# Using Teardown Analysis as a Vehicle to Teach Electronic Systems Manufacturing Cost Modeling

Peter Sandborn, Jessica Myers, Thomas Barron, and Michael McCarthy
CALCE Center for Advanced Life Cycle Engineering
Department of Mechanical Engineering
University of Maryland, College Park, MD 20742
sandborn@umd.edu

**Abstract**

This paper describes the use of product teardowns in an electronic systems cost modeling course at the University of Maryland. As part of a semester-long project, each student must choose a product with significant electronics content and determining the manufacturing cost of the product using a combination of top-down cost analysis (to determine what the product must cost) and a detailed bottoms-up model (that they 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 MacDonald's Happy Meal® toys. Using product teardowns and reverse engineering ideas has proven to be an effective vehicle for educating students on practical manufacturing cost modeling of electronic systems.

**Introduction**

Twenty 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 or contributing to the understanding of the economic tradeoffs associated with their decisions. Yet aside from "generic" engineering economics that focuses on capital allocation problems, electronic system designers have virtually no resources and obtain little or no training in cost analysis, let alone analysis that is specific to electronic systems.

While engineering economics is useful for determining the economic tradeoffs associated with well understood activities and products, estimating application-specific manufacturing, testing, qualification, and maintenance costs requires methodologies and tools that are outside the scope of most engineering economics courses.

Unfortunately, when undergraduate engineers were asked what they thought the cost of a product was (and assigned to produce cost estimates of products in capstone design courses) 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 Fig. 1, but virtually no students, even those who had taken courses in engineering economics, were equipped to competently estimate the manufacturing or lifecycle cost of a product.

This paper describes the use of product teardowns in an electronic systems cost modeling course. A teardown project has been developed and assigned as a semester-long project that supplements a Manufacturing and Life Cycle Cost

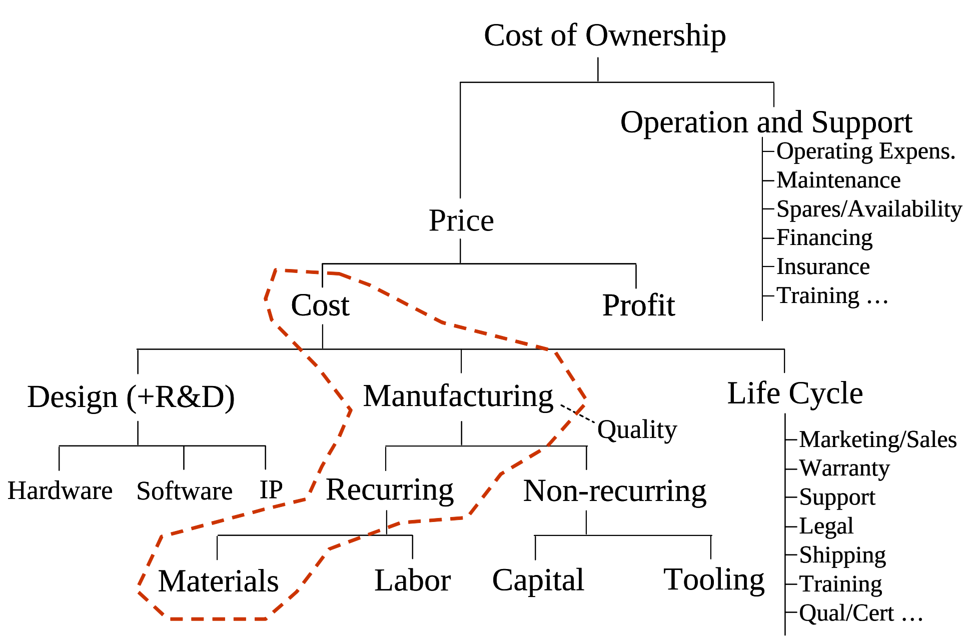


Fig. 1. Cost analysis. The dashed line indicates the limited view of cost analysis shared by many undergraduate engineering students.

Analysis of Electronic Systems course in the Mechanical Engineering Department at the University of Maryland. Product teardowns[1] have been previously used in engineering educational curricula to introduce undergraduate students to general engineering skills in the form of competitive benchmarking of products [2], and product disassembly has been used in introductory engineering courses to teach design processes [3,4]. These previous uses of product reverse engineering, however, have not addressed the analysis of costs, at most treating cost as a qualitative constraint on design without any attempt to perform any type of actual analysis.

