-based modules are being developed. The modules developed include a mixture of lecture materials (in textual and video format), case studies, on-line computational tools, bibliographies, links, and discussion/homework problems. The modules are internet-based and could be hosted by a central organization such as the IEEE.

Introduction

Ten years ago engineers involved in the design of electronic systems did not concern themselves with the cost effectiveness of their design decisions; that was someone else's job. Today the world is different. Every engineer in the design process for an electronic product is also tasked with understanding the economic tradeoffs associated with their decisions. Yet aside from "generic" engineering economics that focus on capital allocation problems, electronic system designers get no training in cost analysis, let alone analysis that is specific to electronic packaging.

A one-semester course on cost analysis for electronic systems has been developed [1]. We are currently working on the development and dissemination of web-based instructional materials based on the existing course and expanding the elements within the course that address life cycle costs, particularly the concepts of life cycle assessment (LCA) and design for environment (DFE). The six modules developed are described in Table 1.

The organizations working on this project are the Computer Aided Life Cycle Engineering (CALCE) Electronic Products and Systems Center in the Mechanical Engineering Department at the University of Maryland, and the Center for Energy and Environmental Resources (CEER) through the Chemical Engineering Department at the University of Texas.

CALCE Electronic Systems Cost Modeling Laboratory (University of Maryland) **-** The Electronic Systems Cost Modeling Laboratory (ESCML) develops modeling methodologies and tools that address all aspects of the life cycle cost of electronic system from hardware fabrication and software development through sustainment and end of life. ESCML is part of the CALCE Center which includes a diverse mix of industry and government funded research programs in electronic packaging and related fields in addition to a progressive educational program currently consisting of 12 core courses in electronic packaging [2]. Over 50 organizations representing the world's leading avionics, automotive, computer, semiconductor, and electronics manufacturers sponsor the Center. CALCE is recognized as a driving force behind the development and implementation of "Physics-of-Failure" approaches to reliability and life cycle prediction, as well as a leader in accelerated testing, and electronic parts selection and management.

Center for Energy and Environmental Resources (University of Texas) – The Center for Energy and Environmental Resources (CEER) at the University of Texas maintains research programs in design for environment, air quality engineering and the energetics of industrial processes. CEER's research programs are funded by federal, state and private sponsors.

Web-Based Courseware Development

Successful completion of the modules enables elements of cost analysis to be introduced into a broader cross-section of engineering courses than it is today. In this section we present an example web-based module for test economics (a description of the module appears in Table 1).

A lecture consists of the combination of audio/visual lecture materials, interactive java calculators, problems, and supplemental materials organized as shown in Figure 1.

Table 1. Description of modules developed in this program.

Module Description	Developer
Test Economics - This module discusses the relationship between defects and faults, develops the concept of fault coverage and relates it to the yield and cost after the execution of a test operation. Armed with a formulation of the yield, cost, and scrap levels resulting from test steps, students develop solutions to a series of test modeling scenerios from electronic system fabrication and assembly.	University of Maryland
Process Flow Analysis - Introduces manufacturing processes as a sequence of steps. Each process step is defined by the inputs received from the previous step in the sequence, and a corresponding set of outputs (matching the inputs) passed to the next step. This module focuses on process step attributes that can be directly linked to costs associated with the process step, i.e., labor, material, tooling, and equipment/facilities content.	University of Maryland
Life Cycle Concepts - Introduces the student to the concept of the life cycle for a product. Within the life cycle context the product may be evaluated as a function of cost, materials inventory, and/or environmental impact. This module, will consider 5 stages within the life cycle: design, procurement, manufacturing, product use, and end-of-life.	University of Texas
Quality and Yield - Various types of defects are introduced along with metrics that can be used to characterize them. The concept of yield is introduced and several yield relations are derived assuming various spatial defect distributions. The accumulation of yield through a process, yielded cost (cost divided by yield), and the relationship between producibility and yield are explored.	University of Maryland
End-of-Life (EOL) - This module discusses the pros and cons of reusing selected portions of a product within new products. The module formulates the necessary relations (based on manufacturing, test, and disassembly concepts) for quantitatively assessing the cost and material waste of various salvage options for electronic assemblies.	University of Texas
Product Sustainment - This module focuses on the costs associated with sustaining an electronic product throughout its field use. Several key sustainment topics are treated including: Maintenance, Reliability, Energy and Material Consumption, and Obsolescence.	University of Maryland

Test Economics Lecture **-** The test economics materials consist of the content shown in Table 2.

