Assessing the Importance of Design Through Product Archaeology

Karl T. Ulrich • Scott Pearson
The Wharton School, 1317 Steinberg Hall–Dietrich Hall, Philadelphia, Pennsylvania 19104
MPM Corporation, 16 Forge Park, Franklin, Massachusetts 02038

This paper assesses the importance of design in determining product costs by measuring the variation in design performance among a set of competing design efforts. This assessment is completed for a set of functionally similar products in a single product category: automatic drip coffee makers. The approach of this study is to measure the *manufacturing content*—the attributes of the design that drive cost—through analysis of the physical products themselves, and to estimate how variation in manufacturing content relates to variation in cost in a hypothetical manufacturing setting. We call this approach *product archaeology*. For the domain of coffee makers, we find significant variation in manufacturing content. This variation in manufacturing content corresponds to a range of estimated manufacturing costs, for a hypothetical manufacturing system, of approximately 50 percent of the average manufacturing cost of the products. We also find that differences in capabilities among product development efforts are the most plausible explanation for the differences in manufacturing content.

(*Product Design; Design for Manufacturing; Competitive Benchmarking; Product Development*)

---

1. Introduction

In the domain of physical products, *product design* is the activity that transforms a set of product requirements into a specification of the geometry and material properties of an artifact. Product designers create and specify the scheme by which the elements of the product will be arranged into an integrated whole; the form, texture, color, and graphics of the exterior of the product; the user interfaces; the materials and production processes for part manufacturing; the joining techniques to hold the product together; and the detailed geometry and material specification of each part. This activity typically is performed by engineers and industrial designers and involves input from representatives of the marketing and manufacturing functions. Product design is part of the broader *product development* activity, which also includes creation of the product requirements, development of the basic product concept, product testing, and production ramp-up. (See Ulrich and Eppinger 1995 for a more complete description of design activities and their relation to product development as a whole.) We treat *technology development* as a distinct activity in which the core technologies that might be embodied in future products are refined and proven.

Product design has received increased attention in the academic and business communities over the past decade. For example, *Business Week* sponsors an annual design competition and devotes dozens of magazine pages each year to product design (Nussbaum 1995). This attention resonates with the widely held belief that product design is important to the success of the manufacturing firm. We assert that for the design activity to be managerially important, there must be significant variation in design performance among competing design efforts. For the variation to be significant it should contribute to competitively important differences in the profitability of the associated products.

Product profits are determined by both revenues and costs. Design may influence revenues by leading to changes in market share and/or price. This influence may come about because of design's role in defining the features of a product, its performance quality, its reli-

0025-1909/98/4403/0352$05.00

ability, and its aesthetic appeal. Many recent examples are suggestive of design's influence on revenues, including the Mazda Miata and Apple Powerbook. Although we know of little research focused directly on the role of design in influencing revenues, many observers believe these new products generated unusually large revenues—even in the established markets for automobiles and computers—largely because of the consumer appeal associated with their designs. While we believe that design is important in determining product revenues, we see a need for more research on the extent and nature of this relationship.

This paper focuses on the importance of design in determining costs. Because the design activity specifies the materials, part production processes, and assembly requirements of a product, product design is one of the determining factors of manufacturing cost. Many have suggested that design determines 80 percent (or some large majority) of manufacturing cost (Miller 1988, Ullman 1992). Several widely publicized case studies of "before and after" designs also illustrate that the cost of a product can be influenced through design (Boothroyd and Dewhurst 1989). This study is intended to measure and quantify the amount of variation in manufacturing cost exhibited among competing design efforts.

We believe that this work is important to industrial practice because determining the importance of design informs resource allocation within the firm. Investments in design capability should be supported by knowledge about the return the firm should expect to receive from this investment. We draw an analogy to several studies from the 1980s. In 1983, Garvin published results of a study of air-conditioner quality performance showing a range of assembly defect rates from 0.15 defects per 100 units to 165 defects per 100 units (Garvin 1983). Clark and Fujimoto (1991) showed that product development lead times in the world automobile industry ranged from 35 months to 97 months. Krafcik (1988) showed that worldwide automobile assembly plant productivity ranged from 15 hours per vehicle to 50 hours per vehicle. These studies served to highlight the importance of quality, product development lead time, and manufacturing productivity. These studies and others led to an awareness of the range of performance levels achieved by different firms in an industry, and therefore to a change within many firms in the level of resources allocated to those issues.

Organization of the Paper

The remainder of this paper is divided into five sections. Section 2 describes the approach and methodology of the research. Section 3 presents the results of the investigation of variation in design performance. Section 4 interprets this variation in terms of variation in manufacturing cost. Section 5 discusses the results and explores possible explanations. Section 6 contains concluding remarks.

To our knowledge, this is the first academic study of the role of design in influencing product cost; it is far from the final word on the subject. In this first paper we can address the research questions for a particular setting, but we can only hypothesize about general applicability. Recalling this limitation in the concluding section of the paper, we identify areas for future research.

2. Approach and Methodology

The basic approach of this study is to measure the *manufacturing content*—the attributes of the design that drive manufacturing cost—of a set of functionally similar products through analysis of the physical products themselves, and to estimate how variation in manufacturing content relates to variation in manufacturing cost in a hypothetical manufacturing setting.

Product Archaeology

We analyze the actual physical products available in the marketplace in order to collect data on manufacturing content. We call this approach *product archaeology*. Product archaeology is one element of the *competitive benchmarking* some firms perform when analyzing their competitors' products (Camp 1989). Through the use of product archaeology we can directly observe many design attributes, such as the number of parts and the number of fasteners (e.g., screws and clips), and we can use established estimation techniques for determining other design attributes such as the assembly labor content and the processing requirements for the fabricated parts.

While several researchers have used the product as the unit of analysis (Clark and Fujimoto 1991, Sanderson and Uzumeri 1995), we know of no academic research on product design that has examined the artifact itself as a source of data. As a research methodology, product archaeology offers several benefits. First, data derived from observations of the product itself are objective and highly reliable. Second, the data are readily available. Research on dozens of manufacturers' products can be performed without permission or access to the company. Third, the data obtained from product archaeology are public information. This allows researchers to talk about specific manufacturers by name and allows the actual undisguised data to be published.

Choice of Domain

We analyze the products in a single category as a starting point in this line of research. We chose consumer automatic drip coffee makers as the product for our study for three reasons. First, many coffee makers implement the same set of product requirements. Each model in our sample is designed around the same brewing process and, according to *Consumer Reports* (1991), delivers coffee that is of equal quality. This allows us to avoid most design differences due to differences in product requirements. Second, coffee makers are relatively simple. The components of coffee makers are large enough to examine easily, and they are sufficiently limited in number to make the study manageable. Third, coffee makers are produced by a diverse group of manufacturers—large and small, U.S. and international.