## Course Design and Curriculum

A one-semester course on cost analysis for electronic systems has been developed and taught at the University of Maryland for approximately five years. The course is taught on the web and a selection of multimedia web-based instructional materials have been previously developed for the course, [5,6]. Approximately 25% of the students in the course are distance students. Recent offerings of the course have included distance students from Apple Computer, Boeing, Delphi Automotive, NASA, NIST, Northrop Grumman, the U.S. Army and other organizations. Versions of the course have also been offered as 2 or 3 day industry short courses.

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

In the first half of the course various manufacturing cost analysis methods are taught: process-flow/technical cost modeling, 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 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, substrate fabrication, and electronic systems testing at various levels.

The course is offered as part of the Electronic Products and Systems graduate curriculum in the Mechanical Engineering Department at the University of Maryland (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 program at the University of Maryland. The majority of the students taking the course have previously taken at least one introductory course in electronic packaging and are therefore familiar with the packaging, technologies and assembly processes used to create electronic products.

## Project Design

Each student in the course is required to identify and obtain a consumer product 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 MacDonald's Happy Meal® toys. Each student is tasked with determining the manufacturing cost of the product they have chosen.

The students are required to approach the problem from both *top-down* and *bottoms-up* directions:[2]

1) First the students must perform a *top-down* cost analysis to determine upper and lower bounds on what the product ought to cost. 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.
2) In the second phase of the project, students are required to create a detailed *bottoms-up* cost model for their product. Students use manufacturing cost modeling methodologies taught in the first half of the course to construct the *bottoms-up* model. The methodologies the students can use include: process flow (technical) cost modeling, cost of ownership, activity based costing, parametric cost modeling, or in many cases a combination of methods. The *bottoms-up* models generally include detailed cost contributions from labor, materials, tooling, equipment, etc.

Students begin by performing a teardown[3] of their selected product from which they create bills of materials and

[1] We are using the term "teardown" instead of "reverse engineering" since [1]: a) reverse engineering really refers to the retrospective development of the technical data necessary to support an existing production item, and b) 90-95% of the literature on reverse engineering today is aimed at software reverse engineering, not hardware.

[2] 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 based on what the product should cost (or must cost) in order to be offered at a known price. In a bottoms-up estimate the cost of each component and/or process step is modeled and those costs are accumulated to produce a final cost estimate. See [7] for a discussion of top-down and bottoms-up cost estimating.

[3] A *teardown* is the analysis of an existing system to assess its content. Teardowns 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 in turn for forecasting R&D directions. In a teardown, products are "reverse-engineered" to provide a disassembly report with a multi-disciplinary "system view." Alternatively, Ulrich and Person [8] have used the term "product archaeology" to describe a technique for analyzing physical products in order to derive and measure their manufacturing content.

descriptions of assembly processes. Students may choose to destructively cross-section printed circuit boards to determine their layer counts and design rules, they may de-solder parts from board, decapsulate die from plastic packages, etc., and are encouraged to photograph details of the disassembled products. Once a teardown is completed the students perform the top-down cost analysis. The top-down analysis is done in the first half of the semester (while learning manufacturing cost modeling in class). In the second half of the semester, students apply the manufacturing cost modeling methodologies to construct the bottoms-up model for their selected product.

The students discover that the *bottoms-up* detailed cost models may have relative accuracy (i.e., may get the ratio of labor to materials costs right), but could have poor absolute accuracy. On the other hand, some smart thinking and "nosing around" enables them to "reverse engineer" a good overall cost number, but won't necessarily tell them how that cost number is broken down amongst labor, equipment, tooling, materials, etc.

The key final task required in the project is to calibrate the *bottoms-up* model using the *top-down* model and produce a final manufacturing cost estimate broken down by labor, materials, tooling, capital equipment, etc.

Project final reports 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 were required to "compare notes" and determine if their top-down estimates were consistent. For example, in Fall 2005 several students worked on calculators. All students who worked on calculators had to produce an analysis of how their estimate compared to others working calculators and why it differed.

### *A. Pedagogical Design*

The project is designed to span an entire 15-week semester. It should be stressed that the reverse engineering project discussed in this paper 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 subprojects each of which have their own due dates and are reviewed by the instructor: 1) identification of a product and performing a tear-down of the product (3 weeks); 2) top-down cost estimate (4 weeks); and 3) bottoms-up cost estimation, calibration of the model, and final report (8 weeks).