Table 2. Test economics module outline.

1. Introduction
2. Fault spectrum
3. Fault coverage
    a. Explanation
    b. Relating fault coverage to yield
        i. Conversion matrix
        ii. Defect clustering
4. Process flow implementation of testing steps
    a. Scrap
    b. Cost of scrap (pass fraction, escape fraction)
5. False positives
6. Wafer probe
7. Test throughput rate
8. Test pattern generation
    a. What are test patterns
    b. Test pattern generation costs
9. Design for test (DFT)
    a. Concept
    b. Area overhead vs. test coverage (cost)
10. Known Good Die (KGD)

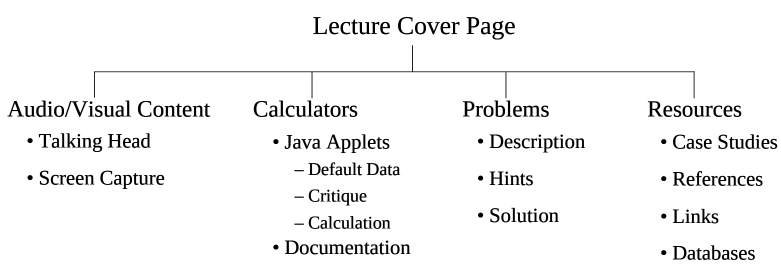

Figure 1. General lecture organization.

The material outlined in Table 2 is covered in two audio/visual lectures. A lecture cover page for the test economics lecture is shown in Figure 2. In most cases the length and content of the lecture material requires that the audio/visual portion be presented in several sections.

The audio/visual portion of the lectures was created using Screen*Watch* from OPTX International [3]. Screen*Watch* can record PowerPoint presentations for Internet or intranet streaming, as well as record a PC desktop. Screen*Watch* records a Windows NT desktop, producing in real-time, a full-motion screen recording of a PC desktop for network streaming. Screen*Watch* files are small; an 800x600, 16 colors desktop recording averages to approximately 8 to 10 megabytes per one hour of recording time. Screen*Watch* files are optimized to stream at low bandwidths, even as low as 14 kbs, which makes Screen*Watch* a useful Internet streaming

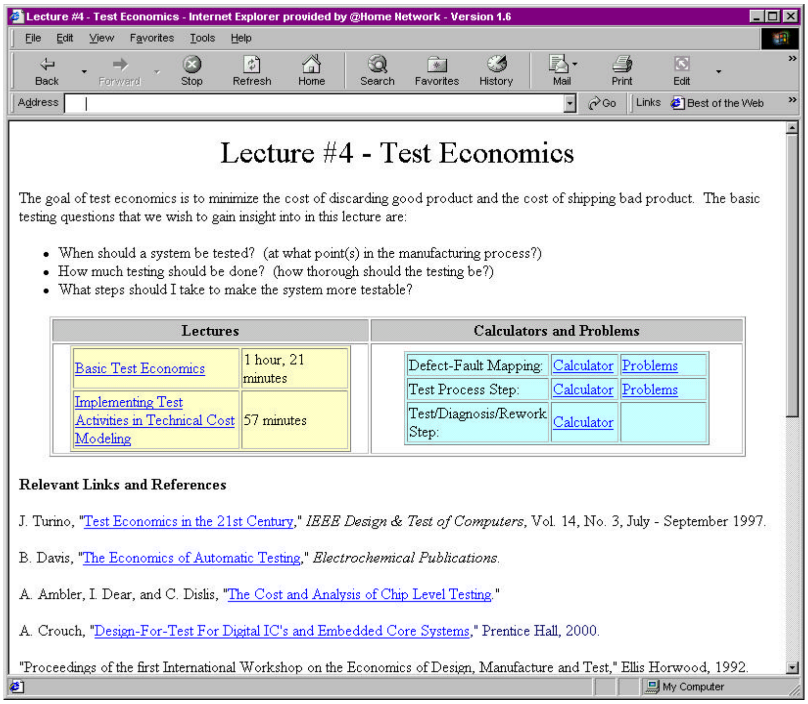

Figure 2. Example lecture cover page.

development tool. Screen*Watch* is fully integrated with RealNetworks technology, allowing Screen*Watch* to be combined with other media file types supported by Real. Screen*Watch* can be combined with text, audio, video and Flash for network streaming through RealServer G2. Using RealPlayer G2, Screen*Watch* recordings can be streamed over an intranet, Internet, or played locally from a CD-ROM, and no plug-in is required for playing Screen*Watch* files because the plug-in is included with RealPlayer G2.

