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Using Teardown Analysis as a Vehicle to Teach Electronic Systems Manufacturing Cost Modelling*

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Product teardowns are used in an electronic systems cost modelling course at the University of Maryland. As part of a semester-long project, each student in the course chooses a product and determines its manufacturing cost using a combination of top-down cost analysis (to determine what the product must cost) and a detailed bottom-up model (that students calibrate using the top-down analysis). Products considered by students range from complex systems such as mobile phones to relatively simple systems such as memory sticks and McDonald's Happy Meal® toys. Using product teardowns and reverse engineering ideas has proved to be an effective vehicle for educating students on practical manufacturing cost modelling of systems and complements typical engineering economics analysis.

Keywords: Teardowns; reverse engineering; product dissection; cost modelling; top-down; bottom-up; electronics

INTRODUCTION

TWENTY YEARS AGO many engineers involved in the design of electronic systems took, at best, a secondary interest in the cost effectiveness of their design decisions; that was someone else's job or an issue to be addressed after the initial release of the product. Note that many electronic products are also initially driven by time-to-market rather than cost, a situation that is not as prevalent for non-electronic products. Today the world is changing. All engineers in the design process for an electronic product are also tasked with understanding or contributing to the understanding of the economic tradeoffs associated with their decisions. Yet aside from general engineering economics that focuses on capital allocation problems, system designers have virtually no resources and obtain little or no training in cost analysis, let alone analysis that is specific to electronic systems.

Unfortunately, when engineering students were asked what they thought the cost of a product was (and assigned to determine cost estimates of products in an undergraduate capstone design course at the University of Maryland) they all too often added up the costs of procuring the bill of materials and declared that to be the cost of the product. Few students are surprised by Figure 1, but virtually no students, even those who had taken courses in engineering economics, were equipped to competently estimate the manufacturing or life cycle cost of a real product.

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We use product teardowns in our electronic systems cost modelling course to provide students with a basis for practical manufacturing cost modelling. A teardown is an analysis of an existing system to assess its content. We use the term 'teardown' instead of 'reverse engineering' since:

a) reverse engineering actually refers to the retrospective development of the technical data necessary to support an existing production item [1],
b) the majority of the literature on reverse engineering today is aimed at software reverse engineering, not hardware.

Teardowns have also been referred to as 'product dissection'. They are often used to establish a knowledge base which, over time, will facilitate the projection of technology trends, developments and capabilities that can be used for forecasting R&D directions. Alternatively, Ulrich and Person [2] have used the term 'product archaeology' to describe a technique for analyzing physical products in order to derive and measure their manufacturing content. Teardown analyses can focus on an examination of the design features that contribute to the time and cost to assemble the product, the cost to market of the product, the materials in the product, or other views of the product [3]. Product teardowns commonly include photographs of the disassembled product, bills of material including costs, manufacturing cost analysis, material analysis and assembly processes. Specific electronic product teardown analyses are available commercially from companies such as Portillegent and iSuppli.

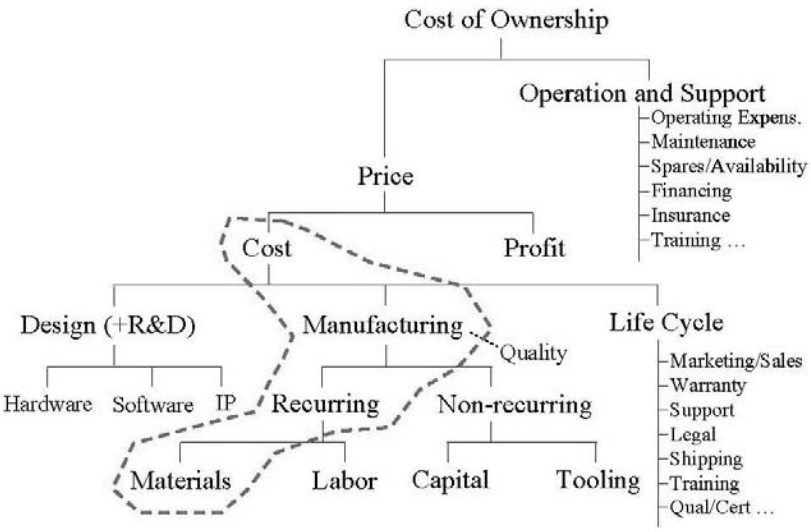

Fig. 1. Cost analysis. The dashed line indicates the limited view of cost analysis shared by many engineering students. We call the sum of everything Cost of Ownership, which consists of the manufacturing cost, the life cycle cost, and, operation and support. Alternatively, in the context of product development and design, the sum of everything is often called Life Cycle Cost and may be broken down into Manufacturing cost and User cost.