In previous offerings of the cost analysis course, we have learned a great deal about students' conceptual knowledge of cost estimation and have developed curricular environments to improve it, e.g., [5], [6]. However, conceptual knowledge is only one part of what students need to know in order to solve complex problems. While homework problems are fine, they also need to know how and when to use the knowledge. By providing students with a complimentary reverse engineering project, we are helping students to make connections between different concepts and avoid knowledge fragmentation.

A particular effort is made to not "over-script" the project, but rather allow the student to be their own master of the tasks. For this reason, each student chooses and obtains their own product to analyze and the instructor does not directly influence the student's work, but rather only provides feedback and evaluation, letting the student "muddle though" the problems themselves. 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, and 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 rise to the occasion and find innovative ways to make quite reasonable top-down analysis arguments.

## Examples of Electronic Product Teardowns and Their Associated Cost Analysis

This section provides selected portions of the analysis from two electronic product teardowns performed by students in Fall 2005.

### *A. 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 toy after disassembly. The list of parts for the toy is given in Table I.

TABLE I
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 |

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 break down for the Furby™ toy [9] is given in Table II.

TABLE II
COST BREAKDOWN FOR A FURBY™ AND THE TAMOGATCHI

| Cost Breakdown for a Furby™ [9] | | | Top-Down Cost Breakdown for Tamogotchi Mini Digital Pet™. The breakdown of manufacturing costs follows [12] | |
|---|---|---|---|---|
| **Expenditure** | **Cost (£)** | **Percent of Total Cost (%)** | **Percent of Total Cost (%)** | **Cost ($)** |
| Cost to Make | £6.00 | 20.47 | 20<br>Materials = 12 ($0.96)<br>Labor = 4 ($0.32)<br>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 |

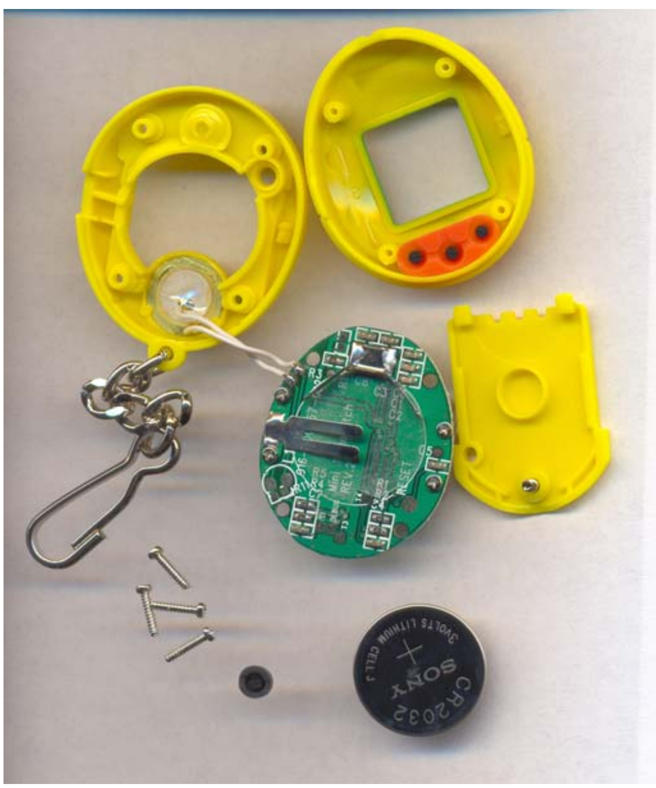


Fig. 2. Tamogotchi Mini Digital Pet™ disassembled. The overall toy dimensions are approximately 1 x 1.5 x 0.625 inches.

Several changes were made to the Furby™ model before it was applied to the Tamagotchi. A currency conversion was employed and the import duty is only applicable to products imported into Great Britain so it was removed. According to the 2001-2002 Toy Industry Fact Book [10], "the majority of toys imported into the U.S. 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 [11], 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% [12]. Thus the retailer mark up for the Tamagotchi has been upped to 21.5% in the simplified model, also shown in Table II.

The bottoms-up model for the toy assumed a total volume of 20 million units. The first step in the bottoms-up analysis was to determine the parts costs (included in the materials cost in Table II). 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 I includes eight 0402 surface mount capacitors. The pricing table (Table III) was obtained for the 0402 size capacitors [14].