We believe that the design of coffee makers involves the same issues as the design of many consumer and industrial products including power tools, automobile instrument panels, and consumer appliances. These products are high-volume, discrete, assembled goods involving mechanical and electrical components. Similar core technologies that remain relatively stable over time are employed within each of these classes of products. Although we believe coffee makers are representative of many products, we devote part of the concluding section of the paper to the extent to which our results from coffee makers can be generalized.

The specific models and manufacturers for our sample are shown in Table 1. For reference purposes, we list the retail price of each coffee maker, a "comparison price" that is adjusted for differences in features such as water-level indicators and timers,[1] the market share of the manufacturer, the number of units sold annually by each manufacturer in the United States, and the country in which the product was made. Figure 1 is an illustration of one of the coffee makers from the sample.

Table 1 **Basic Information About Coffee Maker Manufacturers and Models**

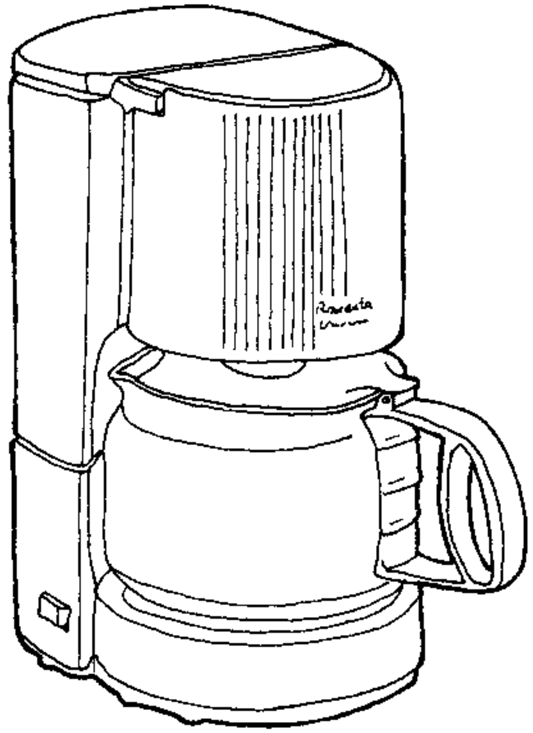
	1991 Share (units)	1991 Units (1000s)	Country of Mfr.	MSRP	Adj. Price
Black & Decker	21%	3275			
DCM90			US	20.00	18.50
DCM900			US	25.00	25.00
Mr. Coffee	27	4211			
International			China	25.00	21.20
SR-12			China	30.00	25.50
Accel			US	38.00	26.60
Expert			US	70.00	33.30
N.A.P.	7	1092			
Norelco 663			US	50.00	21.90
Proctor Silex	18	2807			
A6278			US	35.00	16.60
A8737			China	35.00	23.20
Regal	4	624			
Regal			US	28.00	24.90
Toastmaster	<1	<156			
Toastmaster			Taiwan	23.00	18.70
Braun	9	1404			
KF400			Ger.	40.00	32.50
KF650			Ger.	50.00	35.00
Krups	5	780			
130			Ger.	65.00	47.90
150			Mex.	45.00	43.30
178			Ger.	80.00	50.00
Rowenta	<1	<156			
FG22-0			Ger.	48.00	40.60
FK26-S			Ger.	65.00	43.10

Market share data from Appliance (1991).

---

[1] The adjusted price is intended to be only a rough indication of the relative prices paid for different models of functionally similar products. The pricing adjustments were made as follows. The features were divided into three categories: high-value, medium-value, and low-value. High-value features include drip stops, digital clocks, and reusable filters; medium-value features include analog clocks, water-level indicators, automatic shut-offs, and built-in cleaning cycles; low-value features include brew strength levers, 2–4 cup switches, flavor-seal lids, temperature-level switches, and excess cord storage space. We adjusted prices by −15 percent for each high-value feature, −7.5 percent for each medium-value feature, and −3.75 percent for each low-value feature. These percentages are consistent with the price differences reflected by models available with and without a particular feature. The details of the price adjustment procedure are given in Pearson (1992).

Figure 1 **Example Coffee Maker from Data Set: Rowenta FG220.**



Manufacturing Content

A manufacturing system utilizes equipment, information, tooling, energy, supplies, services, and a work force to transform raw materials and purchased components into finished goods and any associated waste products. Costs are incurred in procuring these resources and in disposing of the waste products. Over a long time period, the unit cost of producing finished goods is the cost of all of the resources consumed (and of the waste disposal) over that time period divided by the total number of units produced.

Cost is inherently an additive property of products. Because production processes can be thought of as collections of resource-consuming activities acting on materials, total unit cost can be modeled as a sum of the costs of these materials and of the resources consumed by the activities. For example, total cost for a high-volume assembled product might be modeled as follows:

$$C = C_{\text{assembly}} + C_{\text{molded-parts}} + C_{\text{sheet-metal-parts}} + \cdots, \quad (1)$$

where, for example, $C_{\text{molded-parts}}$ could in turn be modeled as the cost of plastic resin plus the cost of molding, inspecting, etc. This view of cost as a sum of elements corresponding to different categories of resource consumption is consistent with the traditional approach to cost analysis (i.e., materials, labor, machine use, overhead) as well as with activity-based cost accounting schemes (Kaplan 1990, Ostwald 1992).

Each of the elements of unit cost arises, in general, from attributes of both the product design and of the manufacturing system. For example, assembly cost is determined both by how much assembly is required by the design as well as by how much resource consumption the manufacturing system requires to complete that amount of assembly. Consistent with this view, assembly cost can be modeled as:

$$C_{\text{assembly}} = d_{\text{assembly}} \times m_{\text{assembly}}, \quad (2)$$

where d_{assembly} is a design attribute and m_{assembly} is an attribute of the manufacturing system. The design attribute, d_{assembly}, might be expressed in units of *standard hours of assembly content*, and the manufacturing attribute, m_{assembly}, might be expressed in units of *cost per standard hour*, which might be determined from, among other factors, labor productivity, wage rates, and assembly yields.[2] Similar models consisting of a function of a design attribute and a manufacturing attribute can be constructed for the other elements of cost.

We define *manufacturing content* as the values of the design attributes that "drive" manufacturing cost for an assumed manufacturing system. For a product of the complexity of a coffee maker, manufacturing content can be expressed as a collection of about one dozen attributes. We use the manufacturing content of a product, obtained by product archaeology, as a measure of design performance.