The concept and execution of the teardown project developed and assigned as a semester-long project that supplements a Manufacturing and Life Cycle Cost Analysis of Electronic Systems course in the Mechanical Engineering Department at the University of Maryland, are applicable to non-electronic systems; however, the course we are focusing on appears within an electronic products and systems curriculum. Product teardowns have been previously used in engineering educational curricula to introduce undergraduate students to general engineering skills in the form of competitive benchmarking of products [4], and product disassembly has been used in introductory engineering courses to teach design processes [5, 6, 7]. Formal courses in 'product dissection' have been previously offered by Stanford [8], Pennsylvania State University [9] and others. These previous uses of product teardowns, however, have not explicitly addressed the analysis of costs, at most treating cost as a qualitative constraint on design without attempting to perform any type of actual detailed analysis. In addition, some undergraduate engineering capstone design courses include manufacturing cost analysis details to varying degrees, even including business students in the design teams [10].

COST ANALYSIS COURSE DESIGN AND CURRICULUM

Our one-semester course has been developed and taught at the University of Maryland for approximately eight years. Other cost analysis courses are taught within the engineering departments of most universities including engineering economics and life cycle cost management. Both of these areas are important, but neither provides the cost analysis background that is needed by product design engineers nor has an electronic systems focus.

Engineering economics treats the analysis of the economic effects of engineering decisions and is often identified with capital allocation problems. It provides a rigorous methodology for comparing investment or disinvestment alternatives. Alternatively, the course discussed in this paper focuses on the detailed cost modelling necessary to supply engineering economic analyses with the inputs required for investment decisions.

Life cycle cost management (LCC) courses traditionally focus on 'programme' level cost analyses (often used in the government and defence communities), i.e. LCC provides the background necessary to manage costs associated with large system contracts.

The objective of our course is to provide an in-depth understanding of the process of predicting the costs of products and systems. Elements of traditional engineering economics are melded with manufacturing process modelling, life cycle cost management concepts and selected concepts from environmental life cycle assessment to form a practical foundation for predicting the real cost of electronic products. An outline of the course is shown in Table 1.

As indicated in Table 1, in the first half of the course various manufacturing cost analysis methods are taught including: process-flow/technical cost modelling, parametric, cost-of-ownership and activity-based costing. The effects of learning curves, data uncertainty, test and rework processes and defects are considered in conjunction with these methodologies. In the second half of the

Table 1. Outline of Electronic Products and Systems Cost Analysis Course [11]

Part 1—Manufacturing Cost Analysis
Manufacturing Cost Models
Process-Flow Analysis and Technical Cost Modeling
Quality/Yield
Producibility
Cost of Ownership
Activity-Based Cost (ABC) Modeling
Parametric Cost Modeling
Test Economics
Diagnosis and Rework
Modifications and Uncertainty
Learning Curves
Monte Carlo Analysis
Part 2—Life Cycle Cost Analysis
Life Cycle Costs
Market Window—Schedule Drivers
Return on Investment
Design and Development Costs
Chip Design Costs
Software Cost Estimation
Sustainment (Maintainability)
Introduction to Sustainment
Sparing Analysis
Availability Analysis
Technology Obsolescence
Refresh Planning and Technology Insertion Planning
Warranty Cost Analysis
Sustaiment Cost Analysis
Design for Environment
Introduction to Design for Environment
Life Cycle Assessment (LCA)
End of Life: Disassembly
End of Life: Salvage

course, the product life cycle costs associated with design, sustainment, and end-of-life are addressed. The course uses real-life scenarios from integrated circuit fabrication, electronic systems assembly, electronic substrate fabrication and electronic systems testing at various levels. The course is offered as part of the Electronic Products and Systems graduate curriculum (about 90% of the students are graduate students and 10% are senior undergraduate students). The course is also offered as an elective in the Reliability Engineering curriculum and in the Master of Engineering and Public Policy programme at the University of Maryland. The majority of the students taking the course have previously taken at least one introductory course in electronic systems and are therefore familiar with the technologies and assembly processes used to create electronic products. The course is taught on the web and a selection of multimedia web-based instructional materials have been previously developed for the course [12,13]. Approximately 25% of the students in the course are distance students taking the course on the web. Recent offerings of the course have included distance students from Apple Computer, Boeing, Delphi Automotive, NASA, NIST, Northrop Grumman, the US Army and other organizations. Versions of the course have also been offered as two- or three-day industry short courses, which do not include the teardown project.