TABLE III
PRICING INFORMATION FOR 0402 SURFACE MOUNT CAPACITORS [14]

| 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 III was fit with a logarithmic curve up to a quantity of 2380 (Fig. 3), and then assumed to be constant thereafter. Thus for a large production run a cost of $0.0051 per capacitor can be assumed.

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

TABLE IV
PART COSTS DETERMINED IN BOTTOMS-UP ANALYSIS

| **Part** | **Number Used in Toy** | **Price** | **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<br>Keychain<br>Plastic Washer<br>Cardboard LCD Screen Backing | -- | 0.03 | 0.03 |
| | | | 1.4242 |

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 molded parts included labor within them, so some of the labor costs have already been accounted for in the $1.42. This material cost could still be reasonable if the costs associated with labor rates and other activities are less than $0.18 per unit. Because the number of Tamagotchi's being produced is relatively high, $0.18 per toy may end up being a reasonable number.

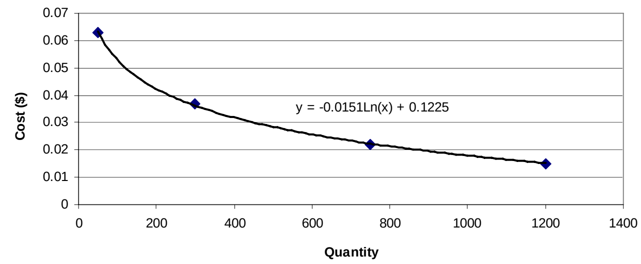


Fig. 3. Cost extrapolation for 0402 surface mount capacitors.

The bottoms-up analysis also included a manufacturing process flow analysis to determine the assembly costs for the toy. Figure 4 shows the assembly process assumed. The total cost of the product up 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 Per derived in the bottoms-up model, $2.21, slightly overshoots the cost derived in the top-down model, $2.00 ($1.60 cost to make, and $.40 to marketing and packaging from Table II). While this represents a ten percent difference in pricing, this is about as accurate a bottoms model could be without actually visiting BanDai. It is impossible to know how many machines, operators, and toys they are producing, and it is doubtful that BanDai breaks down their large expenditures into per toy costs like this model seeks to do. Another reason that the bottoms up cost model would overshoot the top down cost model is that in every case where