Manufacturing Cost Model

We use a cost model incorporating typical values of manufacturing system parameters as a way of estimating the degree to which variation in manufacturing content influences manufacturing costs. Our model is based on many previous modeling efforts by us and other researchers (Suri et al. 1993, Mody et al. 1991, Busch 1987, Ulrich et al. 1993).

---

[2] In this model, long-lived assets, such as assembly equipment and fixtures, are consumed in proportion to the required assembly time of the product. Such a model requires assumptions about the life and utilization of the asset.

The manufacturers in our study make products in at least 12 different plants (the sum of the number of different countries in which each manufacturer assembles products). We do not attempt to model the actual cost structure of each of the manufacturer's production systems. Rather, we use a hypothetical cost model as a way of exploring the degree to which variation in design performance relates to variation in costs. Of course the particular cost structure of a production system determines actual manufacturing costs.

As a base case we adopt a model with parameters typical of a well-run production system in a medium-cost economic environment. As part of the analysis of the results, we consider five other scenarios corresponding to well-run and poorly run systems in low-, medium-, and high-cost economic environments.

3. Determining Variation in Manufacturing Content

In order to determine the manufacturing content of the 18 coffee makers, we established values for a set of attributes through direct observations of the products and their constituent parts. We then estimated the values for additional attributes through calculations or by soliciting information from suppliers.

We disassembled each product and created a bill of materials (BOM) and a feasible sequence of assembly operations. Five attributes can be observed directly from the BOM and the piece parts: the total number of parts, the number of part numbers (i.e., unique parts), the number of plastic molded parts, the number of sheet metal parts, and the number of fasteners (includes screws, nuts, and clips).

The parts custom fabricated by or for the manufacturer are either injection molded plastic or stamped sheet metal. For each injection molded part, we determined the type of polymer, the part mass, the geometric complexity, the part wall thickness, the number of actions (moving parts) required for the mold, and the percentage of the part surface corresponding to each of the five standard surface finish designations. For each sheet metal part, we determined the type of metal, the thickness of the metal sheet, the required length and width of sheet consumed for each part, and an estimate of part complexity on a scale of 1 to 5.

The purchased parts include fasteners, tubing, switches, wiring, heaters, and carafes. We described the fasteners in terms of their type and size, tubing in terms of length and diameter, switches in terms of the type (slider or rocker, lighted or not), and wiring in terms of length, material, strain relief type, gage, and color. We photographed the heaters and carafes. Using the component data and the photographs we solicited price quotes from U.S. suppliers for production quantities of 250,000; 500,000; and 1,000,000 units per year.[3]

The attributes we estimated are listed in Table 2, along with a summary of each estimation technique. (The details of these estimation techniques are in Pearson 1992.)

Recall that some of the coffee makers comprise drip stops, water level indicators, timers, and clocks. Because these features are not offered with all models, we excluded the manufacturing content associated with these features. In most cases, this adjustment involves three steps. First, the additional parts associated with a feature are deleted from the BOM. Second, any geometric details associated with the interface between these deleted parts and the rest of the product are not considered in determining part complexity. Finally, any holes associated with interfaces are assumed to be "covered over." In most cases, the features appear to have been designed as additions to a basic product anyway, and so the adjustment process is simple and unambiguous.

The net result of the product archaeology and associated estimation is the manufacturing content for each product. Table 3 shows the values of all of the attributes of manufacturing content for each of the coffee makers.

Variation in Manufacturing Content

The products in our data set exhibit wide variation in many of the attributes of manufacturing content. One of the attribute values spans a factor of 16 (number of fasteners), while most span at least a factor of 2. Here

---

[3] For our study we assume an annual production volume of 1 million units, but we were interested in what economies of scale may exist in component procurement. Prices drop by about 10% as quoted production quantities double.

Table 2 The Design Attributes Derived from the 18 Coffee Makers Through the Use of Product Archaeology

Attribute	Units	Estimation Method
Assembly Content	Hours	Boothroyd-Dewhurst method for manual assembly (Boothroyd and Dewhurst 1989).
Total Purchased Parts	US$	Quotes from U.S. component suppliers.
Sheet Metal Use	Equivalent kg mild steel	Mass of material consumed for each part (including scrap) converted to equivalent mass of mild steel by ratio of metal cost to mild steel cost (1991 U.S. prices from Serjeantson 1992).
Sheet Metal Processing Time	Hours (×1000)	Sum of the processing times for each sheet metal part (estimated from press rates in Wick et al. 1984).
Sheet Metal Press Requirements	kN-hours	Sum for all sheet metal parts of max. press force times press cycle time. Press force determined from tables in Wick et al. 1984.
Sheet Metal Tooling Fabrication Time	k-hours	Comparison of size and complexity to dies estimated by Harig (1976).
Plastic Use	Equivalent kg polypropylene	Part mass plus allowance for mass of sprues and runners. All resins (e.g., polycarbonate) converted to equivalent mass of polypropylene by ratio of actual resin cost to polypropylene cost (1991 U.S. bulk resin prices from Rauch 1991).
Molding Processing Time	Hours (×1000)	Sum of cycle times for all molded parts. Cycle times from formula in Busch 1987.
Molding Machine Requirements	kN-hours	Sum for all plastic parts of clamp force times mold cycle time. Clamp force determined from part, sprue, and runner area (Busch 1987).
Total Plastic Mass	kg	The mass of all of the plastic parts, sprues, and runners in the product (used for energy consumption calculation).
Mold Fabrication Time	k-hours	Mold making time estimation tool (Pearson 1992).

All attribute values, except for total plastic mass, are estimates.

we summarize a few of the differences among the designs.

A key driver of assembly cost is assembly time. The estimated assembly time of the products ranges from 4.44 minutes (0.074 hours) for the Braun KF400 to 9.60 minutes (0.160 hours) for the Mr. Coffee Expert. This element of manufacturing content closely mirrors the differences in part counts among the products. The KF400 contains 49 parts, of which 5 are fasteners; while the Expert contains 80 parts, of which 32 are fasteners—the most parts and fasteners of any of the products. The product containing the fewest parts is the Krups 150, with 39 parts (including 3 fasteners). The Rowenta FK26-S contained only two fasteners, the fewest of the products.

The key drivers of materials cost are plastic use and sheet metal use. The plastic use in the products (expressed as equivalent kilograms of polypropylene) ranged from 0.87 kg for the Regal to 3.43 kg for the Krups 178. The sheet metal use in the products (expressed as equivalent kilograms of mild steel) ranged from 0.22 kg for the Braun KF650 to 1.33 kg for the Mr. Coffee Expert.