PRODUCT TEARDOWN PROJECT DESIGN

Each student in the course is required to identify and obtain a consumer product with significant electronics content, although the project could certainly be performed with other types of products, mechanical for example, but since our course is focused on electronic systems, the teardown project has been confined to systems with significant electronics content. In the Fall 2005 semester, products considered by students ranged from complex systems such as mobile phones to relatively simple systems such as memory sticks and McDonald's Happy Meal® toys. Each student is tasked with determining the manufacturing cost of the product they have chosen.

Students begin the project by performing a teardown of their selected product from which they create bills of materials and descriptions of assembly processes. Students may choose to destructively cross-section printed circuit boards to determine their layer counts and design rules, they may desolder parts from the board, decapsulate die from plastic packages, etc., and are required to photograph details of the disassembled products. Most of the products chosen for analysis by the students do not have datasheets or other publicly available documentation describing their content and therefore cannot be assessed without disassembly. After the product is disassembled, the students perform the following two tasks:

1) First the students must perform a top-down cost analysis to determine upper and lower bounds on what the product ought to cost. A top-down estimate is established by considering the overall functionality of the product and how that functionality is provided. In a top-down analysis, the cost estimate is made based on the function rather than the components that implement the function. Top-down analysis is determined by what the product should cost (or must cost) in order to be offered at a known price. The students are told that they can use any resources and any information they can find to support their top-down analysis. For example, a student may know the sales price of the product at the store where they purchased it; the student could work backwards from the sales price to formulate the manufacturing cost by estimating profit margins, transportation costs, inventory costs, etc. There is no one right answer for the top-down analysis; the key to the exercise is that we force the students to "defend" their top-down analysis, i.e. they must convince the instructor that they have formulated a reasonable estimation.
2) In the second phase of the project, students are required to create a detailed bottom-up cost model for their product. In a bottom-up estimate the cost of each component and/or process step is modelled and those costs are accumu-

lated to produce a final cost estimate. Students use manufacturing cost modelling methodologies taught in the course to construct the bottom-up model. The methodologies the students can use include: process flow modelling, technical cost modelling, cost of ownership, activity based costing, parametric cost modelling, or in many cases a combination of methods. The bottom-up models generally include detailed cost contributions from labour, materials, tooling, equipment, etc.

The top-down analysis is done in the first half of the semester (while learning manufacturing cost modelling in class). In the second half of the semester, students apply the manufacturing cost modelling methodologies to construct the bottom-up model for their selected product. See [14] for a discussion of top-down and bottom-up cost estimating.

The final task required in the project is to calibrate the bottom-up model using the top-down model and produce a final manufacturing cost estimate broken down by labour, materials, tooling, capital equipment, etc. The students discover that the bottom-up detailed cost models may have relative accuracy (i.e. may get the ratio of labour to materials costs right), but may have poor absolute accuracy. On the other hand, some smart thinking enables students to 'reverse engineer' a good overall cost number (the top-down analysis result), but won't necessarily tell them how that cost number is broken down between labour, equipment, tooling, materials, etc.

Final reports from the project include analysis details and detailed product descriptions with photographs of the disassembled product and bills of materials. Students must also provide a detailed discussion of the accuracy of their predictions, i.e. they must quantitatively address the magnitude of the uncertainties in their estimations.

Part of the way through the semester (at one of the mid-point reviews), students working on similar products are required to compare notes and determine if their top-down estimates are consistent. For example, in Fall 2005 several students worked on calculators. All of these students had to produce an analysis of how their estimate compared to others and why it may differ.

The project is designed to span a 15-week semester. We wish to stress that the teardown project discussed here is not the subject of a project-oriented or 'capstone' course, but rather performed by the students concurrently with other course activities (lectures, homework, exams, etc.). The project is broken into three milestones each of which has its own due date and is reviewed by the instructor:

1) identification of a product and performing a teardown of the product (3 weeks);
2) top-down cost estimate (4 weeks);
3) bottom-up cost estimation, calibration of the model and final report (8 weeks).

Project grading

Although students performing the teardown project must satisfy a series of milestones during the semester their project grade is based on the final report, Table 2.

As an added incentive in Fall 2005, the students were told that the best projects would be included in this paper and that the students who developed those project would be co-authors of the paper.