The primary advantage of using Screen*Watch* in this courseware application is its support of full-motion screen capture recording of a computer's desktop area in real time. This enables two key elements for our courseware: 1) the ability to draw on the screen during the lecture, shown in Figure 3, and 2) the ability to show and demonstrate software other than static images during the lecture, Figure 4.

To enable full-motion screen capture, Screen*Watch* uses a display capture method to capture the data sent to the display driver and then save the information to a file, usually in a proprietary format. OPTX developed a proprietary display driver for recording a PC desktop in full motion and real time. The Screen*Watch* Recorder intercepts the data sent to the Screen*Watch* display driver on the recording PC, and then saves the information for playback in a proprietary format, which is the format used for streaming with RealNetworks. The Screen*Watch* method of screen recording produces a recording of a PC desktop, providing exceptional quality for network streaming, even at low bandwidths.

During the audio/visual lectures, students may be directed to pause the presentation and use the calculator tools provided with the courseware to explore various concepts. The calculators are Java based and delivered to the student on the same website that supplies the lecture. The calculators may be composed of several linked calculations, such as the calculator shown in Figure 5, which takes the student from a conversion matrix that relates defects and faults through the determination on defect coverages in five distinct steps (three are shown in Figure 5). Each calculator includes built-in default data that can populate all fields with valid values. In addition, all inputs entered by a student can be automatically critiqued for consistency by the tool and feedback appears in the form of a dialog box indicating errors and warnings with regard to input data. The input and output fields in the calculators are linked by color, i.e., a student may choose a particular output field in one portion of the calculator and observe where it appears as an input later in the analysis process.

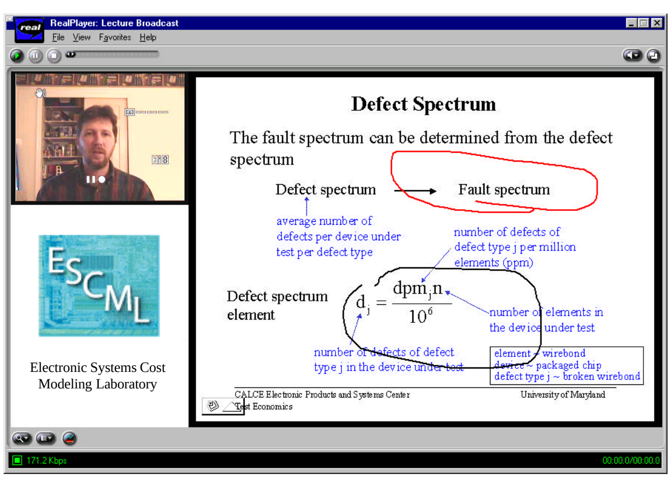

Figure 3. Realplayer audio/visual window. Lines are drawn on the screen in real time during the lecture.

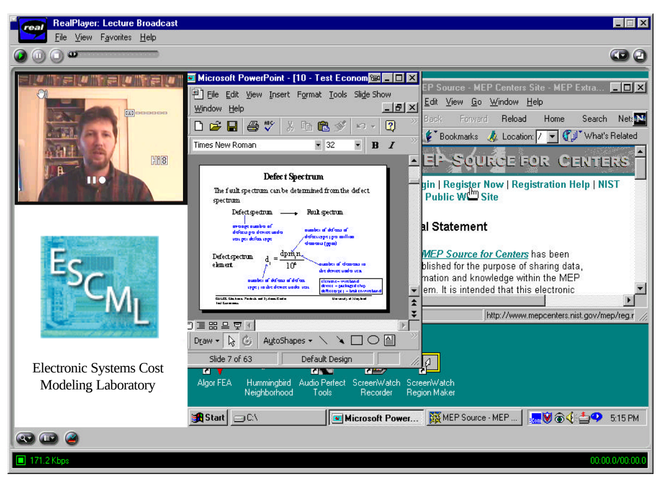

Figure 4. RealPlayer window showing access to other applications running on the desktop.