The purchased parts content of the products (estimated prices from U.S. suppliers) ranges from $3.28 for the Rowenta FG22-O to $5.03 for the Krups 150. Note that much of this variation is due to differences in the required quantities of similar purchased components such as screws, rather than to differences in the cost of a particular type of component. The molding process time requirements range from 80 seconds (0.0223 hours) for the Mr. Coffee International to 135 seconds (0.0376 hours) for the Mr. Coffee Expert. The sheet metal processing time ranged from 3 seconds (0.00083 hours) for the Rowenta FK26-S to 9 seconds (0.0025 hours) for the Mr. Coffee International, SR-12, and Accel models.

4. Estimating Variation in Manufacturing Cost

Analysis of the products reveals substantial variation in the values of the design attributes. In this section, we

Table 3 Manufacturing Content for Coffee Makers

	Assembly Content (BDI hours)	Total Purchased Parts (US$)	Sheet Metal Use (eqv. kg mild steel)	Sh. Metal Processing Time (hours × 1000)	Sh. Metal Press Req'ts (kN-hours)	Sh. Metal Tooling Fabrication Time (k-hours)	Plastic Use (equiv. kg. polypropylene)	Molding Processing Time (hours × 1000)	Molding Machine Req'ts (kN-hours)	Total Plastic Mass (kg)	Mold Fabrication Time (k-hours)	Tooling Lead Time (weeks)	No. of Parts	No. of Molded Parts	No. of Unique Parts	No. of Fasteners
Black and Decker																
DCM90	0.110	4.39	0.86	1.67	0.52	1.10	1.25	33.70	71.1	1.17	11.9	6.8	52	15	43	11
DCM900	0.094	3.64	0.41	2.08	0.59	1.35	1.11	29.50	66.6	1.00	14.5	15.6	46	12	42	4
Mr. Coffee																
International	0.110	3.83	1.29	2.50	0.96	2.15	0.75	22.30	52.6	0.67	7.8	8.2	71	7	50	23
SR-12	0.102	4.82	1.29	2.50	0.96	2.15	0.93	23.90	56.8	0.88	11.6	10.9	54	9	42	15
Accel	0.122	4.22	1.02	2.50	0.96	1.95	1.35	35.50	87.4	1.25	15.8	23.1	67	12	46	23
Expert	0.160	5.03	1.33	1.67	0.70	1.50	1.35	37.60	87.5	1.23	15.3	11.9	80	13	46	32
N.A.P.																
Norelco 663	0.079	3.68	0.98	2.08	0.89	1.05	1.39	23.90	69.7	1.10	12.3	16.6	41	11	33	9
Proctor Silex																
A6278	0.103	3.67	1.04	2.08	0.89	1.70	0.95	28.90	60.3	0.89	11.6	8.9	47	12	36	11
A8737	0.129	4.06	0.55	2.08	0.70	1.35	1.27	38.70	77.1	1.08	14.9	12.3	61	14	43	22
Regal																
Regal	0.094	3.52	0.49	2.08	1.00	0.80	0.87	25.50	63.8	0.75	12.4	14.4	42	10	31	14
Toastmaster																
Toastmaster	0.105	4.37	0.30	1.25	0.45	0.55	1.71	33.00	73.0	1.14	13.4	13.5	57	12	57	11
Braun																
KF400	0.074	4.03	1.15	1.67	0.63	1.85	0.97	30.10	59.3	0.77	17.6	19.3	49	16	43	5
KF650	0.092	3.91	0.22	1.25	0.45	0.85	1.95	36.50	78.7	1.17	17.7	24.7	42	14	37	4
Krups																
130	0.092	4.99	0.34	1.25	0.45	0.85	2.10	33.50	77.8	1.21	17.9	21.6	47	13	40	4
150	0.078	5.03	0.34	1.25	0.45	0.85	2.08	25.60	54.6	0.89	13.4	14.2	39	10	36	3
178	0.117	4.57	0.39	1.67	0.52	1.10	3.43	35.40	73.4	1.06	15.6	16.0	52	13	44	7
Rowenta																
FG22-O	0.090	3.28	0.30	1.25	0.45	0.80	1.03	27.30	53.8	0.86	15.1	10.4	46	13	36	5
FK26-S	0.101	3.85	0.27	0.83	0.26	0.55	1.33	34.80	77.9	1.14	21.2	24.0	60	16	43	2
Mean	0.103	4.16	0.70	1.76	0.66	1.25	1.43	30.87	69.0	1.01	14.4	15.1	53	12	42	11
Minimum	0.074	3.28	0.22	0.83	0.26	0.55	0.75	22.30	52.6	0.67	7.8	6.8	39	7	31	2
Maximum	0.160	5.03	1.33	2.50	1.00	2.15	3.43	38.70	87.5	1.25	21.2	24.7	80	16	57	32

All attributes, except part counts and masses, are estimates.

explore the degree to which this variation corresponds to significant variation in manufacturing cost. We adopt the basic cost model represented by Equation (3). The structure of the cost model is consistent with product cost estimation techniques used widely in industry. (See, for example, Burt et al. 1990 and Ostwald 1992.)

Following is a brief explanation of how each term is modeled. The appendix gives the specific algebraic expressions relating the manufacturing system parameters and the design attributes from the product archaeology to the terms in the cost model.

$$\begin{aligned} C = {} & C_{\text{assembly}} + C_{\text{purchased-parts}} + C_{\text{molded-parts}} \\ & + C_{\text{sheet-metal-parts}} + C_{\text{tooling}} + C_{\text{supervision}} \\ & + C_{\text{inventory}} + C_{\text{facilities}} + C_{\text{energy}}, \end{aligned} \quad (3)$$

where, for example,

$$C_{\text{assembly}} = \frac{\text{assembly-content} \times \text{assembly-labor-cost}}{\text{assembly-productivity} \times \text{assembly-yield}}, \quad (4)$$

and assembly-content is in units of Boothroyd-Dewhurst hours, assembly-labor-cost is in dollars per hour, assembly-productivity is a nondimensional ratio reflecting the productivity of the assembly workforce relative to the Boothroyd-Dewhurst metric, and assembly-yield is the fraction of products assembled correctly. Assembly content is a characteristic of the design, while labor cost, assembly productivity, and assembly yield are characteristics of the manufacturing system.

Costs

- The cost of purchased parts is modeled by the price quotes we obtained from U.S. suppliers divided by a sourcing efficiency, reflecting either more or less effective purchasing efforts, and a purchased parts yield.
- The cost of molded parts is determined by raw material usage, cycle time, required capacity, machine cost, operator wages, molding yields, and the number of machines run by each operator. The cost of sheet metal parts is determined in a similar fashion.
- The cost of tooling is determined by the estimated tooling fabrication time times the tooling shop rate, divided by the tooling life.
- The cost of supervision is determined from the estimated assembly cost, the assembly labor cost, the plant span-of-control, and the supervisory labor cost.
- The cost of inventory is determined from the inventory level, expressed as equivalent days of finished goods inventory, the unit variable cost, and an inventory holding cost rate.
- The cost of facilities is determined by estimating the relative size of a production facility required to produce 1 million units per year given the assembly and fabrication requirements determined by the manufacturing content and the assumed manufacturing parameters. A baseline of 5,000 square meters of space is assumed.
- The cost of energy is determined by estimating the cost of melting and processing the plastic in the product. This is the most significant energy consumption associated with the product. We did not attempt to estimate the other energy requirements for stamping, materials handling, or small power tools.