Pedagogical design

In previous offerings of the cost analysis course, we have focused on the students' conceptual knowledge of cost estimation and have developed curricular environments to improve it [12, 13]. However, conceptual knowledge is only one part of what students need to know in order to solve complex engineering problems. While homework

Table 2. Project final report grading criteria (provided to students with the product assignment)

1. (20 points) Description
   a. Clear, detailed pictures of product teardown
   b. Pictures labeled to show part names and locations
   c. Description in words of the materials and assembly details (including describing attributes that cannot be seen in the pictures)
   d. General product area and market described
2. (20 points) Top-down model
   a. Discussion of manufacturer's marketing strategy if relevant
   b. Parametric studies with similar products if relevant
   c. Use of public disclosure numbers (operating margins, etc.) for the manufacturer or, if manufacturers are not public, obtaining similar information for their competitors
   d. Public disclosure numbers for retailers (to determine their margins)
   e. Inclusion of transportation and inventory charges
   f. Similarity analysis with other products for which cost breakdowns are known
   g. Import taxes if relevant
   h. References that support the numbers used
3. (20 points) Bottom-up model
   a. Volume forecasting for part costs (projection of part costs to high volumes)
   b. Detailed analysis of labour costs where the product is manufactured
   c. Analysis of cost and yield
   d. Pie charts or equivalent of cost breakdowns
4. (10 points) Correlation and model calibration
   a. Discussion of sources of discrepancies between the top-down and bottom-up models
   b. Determining scaling factors between the two solutions
   c. Sensitivity analysis of bottom-up inputs to match top-down estimate
5. (10 points) Uncertainty analysis and discussion (model accuracy)
   a. Design of experiments
   b. Sensitivity analysis (including tornado charts)
   c. Monte Carlo analysis if relevant
6. (5 points) Discussion of project strengths and weaknesses
7. (15 points) Intangibles
   a. Overall completeness of project
   b. How well does the whole story hang together?
   c. Summary and conclusions

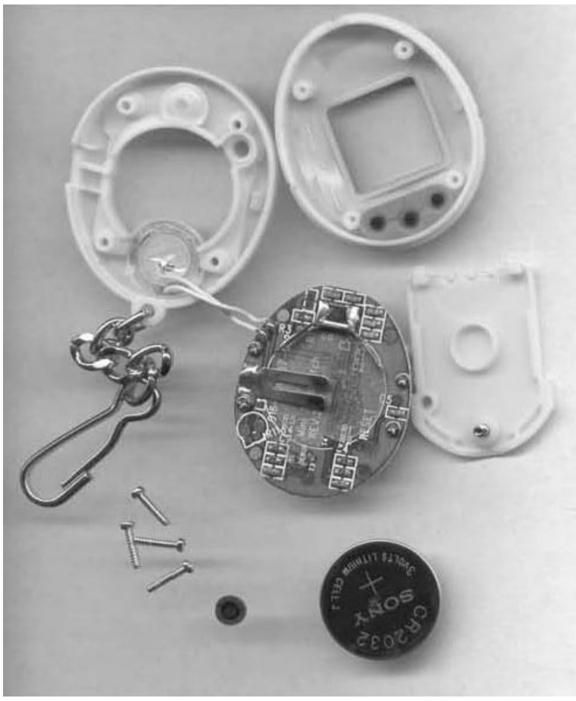

Fig. 2. Tamogotchi Mini Digital Pet™ disassembled. Overall toy dimensions: approx. 1 × 1.5 × 0.625 inches.

Table 3. Parts list for Tamogotchi Mini Digital Pet™

Part	Quantity in Product
Capacitors (0402)	8
Resistors (0402)	5
Crystal Oscillator	1
Electrolytic Capacitor	1
Speaker (Piezoelectric)	1
Battery (3V)	1
LCD Screen	1
Printed Circuit Board	1
Plastic Housing	1
Clear Plastic Screen	1
Soft Plastic Button Pallet	1
Integrated Circuit	1
Screws	4
Keychain	1
Plastic Washer	1
Cardboard LCD Screen Backing	1

problems are useful, students also need to know how and when to use the knowledge. By providing students with a complementary teardown project, we are helping them to make connections between different concepts and avoid knowledge fragmentation that hinders their ability to solve real engineering problems (see Figure 7 for a summary of the targeted performance outcomes).

A particular effort is made to not 'over-script' the project, but rather allow students to be their own master of the tasks. For this reason, all students choose and obtain their own product to analyze and the instructor does not directly influence a student's work, but rather only provides feedback and evaluation, letting the student 'muddle though' the problems unaided. Every product chosen for analysis is different and presents a unique set of analysis problems for the student, e.g. the top-down analysis process is not written down anywhere, not taught in class, not the same for any two products—rather the students are told to act as engineers and 'find a way to make it work'—surprisingly many students are able to find innovative ways to make reasonable top-down analysis arguments.