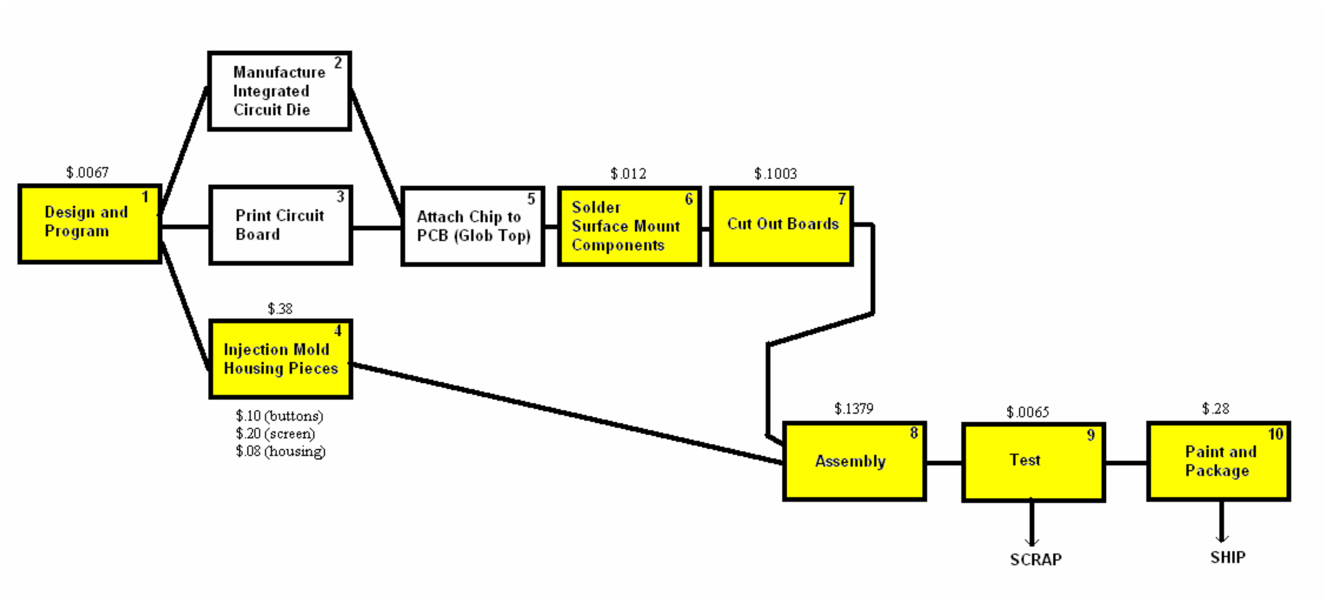


Fig. 4. Assembly process modeled for the toy. The per step per product instance costs are included above each process step.

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 arbitrarily 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.

### *B. Flash Memory Drive*

The second example considered is a 128MB USB flash memory drive shown in Fig. 5. Much of the analysis of the flash memory drive is similar in method to the toy discussed in section A and will not be reproduced herein. However, the top-down cost modeling portion of the analysis of this product differs and will be described herein. The sales price of a 128MB USB flash memory drive was determined from [15] to be $17.00 (for a quantity of 1000). In this case, the top-down analysis worked backwards from sales price to determine the manufacturing cost. The first step was to determine the percentage by which a retailer will raise the price when selling a flash drive to the consumer. The net profit margin for the top 10 electronics retail stores was obtained from [16] and an average of the profit margin from the ten stores was determined to be 5.13% making the manufacturer sale price (1 – 0.0513)17 = $16.13. To determine the manufacturer's gross margin (the difference between net sales and the cost of good sold), SanDisk Corporation (not the manufacturer of this device, but a public company who is a leader in the manufacture of USB flash drives along with other products that utilize flash components) was examined [17]. 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.

Fig. 5. 128MB USB flash memory drive prior to disassembly – left, disassembled – right. The overall dimensions are approximately 2.5 x 0.75 x 0.375 inches.

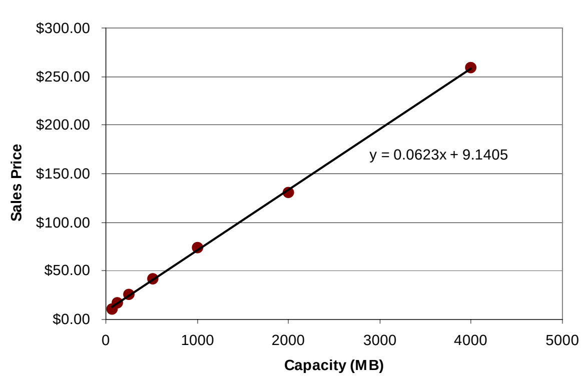


Fig. 6. Sales prices of USB flash memory drives from [15].

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 [15] and extrapolating to a 0MB drive, the fraction of the sales price associated with the flash memory chip can be determined, Fig. 6. The theoretical sales price of a flash memory drive that does not contain a flash memory chip would be $9.14 each. This implies that the flash memory chip represents 46.24% 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.

In many cases, we found that the simplest products were the most difficult to model from a top-down perspective. For example, MacDonald'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 (if any) MacDonald's makes on the meal (since 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).

## Discussion and Conclusions

Many students indicated that they gained some measure of respect for performing cost analysis – it wasn't as easy as they thought, and obtaining 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 and diversity of data necessary to populate their models. In reality, if individuals were to perform similar analysis for an employer, it is likely that they would have access to slightly more/better data than what 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 the calibration of the bottoms-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 endeavors while emphasizing the role of engineering judgment.

Some students struggled with the open-endedness of the project. They have come to believe through years of coursework that technical problems are all well posed (not overconstrained, not underconstrained), with all the boundary conditions defined. This project was purposely left underconstrained, which suited some students very well and left others floundering. Some students suggested that the final reports generated in Fall 2005 be archived and available to students who perform the project in future versions of the course, however, the authors of this paper have concluded that this may defeat part of the purpose of this project.

Part of 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 the course also focuses on bottoms-up analysis, while the project forced students to think top-down too.

An attempt was made to assess if the project reduced the knowledge fragmentation that has plagued students in this course in years past. 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).

Cost modeling 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 proven to be an effective vehicle for educating students on practical manufacturing cost modeling of electronic systems. One student in the course suggested that modern engineers need to "think like an MBA, but act like an engineer".

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