Note that we have defined manufacturing cost in a way that does not include much of what would normally be considered plant overhead or "system costs." There is no estimate of, among other elements, purchasing, shipping, receiving, quality control, materials handling, or senior plant management. In previous research involving a consumer camera manufacturing facility (Ulrich et al. 1993), we found that these system costs accounted for approximately 20 percent of the total manufacturing costs. Some of these system costs are approximately invariant with respect to widely differing product designs. For example, the cost of operating the shipping department is independent of the specifics of the product design. However, some of these system costs do depend on the details of the product design. In our previous study, we found that the key drivers of these costs were assembly time, the number of parts, and the number of vendors supplying parts. The number of vendors is only partially related to the design, and for the coffee maker sample, assembly time and the number of parts are both positively correlated with the total estimated manufacturing cost. As a result, we would expect that the addition of system costs to our model would enlarge rather than diminish the observed variation in estimated costs.

Table 4 displays the estimated manufacturing cost for each of the 18 coffee makers for a hypothetical manufacturing system. The parameters used in the cost model are shown in Table 5. These parameters are intended to approximate a well-run plant in a medium-cost economic environment (e.g., southern United States). The sources for these values are given in the appendix.[4]

---

[4] An analysis of the uncertainty in these estimates is available from the authors upon request.

Table 4 Estimated Manufacturing Costs

Mfr. and Model	Est. Mfg. Cost	Adj. Retail Price
Black & Decker		
DCM90	7.53	18.50
DCM900	6.45	25.00
Mr. Coffee		
International	6.56	21.20
SR-12	7.74	25.50
Accel	7.84	26.60
Expert	9.11	33.30
N.A.P.		
Norelco 663	6.55	21.90
Proctor Silex		
A6278	6.57	16.60
A8737	7.48	23.20
Regal		
Regal	6.05	24.90
Toastmaster		
Toastmaster	7.61	18.70
Braun		
KF400	6.87	32.50
KF650	7.36	35.00
Krups		
130	8.55	47.90
150	8.16	43.30
178	9.28	50.00
Rowenta		
FG22-O	5.92	40.60
FK26-S	7.09	43.10
Mean	7.37	
Minimum	5.92	
Maximum	9.28	

Significance of Variation in Manufacturing Content in Influencing Manufacturing Cost

The significant variation in manufacturing content of the products translates into significant variation in manufacturing costs for the hypothetical manufacturing system. The average estimated cost for the products is \$7.37. We estimate the cost of the least costly product, the Rowenta FG22-O, to be \$5.92; and the most costly product, the Krups 178, to be \$9.28, a range of \$3.36. We view the magnitude of this range as large and highly significant relative to the size of profit margins that are typical in the small appliance business. For example, Mr. Coffee earned gross margins of 28.5% in 1991, or \$4.28 on a coffee maker with a factory price of \$15.00 (SEC 1993).

Although in absolute terms the differences in estimated manufacturing costs due to differences in manufacturing content seem important, we are also interested in how the magnitude of this difference compares to that which one might expect due to differences in the cost structures of alternative manufacturing systems. To explore this question, we consider five other sets of manufacturing system parameters corresponding to other hypothetical settings. In addition to the base case scenario (a well-run plant in a medium-cost economic environment), we consider poorly and well-run facilities in low-, medium-, and

Table 5 Cost Model Parameters

Parameter	Value
Assembly and Operator Labor Cost, Including Benefits (US\$/hr)	11.00
Supervisory Labor Cost, Including Benefits (US\$/hr)	16.50
Tool Making Cost, Shop, and Labor (US\$/hr)	38.00
Days Operation per Year	240
Hours per Day	16
Facility Cost (US\$/m^2/yr)	25.00
Assembly Productivity	1.20
Assembly Yield	1.00
Sourcing Efficiency	1.05
Purchased Parts Yield	1.00
Polypropylene Cost (\$/kg)	0.84
Mild Steel Cost (\$/kg)	0.33
Molding Machines per Operator	3
Molded Part Yield	0.995
Stamping Machines per Operator	1
Stamped Part Yield	0.995
Equipment Utilization	0.80
Span of Control	10
Inventory Level, including raw materials, WIP, and finished goods (expressed in equivalent days of finished goods)	30 days
Molding Machine Cost (US\$)	
Basic molding machine cost	21383
Molding machine capacity cost	+59 per kN capacity
Stamping Machine Cost (US\$)	
Basic stamping machine cost	30400
Stamping machine capacity cost	+73 per kN capacity
Inventory Holding Cost	20% per year
Cost of Capital	10% per year
Plastic Regrind Rate	20%
Useful Machine Life	6 years
Energy Cost	0.10 \$/kw-hr
Production Rate	1,000,000 units/year
Tool Life	1,000,000 units

high-cost economic environments. The parameter values for these situations are given in the appendix. The estimated cost of each product for each of the six scenarios is shown in Table 6.

The cost scenarios in Table 6 span a wide range of hypothetical manufacturing systems, corresponding approximately to the best and worst systems we have observed world-wide for assembled goods made from injection molded and stamped components. The difference in estimated cost for the same product produced across the range of hypothetical manufacturing systems is large, on average 65 percent of the average cost.