EXAMPLES OF ELECTRONIC PRODUCT TEARDOWNS AND COST ANALYSIS (PERFORMED IN 2005)

Electronic toy

A Tamogotchi Mini Digital Pet™ made by BanDai America was selected for analysis by one student. The toy, purchased at Target™ for $7.99 features an LCD screen that displays the pet and three buttons used to interact with the pet. This toy is a contemporary version of the original Tamogotchi™ introduced in 1997. Figure 2, shows the

Table 4. Cost breakdown for a Furby™ and the Tamogatchi

Cost Breakdown for a Furby™ [15]			Top-Down Cost Breakdown for Tamogotchi Mini Digital Pet™. The breakdown of manufacturing costs follows [16]	
Expenditure	Cost (£)	Percent of Total Cost (%)	Percent of Total Cost (%)	Cost ($)
Cost to Make	£6.00	20.47	20 Materials = 12 ($0.96) Labour = 4 ($0.32) Other = 4 ($0.32)	$1.60
Air Freight	£6.00	20.47	20	$1.60
Import Duty	£0.65	. . .		
Delivery to Warehouse	£0.18	0.614	0.5	$0.04
Product Safety Testing	£0.50	1.705	2	$0.16
Marketing and Packing	£1.50	5.117	5	$0.40
Delivery to Retailers	£0.30	1.023	1	$0.08
Toy Importer's Mark Up	£4.54	15.489	15	$1.20
Retailer's Mark Up	£5.85	19.959	21.5	$1.72
VAT (Value Added Tax)	£4.47	15.25	15	$1.19
	£29.96	100	100	$7.99

toy after disassembly. The list of parts for the toy is given in Table 3.

The top-down cost analysis for the Tamogotchi toy was performed via similarity to another toy manufactured in China and marketed in the United States. The cost breakdown for the Furby™ toy [15] is given in Table 4.

Several changes were made to the Furby™ model before it was compared with the Tamagotchi. According to the 2001–2002 Toy Industry Fact Book [17], 'the majority of toys imported into the US were unconditionally free of duty as of January 1, 1995'. Thus the contribution of import duty to the total cost has been ignored when calculating cost breakdown percentages. Also, the Furby has a retailer's mark up of 19.959%, which is slightly lower than what other sources suggest. The MIT Enterprise Forum [18], suggests that the mark up for discount retailers like Wal-Mart, Target and K-B Toys is above 20%, and another source believes the mark up to be as high as 28% [16]. Thus the retailer mark up for the Tamagotchi was increased to 21.5% in the simplified model, also shown in Table 4.

The top-down model of the Tamagotchi's price suggests that 20% of its retail price is used to buy raw materials and manufacture the product. Since the Tamagotchi retails at $7.99, this means that it costs approximately $1.60 to produce the toy, and that $0.96 is spent on raw materials and $0.64 is spent on labour and other costs. Note that although the VAT is initially paid by the manufacturers, it is not included in the cost of manufacture [19], since this cost is eventually passed on to the consumer.

The bottom-up model for the toy assumed a total volume of 20 million units. The first step in this analysis was to determine the parts costs. The analysis of one part is provided here as an example (remember, graduate students are not generally able to obtain actual quotes for 20 million parts from distributors). The bill of materials in Table 3 above includes eight 0402 surface mount capacitors. The pricing table (Table 5) was obtained for the 0402 size capacitors [20].

Table 5. Pricing Information for 0402 Surface Mount Capacitors [20]

Quantity	Price per Part ($)
1 to 99	0.063
100 to 499	0.037
500 to 999	0.022
1000 and up	0.015

The data in Table 5 were fit with a logarithmic curve up to a quantity of 2380 (Figure 3), and then assumed to be constant thereafter. Thus for a large production run a cost of $0.0051 per capacitor was assumed.

Performing similar extrapolations to determine the cost of all the parts in the bill of materials, and summing up all the costs associated in the bill of materials results in Table 6.

The final per unit cost of raw materials is $1.42, which is higher than the $0.96 predicted by the top-down model. However, the cost estimates for the injection moulded parts in Table 6 included labour, so some of this cost has already been accounted for in the $1.42. This material cost could still be reasonable if the costs associated with labour rates and other activities are less than $0.18 per unit. Because the number of Tamagotchi's being produced is high, $0.18 per toy may be a reasonable sum.

The bottom-up analysis also included a manufacturing process flow analysis to determine the assembly costs for the toy. Figure 4 shows the assembly process assumed. From the process flow the total cost of the product through the test step is $1.70, and, assuming a 90% yield on the toys, the total cost per good product is about $1.89. Note, for such an inexpensive product, no rework is assumed.