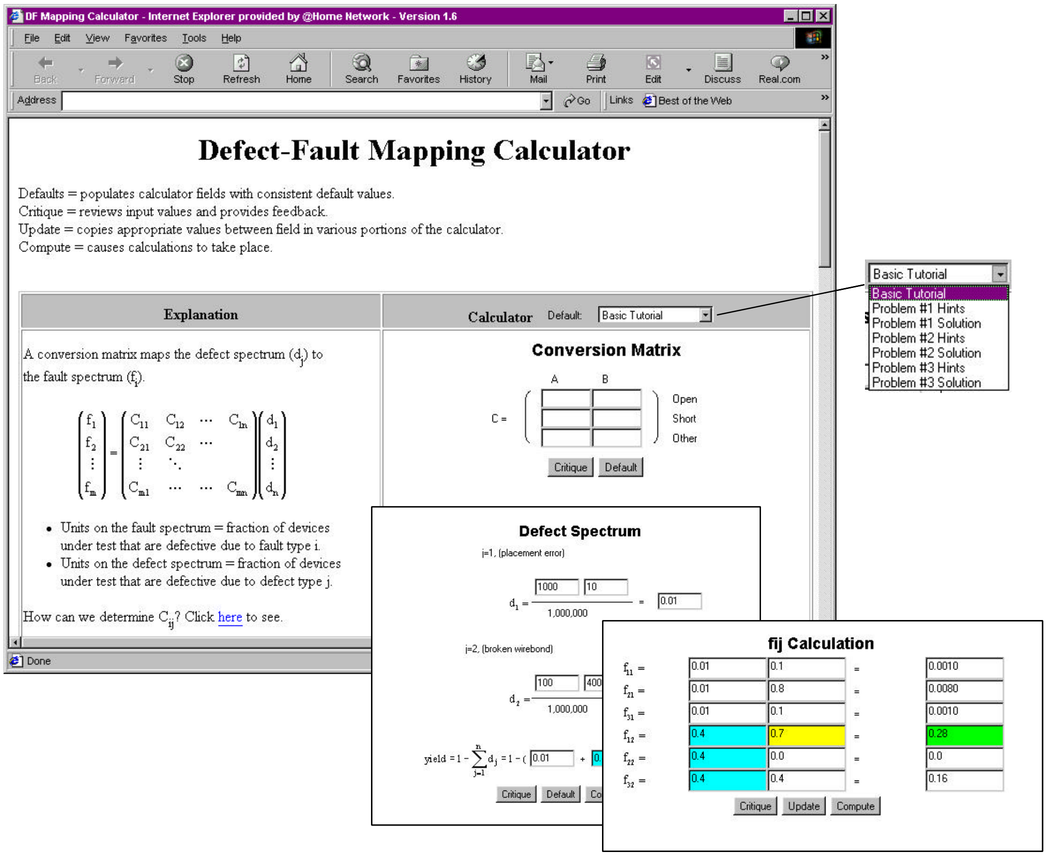

Figure 5. Defect-fault mapping calculator. Explanatory information appears in the left column and the various portions of the calculator appear on the right. This calculator contains five pieces: Conversion Matrix, Defect Spectrum, f_{ij} Calculation, Full Matrix, and Fault Coverage.

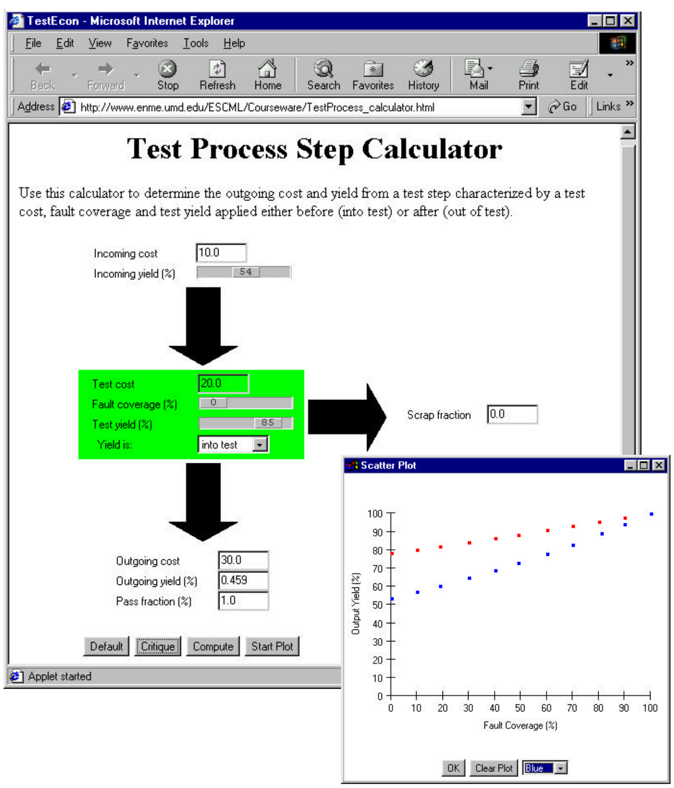

Figure 6. Test process step calculator. The associated plotting tool allows students to graph each solution they generate.