The relative magnitude of the variation in cost due to different assumptions about the manufacturing systems compared to the variation in costs due to differences in manufacturing content is one indicator of the relative importance of the design and manufacturing activity of the firm. Many have implied that design decisions are

Table 6 **Estimated Cost for 18 Coffee Makers Produced by Six Hypothetical Manufacturing Systems**

	Manufacturing System										
	Low-Cost Env Poorly Run	Med-Cost Env Poorly Run	High-Cost Env Poorly Run	Low-Cost Env Well Run	Med-Cost Env Well Run	High-Cost Env Well Run	Mean	Min	Max	Range	Range % of Mean
Black and Decker											
DCM90	7.73	9.90	12.24	6.39	7.53	8.79	8.76	6.39	12.24	5.86	67%
DCM900	6.58	8.46	10.52	5.46	6.45	7.57	7.51	5.46	10.52	5.06	67%
Mr. Coffee											
International	6.61	8.66	10.85	5.45	6.56	7.76	7.65	5.45	10.85	5.40	71%
SR-12	8.05	10.00	12.11	6.70	7.74	8.91	8.92	6.70	12.11	5.41	61%
Accel	7.94	10.33	12.93	6.57	7.84	9.25	9.14	6.57	12.93	6.36	70%
Expert	9.11	12.10	15.31	7.50	9.11	10.85	10.66	7.50	15.31	7.81	73%
N.A.P.											
Norelco 663	6.87	8.44	10.17	5.72	6.55	7.49	7.54	5.72	10.17	4.45	59%
Proctor Silex											
A6278	6.66	8.67	10.84	5.50	6.57	7.75	7.66	5.50	10.84	5.33	70%
A8737	7.47	10.00	12.72	6.15	7.48	8.96	8.80	6.15	12.72	6.58	75%
Regal											
Regal	6.12	7.96	9.95	5.07	6.05	7.13	7.05	5.07	9.95	4.88	69%
Toastmaster											
Toastmaster	7.87	9.95	12.20	6.52	7.61	8.81	8.82	6.52	12.20	5.68	64%
Braun											
KF400	7.25	8.81	10.56	6.07	6.87	7.83	7.90	6.07	10.56	4.49	57%
KF650	7.66	9.58	11.69	6.37	7.36	8.50	8.52	6.37	11.69	5.33	62%
Krups											
130	9.06	10.95	13.04	7.57	8.55	9.68	9.81	7.57	13.04	5.48	56%
150	8.78	10.36	12.10	7.34	8.16	9.11	9.31	7.34	12.10	4.76	51%
178	9.73	12.03	14.54	8.06	9.28	10.63	10.71	8.06	14.54	6.48	60%
Rowenta											
FG22-O	6.00	7.77	9.72	4.98	5.92	6.98	6.90	4.98	9.72	4.74	69%
FK26-S	7.24	9.28	11.53	6.03	7.09	8.33	8.25	6.03	11.53	5.51	67%
Mean	7.60	9.63	11.83	6.30	7.37	8.57					
Minimum	6.00	7.77	9.72	4.98	5.92	6.98					
Maximum	9.73	12.10	15.31	8.06	9.28	10.85					
Range	3.73	4.33	5.59	3.08	3.36	3.87					
Range as % of mean	49%	45%	47%	49%	46%	45%					

much more important than manufacturing decisions by claiming that "design determines 80 percent of manufacturing costs." Our sensitivity analysis suggest that design and manufacturing decisions are both highly significant and of roughly equal importance in determining costs for this product context.

5. Sources of Variation

To support the hypothesis that design is managerially important, the differences in manufacturing content that we observe must be substantially attributable to differences in the capabilities of the teams that designed the products. There are at least three competing hypotheses to be addressed. First, the products may exhibit different levels of quality; that is, they may be different in ways that are both important to consumers and that are expensive to achieve. Second, the products may be the result of rational design processes which attempt to minimize cost under different factor price conditions, leading to designs which may be different, but in ways that are optimal given a firm's economic environment. Third, the differences may arise from sampling products designed at different times over a period in which the capabilities of the entire industry are changing. Here we examine each of these explanations in light of the empirical evidence.

Quality Differences

An assumption underlying our analysis is that the products all satisfy the same product requirements. Furthermore, we have focused our analysis on the components of the products corresponding to an identical set of features, eliminating from consideration such features as drip stops and timers. Although the products perform identically in terms of their core function of making coffee, the products are, of course, not identical. What is the degree to which the differences among the products, as perceived by customers, correspond to differences in cost? In other words, might some desirable attribute of the products be costly and account for the differences in product cost we have identified? The two categories of attributes we view as most likely to support this explanation are (1) the quality of the industrial design and (2) the "reliability quality" of the products.

Although the coffee makers are functionally similar, they do exhibit significant differences in industrial design, the aesthetic and ergonomic characteristics of the products. The appearance of a product, and therefore its industrial design, influences consumer behavior. Firms may be willing to suffer higher manufacturing costs in order to achieve more desirable levels of industrial design. As part of this study we tested the hypothesis that the quality of industrial design is positively correlated with estimated manufacturing cost. (The details of this test are reported in Pearson 1992.) We measured industrial design quality by asking 9 professional product designers to rank order the 18 products with respect to aesthetics and ergonomics. In summary, we found that the designers' opinions were significantly consistent with one another. However, there was no significant correlation between estimated manufacturing cost and either aesthetics or ergonomics. We did find a significant positive correlation between industrial design quality and the estimate of one element of manufacturing cost, tooling cost ($p < 0.005$) and with estimated tooling lead time ($p < 0.01$). One explanation for this result is that industrial designers almost always add geometric complexity to a product in order to create visual interest. This additional complexity may not require more material or processing time, but may require more tooling complexity and therefore more tooling cost and tooling fabrication time. Because the production volumes of coffee makers are so high, the tooling cost differences amount to only a few cents per product and do not account for very much of the variation in costs observed among the products.

Perhaps there are differences in manufacturing costs arising from differences in "reliability quality." There are only a few failure modes for coffee makers. Based on interviews with two coffee maker designers, we found that failure of the heating elements due to calcification of the heater tube is the primary failure mode of the product. Because all the heating elements have basically the same tube geometry, this calcification should occur with equal frequency in all of the models. (Calcification is caused simply by the mineral deposits left when the water is boiled.) Occasionally the electromechanical components—the thermostat and switch—fail. In fact, Black & Decker, Proctor-Silex, and General Electric (prior to selling its business to Black & Decker) have all had major thermostat failures and product recalls (*Wall Street Journal* 1994, Brown 1991, *HFD* 1990). We found the cost differences among the most expensive and least expensive switches and thermostats to be on the order of \$0.20, so the relationship between this aspect of quality and cost is at most slight. Interestingly, the European brands (Braun, Krups, and Rowenta) have strong reputations for product quality, yet field products with manufacturing content no higher than average.

Because aesthetics and quality may be reflected in the prices consumers are willing to pay for coffee makers, we also investigated the relation between manufacturing content (represented by the estimate of manufacturing cost) and the selling price of the coffee makers. The manufacturers' suggested retail prices for the coffee makers in our study range from \$19.99 to \$79.99. Some of this range in price is related to differences in features, such as timers and water level indicators, which we explicitly excluded from our estimates of manufacturing costs. In our extended study, we adjusted the retail price for these differences in features.[1] While our price adjustment procedure is approximate, the hypothesis that price and estimated cost (for a specific hypothetical manufacturing system) are positively related is not supported by our data. Some of the most expensive models have the lowest estimated manufacturing costs, and some of the least expensive models have relatively high estimated manufacturing costs. For example, the Rowenta FG22-O sells for a feature-adjusted price of \$40.60 (unadjusted price is \$49.99), while we estimate its cost to be \$5.92 for a well-run plant in a medium-cost environment. The Toastmaster sells for a feature-adjusted price of \$18.70 (unadjusted price is \$22.99), while we estimate its cost to be \$7.61. Note that this analysis specifically does not address the relation between prices and the manufacturers' actual costs, but rather examines the relation between price and the manufacturing content of the products, as reflected by the estimated manufacturing cost for a hypothetical manufacturing system.