The total cost to manufacture and package a Tamagotchi Digital Pet derived in the bottom-up model, $2.21, slightly overshoots the cost derived in the top-down model, $2.00 ($1.60 cost to make, and $0.40 for marketing and packaging from Table 4). This represents a ten percent difference in pricing, which is about as accurate a bottom-up model can be without actually visiting BanDai. It

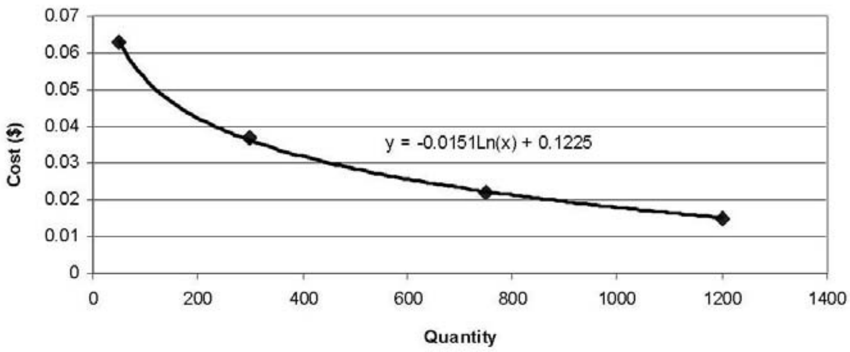

Fig. 3. Cost extrapolation for 0402 surface mount capacitors.

Table 6. Part costs in bottom-up analysis

Part	Number Used in Toy	Price/part	Total per Unit Cost
Capacitors (0402)	8	0.0051	0.0408
Resistors (0402)	5	0.007	0.035
Crystal Oscillator	1	0.025	0.025
Electrolytic Capacitor	1	0.061	0.061
Speaker (Piezoelectric)	1	0.0504	0.0504
Battery (3V)	1	0.0594	0.0594
LCD Screen	1	0.0426	0.0426
Printed Circuit Board	1	0.3	0.3
Plastic Housing	1	0.08	0.08
Clear Plastic Screen	1	0.2	0.2
Soft Plastic Button Pallet	1	0.1	0.1
Integrated Circuit	1	0.4	0.4
Screws			
Keychain			
Plastic Washer			
Cardboard LCD Screen Backing	–	0.03	0.03
			1.4242

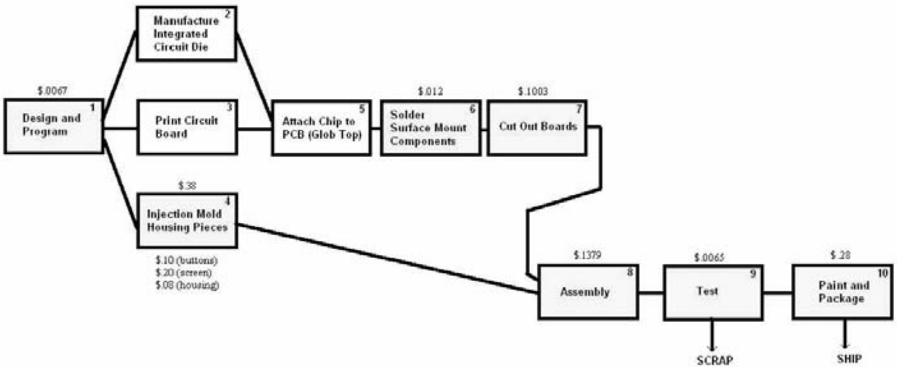

Fig. 4. Assembly process modelled for the toy. The costs per step per product are above each process step.

is not known how many machines, operators and toys they are producing, and it is doubtful that BanDai breaks down its large expenditures into per toy costs like this model seeks to do. One reason that the bottom-up cost model would overshoot the top-down cost model is that in every case where an upper or lower limit monetary value was needed for a part, the upper limit was taken. Also, another source of error is the yield. The yield was assumed to be 90%, but if the yield is varied, many different final costs can be found. A 100% yield gives a total cost close to $2.02, which almost exactly matches the top-down model.

Flash memory drive

The second example considered was the 128MB USB flash memory drive shown in Figure 5. Much of the analysis for this is similar in method to the toy discussed in the previous example and will not be reproduced. However, the top-down cost modelling portion of the analysis of this product differs and will be described. The sales price of a 128MB USB flash memory drive was determined from [21] to be $17.00 (for a quantity of 1000 in 2005). In this case, the top-down analysis worked backwards from the sales price to determine the manufacturing cost. The first step was to determine the percentage by which a retailer will raise the selling price. The net profit margin for the top 10 electronics retail stores was obtained from [22] and an average of the profit margin from the ten stores was determined to be 5.13% making the manufacturer sales price (1–0.0513)17 = $16.13. To determine the manufacturer's gross margin (the difference between net sales and the cost of goods sold), SanDisk Corporation (not the manufacturer of this device, but a public company which is a leader in the manufacture of USB flash drives along with other products that utilize flash components) was examined [23]. The gross margin for SanDisk was determined to be 39.79%. The USB flash memory drive was assumed to be representative of the average product from SanDisk. Therefore the estimated manufacturing cost of the flash memory drive is (1–0.3979) 16.13 = $9.71.