An alternative form of a calculator is shown in Figure 6. This calculator allows students to explore the cost and yield of products after a test operation is performed. Students can vary the fault coverage, test cost, and test yield in addition to the incoming cost and yield to determine the resulting cost and yield after the test activity. Students can initiate plots to record the data as they use the calculator.

Along with the calculators, the web site provides problems that the students can use the calculators to solve. The problems are arranged in a hierarchy from straightforward to more difficult. The easiest problems simply provide values for students to plug into the calculators, harder problems range from exercises that require students to explore more subtle points of the analysis with the calculation tools to design problems.

With each problem we supply a hierarchy of hints and solutions. The one unique attribute of this implementation is that the hints and solutions to each problem are interactive. For example, in the upper right corner of the Defect-Fault Mapping Calculator students can set the context of the “Default” button used within the calculator to shadow any of the problems (shown in Figure 5).

Life Cycle Assessment (LCA) and Design for Environment (DFE) **-** Design for Environment (DFE) is becoming a common element in the concurrent engineering process, or the "Design for X" approach. There are many elements to DFE, but the two that are receiving the greatest attention for electronics are Life-Cycle Assessment (LCA), and end-of-life EOL. These are being driven strongly by current activities in Europe where there is demand for accountability along the supply chain. In addition, the European Union's Waste Electrical and Electronic Equipment (WEEE) Directive [4] has made material selection and end-of-life issues critical for original equipment manufacturers (OEMs) who wish to market products in Europe.

The growing interest in Life-Cycle Assessment (LCA), as part of the Design for Environment (DFE) process, has led to the introduction of methodologies and approaches to incorporate broader environmental considerations into design and business decision-making. The life cycle concept may involve evaluation of a product as a function of cost, materials inventory, and/or environmental impact. This module will consider 5 stages within the life cycle: design (including material selection), procurement, manufacturing, product use, and end-of-life. A full environmental LCA includes three stages (sometimes referred to as the 3 "I's"): inventory, impact, and improvement. While the nature of the "impact' and "improvement" will be discussed in the course, the focus will be on the inventory stage, which is at the heart of any LCA.

The first lesson addresses the reasons for performing an life cycle assessment, including pollution prevention and minimization, conservation of non-renewable resources and ecological systems, development and utilization of cleaner technologies, and recovery of components and materials at a product's end-of-life. How the design of a product (including material selection) may affect these parameters is discussed. The nature of a life-cycle assessment is presented, including the concerns at various stages of a product's life.

The second lesson covers the 3 stages of the LCA: inventory, impact, and improvement. The objectives and challenges inherent in each of the three stages of the life cycle assessment are shown. Specific exercises illustrate the complexities and potentially inconclusive answers that may result when performing these analyses. The metrics that are commonly used are presented and the approaches taken by several commercially available tools are illustrated. The concept of a functional unit (for products) and use-clusters (for processes) is presented, and the critical nature of defining system boundaries is demonstrated. Data uncertainty is illustrated and discussed. Examples and exercises include electronic assemblies as well as simpler, more commonly used products. This enables the module to be used in both engineering and non-engineering curriculums.

The third lesson shows the student how to perform life-cycle inventories using mass and energy balance (input - output) techniques and demonstrates how to include cost and quality metrics in the analysis. Both electronic and non-electronic products are illustrated. The importance of process yield, product lifetimes, and material recoverabilities are presented and calculated in several exercises.

The fourth lesson covers impact analysis, including the difficulties associated with selecting appropriate metrics and making "apples to oranges" comparisons. Impact classifications such as global warming, acidification, human toxicity, and land use are presented and discussed. Specific examples in the electronics industry, such as use of halogenated flame retardants are presented.