Based on this evidence we do not find significant support for the explanation that differences in manufacturing content among the products are substantially explained by differences in product quality.

Tradeoffs with Respect to Factor Prices

One might expect that firms would optimize their designs to exploit the particular cost structures within which they operate. The most obvious example of such a strategy would be a firm operating in a high-wage environment minimizing the assembly content of its design at the expense of some other attribute such as materials content, or a firm in a low-wage environment doing the opposite.

We do not have sufficient data on actual factor prices or firm-specific accounting systems to test for the presence of all such optimization. However we can test for optimization with respect to the largest difference in factor prices, assembly labor cost, by comparing the assembly content of products assembled in low-wage environments with that of products assembled in high-wage environments. Thirteen products were assembled in the United States or Germany, while five products were assembled in Mexico, China, or Taiwan. The mean estimated assembly time for the 13 products assembled in the United States or Germany is 0.102 hours. The mean estimated assembly time for the five products assembled in China, Taiwan, and Mexico is 0.105 hours. (The standard deviation of the 18 data points is 0.021.) Based on a t-test, the difference between the means of these two samples is not statistically significant.

In addition to the suggestive statistical evidence, we also suspect that firms are not explicitly making subtle design tradeoffs to conform to differences in factor prices because many of these products are shifted from one assembly plant to another over the life of the product. For example, both Krups and Braun have produced a product in Germany and then in Mexico.

Another property of the designs in this sample is that the ordering by cost of the 18 products changes very little under widely different assumptions about manufacturing system parameters and factor prices. Low-cost designs remain low-cost designs, and high-cost designs remain high-cost designs under all of the scenarios we have considered. For example, the Rowenta FG22-O is strictly dominant, remaining the lowest cost design under all of the hypothetical scenarios. The product with the highest manufacturing content in the sample is either the Mr. Coffee Expert or the Krups 178 in all the scenarios. The outcome does depend on the relative cost of assembly labor, purchased components, and plastic. The Expert has very high assembly content and uses a lot of purchased parts (mostly screws and other fasteners). The Krups 178 uses a lot of expensive plastic materials. Despite these differences, both products remain very expensive designs under all the scenarios.

We do believe that some design tradeoffs exist. For example, reducing fastener count and therefore assembly content will generally require slightly more plastic use, assuming an otherwise identical design. This assumes that firms operating at the efficient frontier of design could make slight adjustments to their designs to optimize them for different relative prices of assembly labor and plastic. However, for this sample, we believe the magnitude of manufacturing content differences due to such optimization is small compared to the observed variation in manufacturing content.

Time Effects

The third explanation we consider is that the design capability of the entire industry is changing over time. Such a phenomenon, in combination with the existence in the marketplace of designs of different ages, would explain differences in manufacturing content among the products in our sample.

Although we do not know the precise time period over which the design decisions were made for each product, we do know the product introduction dates. Using this information, we can test the hypothesis that introduction date is negatively correlated with manufacturing content. (Presumably the capabilities of the industry are improving with time.) Using the estimated manufacturing cost of each product (for the well-run, medium-cost-environment scenario) and the year of introduction as variables, we do not find statistical support for this hypothesis.

Eight of the eighteen products in the sample were introduced in 1990 or 1991, while the rest were introduced from 1985 to 1989. The wave of new products introduced in 1990 and 1991 was almost certainly designed without knowledge of the contemporary designs, because product development lead times in this industry typically are at least two years. However, the designers of these products would have had easy access to the products introduced before 1990. The average assembly time of products introduced in 1990 or 1991 is slightly lower than that of their predecessors ($7.26 versus $7.47), although this difference is not statistically significant.

We have some anecdotal evidence that later design efforts took full advantage of the knowledge of existing designs in the marketplace. Several articles in appliance industry publications chronicle the development of the Black and Decker DCM900, including a discussion of the extensive benchmarking of competitive products done by the development team (Babyak 1991). Our interviews with two coffee maker designers confirm that such benchmarking occurs, but is not universal.

We believe that the cost performance of the entire industry does improve over time, although we do not have statistically significant evidence of such improvement. However, any such improvement from year to year appears to be small relative to the range of performance exhibited across contemporaneous design efforts.

Product Design Capability

The final explanation for the differences in manufacturing content among the products is that the design teams possessed different levels of design capability. This view is supported in part by the elimination of the competing hypotheses, but there is also direct evidence of differences in capabilities. We observe differences in design approaches among the products that correspond to significant differences in manufacturing content. As an illustration of the differences in these approaches, and therefore in the capabilities of the associated design teams, we describe three design approaches that seem to lead to the lowest estimated manufacturing costs.

First, low-cost designs tend to exploit the ability of injection molding to achieve high levels of geometric complexity at very low cost. For example, several of the molded bases of low-cost designs include geometric features into which the power cord can be woven in order to eliminate the need for a separate part to accomplish the function of "strain relief" (the prevention of the cord from being pulled out of the product). Similarly, some of the low-cost designs include only two rubber feet assembled to the base of the product—sufficient to prevent sliding and rotation of the product—with two additional feet molded into the main plastic base part to provide necessary stability. Some of the higher-cost designs include four rubber feet, each of which must be assembled onto the base of the product.

Second, low-cost designs reflect a careful partitioning of the overall geometry of the product into individual plastic piece parts. In general, the low-cost designs consolidate many geometric features into a single part. (See

Ulrich et al. 1993 for a thorough discussion of strengths and weaknesses of this design tactic.) Achieving this consolidation requires that part boundaries be defined such that there are few parts, but that these parts can be molded within the process constraints of injection molding.

Finally, low-cost designs reflect resourceful decisions about the quantity and type of materials required. The dominant material for coffee makers is polypropylene; however, some of the components on some of the models are made of polycarbonate, a much more expensive polymer (by a factor of two or three). The relative merits of the two materials are covered at length in Freeze (1990), but in short, polycarbonate provides better surface finishes and distorts less when the molded parts cool. Some designers were able to mask the imperfections in large polypropylene surfaces through the clever choice of surface features, such as ribs and grooves. These techniques allowed the use of less expensive plastics with no compromise in part quality. Other designers optimized the structural properties of parts in order to minimize the required plastic thickness while maintaining the rigidity of the product.