An assumption was made that the USB flash memory drive manufacturing cost really consists of two components: 1) the flash memory chip, and 2) everything else. By curve fitting the sales prices of different size USB flash memory drives obtained from [21] and extrapolating to a 0MB drive, the fraction of the sales price associated with the flash memory chip can be determined (Figure 6). The theoretical sales price of a flash memory drive that

Fig. 5. 128MB USB flash memory drive before disassembly—left, disassembled—right. Overall dimensions approx. 2.5 × 0.75 × 0.375 inches.

does not contain a flash memory chip would be $9.14 each. This implies that the flash memory chip represents 46.24% (1-9.14/17) of the total price of the flash memory drive. In the case of the 128MB USB flash memory drive, the chip should cost approximately $4.49, while the rest of the drive (all other components, assembly and testing) costs $5.22.

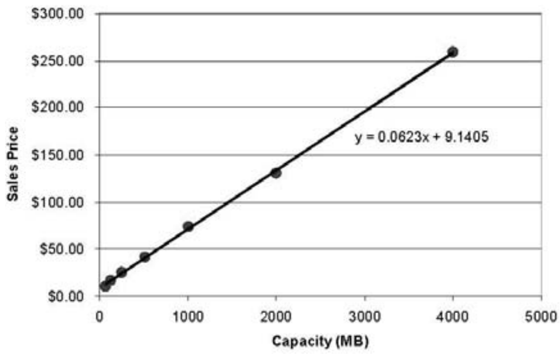

Fig. 6. Sales prices of USB flash memory drives from [21].

ASSESSMENT OF EDUCATIONAL BENEFITS

The course that the teardown project is included within has been assessed according to assigned ABET performance outcomes (although the course is a graduate course, it has been assessed using the same criteria applied to undergraduate courses in the Mechanical Engineering Department at the University of Maryland). At the end of each semester, the course performance outcomes are assessed through student feedback surveys and a quantitative analysis determined from the performance of the students in exams.

All students are requested to complete an anonymous Course and Instructor Evaluation at

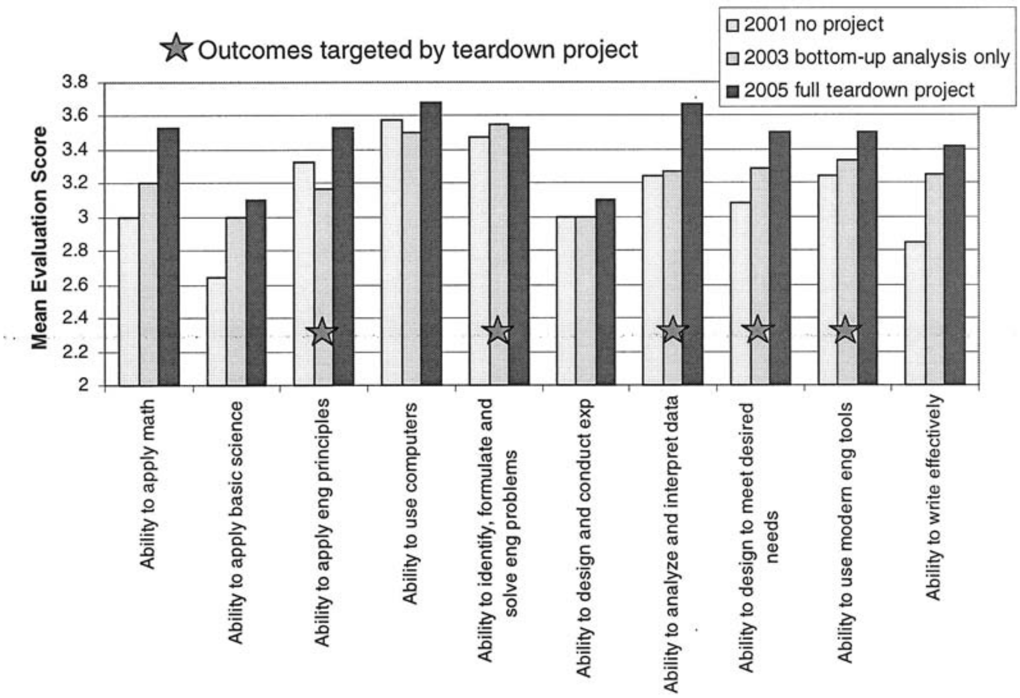

Fig. 7. Student responses from the three most recent offerings of the course through Fall 2005 for ten possibly relevant questions from the Student Development Assessment portion of the survey. The student responses include a cross-section of all students who have taken the one-semester graduate course at the University of Maryland, both on-campus students and distance students are included. Industry short-course students do not do a teardown project and are not included. Maximum evaluation score = 4.0.