The final lesson discusses full vs. streamlined LCAs [5] and allows the student to construct several streamlined analyses in order to perform tradeoff analyses. The challenges of making the "right" decision will be discussed as well as the potential design opportunities that create win-win changes in a product. Examples of "good intentions - unintended consequences" provide a final cautionary note.

Product Design, Procurement, and Materials Selection **-** The types materials used in various subassemblies of a computer workstation are discussed along with potential environmental issues associated with extraction, processing, and end-of-life of these various materials. The impact of component selection on downstream processes and related environmental issues is also presented. The student is encouraged to look for win-win options and designs and to avoid assuming that choosing an environmentally conscious material or component results in higher cost or lower performance. Examples from industry are used to illustrate how material reduction in a product (typically a desirable performance metric for electronic products) often reduces cost and process waste and should decrease resource demands at end-of-life. Another example shows how switching to from aluminum to glass disk improved performance while decreasing waste and increased recycling options, [6].

A calculator allows the student to perform tradeoff analyses between different types of parts and final outputs (cost, yield and waste). Incoming parts vary by cost, incoming quality, and material (which affects the assembly process). A second calculator demonstrates the effect of increasing the number of materials on cost of recovery and purity of recovered materials at end-of-life

Reuse, Refurbishment (Upgradability and Repair), and Remanufacturing **-** Many original equipment manufacturers (OEMs) of electronic equipment are becoming increasingly sensitive to designing products with future upgrades in mind. Products that have separately repairable and replaceable components, parts, and subassemblies that are easily accessible presumably helps prevent the premature retirement of equipment and protects the customer's investment. There are challenges associated with this approach, however. Components must be held in inventory and decisions must be made as to how long an OEM wishes to support a product in the field. Creating and managing inventories of large numbers and varieties of parts may not be cost effective and the economics may not be obvious. For example, IBM has shown that while the value of components decreases during the first 5 to 7 years of a product's life, the value actually increases beyond that due to scarcity issues, [7]. This section of the module discusses the challenges related to reverse logisitics, inventory management, modularity opportunities and constraints, mechanisms for reintroduction into marketplace, quality and reliability issues (test or not to test).

An exercise is provided to calculate the costs of inventory, storage and transportation. It also allows the student to see the benefits of modular construction and minimization in the number and variety of components.

Disassembly **-** Many companies have redesigned equipment so it can easily be disassembled with simple tools such as a screwdriver, or have eliminated the need for tools all together by employing the use of clip or snap fasteners. Models that address the disassemblability of electronic systems are developed and used to assess various systems. Models developed include: difficulty scores and energy/entropy calculations.

Recyclability (Material and Component Recovery **-** Most electronic equipment consists of a mixture of metals, plastics (both thermoplastics and thermosets), and glass. Metals (especially precious metals) are recovered through relatively well understood and economic methods. Unfortunately the amount of metals in electronics is on the decrease. The glass is typically contained in the monitor or CRT and much of it contains significant amounts of lead. Most glass is sent to a metal smelter where the lead is recovered and the glass acts as a flux in the smelting process. There are a few operations that recover the glass and sell it back to CRT manufacturers in a closed loop recycling system. The engineering thermoplastics, which are increasing in relative volume in electronics equipment, are the most problematic. Recycling of many plastic products (such as bottles and film) has been quite successful. However, these are typically made of a single plastic and do not have other (non-plastic) materials affixed to them. In contrast, a single electronic product may use 10 to 20 different types of plastics, some of which may be painted or coated, and all of which are attached to other parts that are made of plastic (probably of a different composition), glass, or metal. This contamination with non-plastic materials and by co-mingling of different types of plastics makes recycling technically difficult and therefore economically problematic. The barriers to recycling of engineering thermoplastics have been the subject of ongoing Stakeholder Dialogues at Tufts University funded in part by EPA and DoE [8].

Many companies have DfE guidelines aimed at facilitating the recyclability of their products. These may include elimination of hard to remove labels and foams, minimization of plating and painting of parts, minimization of the number of different materials used in an individual product, and avoidance of the attachment of incompatible materials.

Exercises are provided to determine the cost, the success, and the insertion of recovered materials and components into a new product.

Summary

Implementation of the internet-based system cost analysis software at the Universities of Maryland and Texas is continuing. The implementation includes the development and application of novel web-based calculation tools for supporting the delivery of multimedia courseware.

The next step, which is beginning at this time, is to use the new materials within both courses focused on cost analysis and boarder courses in the electronics and manufacturing areas.

Acknowledgement

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