the end of the semester. The evaluation consists of three evaluation parts: I. Class Evaluation, II. Student Development Assessment, III. Evaluation of Studio/Lab Courses. In each part of the evaluation, students rate their experience in the course using one of six responses A–E where A = strongly agree (scored as a 4) to E = strongly disagree (scored as a 0), and NA = not applicable (not scored). The portion of the evaluation that is relevant to assessing the educational benefits of the teardown project is the Student Development Assessment. Figure 7 shows the responses from the three most recent offerings of the course through Fall 2005 for ten relevant questions from the Student Development Assessment portion of the survey. Over the three semesters shown, 50 students have completed the survey. In 2001, no project was included in the course, in 2003 a version of the teardown project that only included the bottom-up analysis was used, and 2005 employed the entire teardown project (top-down, bottom-up and calibration) described in this paper. Of the outcomes that are targeted by the teardown project, all show increases as the project was phased into the course with the exception of the ability to identify, formulate and solve engineering problems, which showed little change. The fact that this performance outcome was not significantly changed (from the student's viewpoint) by the inclusion of the teardown project may be due to that fact that this outcome is already rated high for the course and a degree of frustration that some students expressed with performing the "open-ended" top-down analysis in the project (see discussion in the next section).

An attempt was also made to assess whether the project reduced the knowledge fragmentation. The final exam historically includes problems that combine multiple course topics together. Final exam scores from Fall 2003 and Fall 2005 were compared to assess improvement. Fall 2003 final exam scores were $\mu = 69.4$ ($\sigma = 12.8$), and Fall 2005 were $\mu = 78.5$ ($\sigma = 19.1$).

Student feedback

Many students indicated that they gained some measure of respect for performing cost analysis—it wasn't as easy as they thought, and determining an accurate estimation was deceivingly difficult. The students also indicated that they perceived the usefulness of good cost estimates in decision making. Numerous students complained about the lack of data necessary to populate their models. In reality, if individuals were to perform a similar analysis for an employer, it is likely that they would have access to more/better data than they had for this project. However, scarcity of data is a fact of life and how good an estimate is obtained is a function of how resourceful a detective the engineer is.

Many students, in particular the distance students (who are full time employed), commented that the required top-down analysis (and calibration of the bottom-up analysis with the top-down analysis) enveloped many aspects of real engineering that they had not otherwise been exposed to in their coursework. The distance students also pointed out that the project exaggerated common dilemmas associated with many engineering endeavours while emphasizing the role of engineering judgment.

Some students struggled with the open-endedness of the project. These students have come to believe through years of coursework that technical problems are all well posed (not over-constrained, not under-constrained), with all the boundary conditions defined. This project was purposely left under-constrained, which suited some students very well and left others floundering.

CONCLUSIONS

The purpose of the project was to balance the theoretical focus in lectures and homeworks against the analysis of a real system. Much of the content of traditional course materials also focuses on bottom-up analysis, while the project forced students to think top-down as well.

In many cases, we found that the simplest products were the most difficult to model from a top-down perspective. For example, McDonald's Happy Meal® toys are extremely simple; however, they are sold as part of a meal that includes other products, and it is not clear what level of profit McDonald's makes on the meal (since part of the purpose of the Happy Meal is to entice youngsters who are accompanied by adults who order higher profit products and many of the toys are also cross-promotional advertisements). We have also learned that while some students have a very well-developed knowledge of the fundamentals, they have very poorly developed 'detective' skills, i.e. if the data necessary to solve the problem are not placed in front of them, they are lost and unable or unwilling to accept and use data that are not precisely what their model requires—approximately 10% of the students spend several weeks trying to convince the instructors that top-down modelling is not possible for their selected product because the manufacturer refuses to provide them with cost data or will not return their calls or emails.

Cost modelling is a resource for electronic system designers who want to be able to assess the cost (economic) impact of their design decisions on the manufacturing of a system and its life cycle. Using product teardowns and reverse engineering ideas has proved to be an effective vehicle for educating students on practical manufacturing cost modelling of electronic systems. When this project was originally conceived for this course, its purpose was to integrate the course knowledge together in a practical way; however, we have learned that the real value of the project has less to do with cost analysis and more to do with the development of practical problem solving skills.

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