Some of these techniques can be viewed as good general practices for high-volume product design. Such techniques are described in handbooks and can be developed as a capability through education and experience. However, some of the techniques are protected by intellectual property rights, primarily utility patents. As an indication of the level of patent activity in the industry, a keyword search of utility patents from 1971 revealed 658 U.S. patents related to coffee makers, some of which are related to design techniques. Patent protection is one explanation for how differences in manufacturing content can persist even in the face of observations by manufacturers of their competitors' products.

6. Concluding Remarks

The goal of this paper is to assess the importance of design in determining product costs, and by implication, profitability. For the domain of coffee makers, we found significant variation in manufacturing content—corresponding to a range of estimated manufacturing costs for a hypothetical manufacturing system of approximately 50 percent of the average manufacturing cost of the products. After considering a set of competing hypotheses, we conclude that differences in capability among product development efforts are the most plausible explanation for the variation in manufacturing content.

This research examines a specific product category in detail, but we hope the results illuminate product design issues in general. Coffee makers are high-volume, discrete, assembled products incorporating electrical and mechanical elements. The primary fabricated components are injection molded and stamped. These characteristics are shared by many consumer and industrial products including automobile parts, other small appliances, power hand tools, housewares, toys, and lighting. We would expect the manufacturing content of such products to exhibit similar properties to coffee makers, but we are not certain if the results would be similar for substantially different categories such as consumer electronics, heavy equipment, or computers. To structure the question of broader applicability, we pose the results from the domain of coffee makers as three hypotheses about product design in general.

First, differences in design practices correspond to significant differences in manufacturing content, and therefore manufacturing costs. This hypothesis might be labeled *design matters*. For coffee makers, we find that manufacturing content, as reflected by estimated manufacturing costs, varies over a range of approximately 50 percent of the average estimated manufacturing cost. Coffee makers are a very mature product category with a very stable core technology. We would expect the range of manufacturing content to be larger in less mature product categories, and smaller in more commodity-like categories.

The second general hypothesis is that for a given set of product requirements, low-cost designs can be achieved without compromising product quality. Drawing an analogy to the quality movement, this hypothesis might be labeled *design is free*. In the domain of coffee makers, we find that two key dimensions of quality, industrial design quality and reliability quality, are not significantly correlated with manufacturing content. It is especially striking that some of the products positioned as high-price, high-quality products have the lowest manufacturing content in our data set (e.g., the Rowenta FG22-O). (See, for example, the prices and estimated costs shown in Table 4). By *design is free* we mean that while the design effort itself may consume significant resources, efforts to reduce manufacturing content do not necessarily lead to lower quality products as perceived by consumers.

The third general hypothesis is that different firms exhibit competitively significant differences in design capability. This hypothesis might be stated as *design is hard.* For coffee makers we observe that the approaches taken by different design teams are quite different and result in quite different outcomes. We hypothesize that design is like most other human pursuits in that a collection of teams will exhibit a distribution of performance capabilities. We further hypothesize that the variation in performance will generally be competitively significant.

This study is exploratory and many important questions remain unanswered. In addition to the question of whether our findings apply to other product contexts, we see four directions for further work:

(1) How can design capability be acquired and developed? Companies like Braun have very low employee turnover, employ design leaders, and espouse clear design principles (Freeze 1989). Do these managerial practices lead to the development of design capability? Which design methodologies, if practiced, lead to good designs? How important are the skills and talents of individual designers relative to a firm's organization and development methodology?

(2) How does product design influence revenues? There is much anecdotal evidence that differences in design performance influence consumer appeal, and therefore revenues. How significant is this influence? Where is the most significant leverage: aesthetics, ergonomics, unique features, reliability?

(3) How do competitive interactions relate to optimal design policies? In a highly competitive industry in which nonproprietary innovations can be copied, how much investment in design capability is warranted? Would it be better to lead in design innovation or follow?

(4) What are the dynamics of design improvement over product and technology life-cycles? We hypothesize that the range of design performance with respect to manufacturing content is high in the early phases of a technology life-cycle but narrows as a dominant design emerges and as differences among products begin to diminish.

Implications for Practitioners

Given the cost model and the design data, we can explore some of the decisions a firm faces when trying to reduce costs. For situations like the one we examine, there are at least three managerial approaches to reducing costs: improvements in design, changes in the economic environment, and changes in production management practices.

Consider the specific example of the Krups 178, one of the two products with the highest manufacturing content. Assume that the product were made, by a firm "Acme," in a poorly run plant in a high-cost economic environment. We estimate the manufacturing cost under these conditions to be $14.54. Acme could move to a low-cost environment, retaining the same design. If its new plant were poorly run, Acme could reduce its costs to $9.73. If the plant were well-run, it could reduce its costs to $8.06. Acme could also redesign its product. Assuming a design like that of the Rowenta FG22-O could be achieved, Acme could reduce its costs to $9.72 in the original plant. If it improved its plant operations at the same time, Acme could reduce its costs to $6.98. Perhaps Acme could improve its design, move its plant, *and* improve its operations. Under these conditions it could achieve a cost of $4.98. Of course, a decision about where to focus improvements depends not only on the savings but on the required investment. The result we find most interesting is that for product domains with cost structures like that of coffee makers, cost reduction through redesign of the product may be an extremely attractive alternative to moving operations to a low-cost economic environment. For practitioners, such analysis has the potential to inform decision makers about the benefits of a variety of different design and manufacturing scenarios.

Product Archaeology as a Research Methodology

Much of the research that has been done in product development has relied on subjective data drawn from interviews and surveys. For example, in the MIT International Motor Vehicle Research Program study (MacDuffie 1991), the design-for-assembly variable for automobiles was determined by asking manufacturers to rate subjectively the ease of assembly of other manufacturers' products. In our view, many of the success factors of product development are difficult to address at an aggregate level based on subjective data. We have developed the product archaeology methodology as an approach to gathering objective data for product development research. The methodology offers several benefits. A relatively large sample size can be explored without intensive interaction with many manufacturers. The artifact provides completely accurate data; it doesn't forget, omit, or misrepresent information. Because the artifact is publicly available, the names of products and manufacturers can be freely disclosed.[5]

Appendix

Manufacturing Cost Model

The manufacturing cost model consists of the terms in the following expression:

$$C = C_{\text{assembly}} + C_{\text{purchased-parts}} + C_{\text{molded-parts}} + C_{\text{sheet-metal-parts}} + C_{\text{tooling}} + C_{\text{supervision}} + C_{\text{inventory}} + C_{\text{facilities}} + C_{\text{energy}}.$$

Table A1 **Assumed Manufacturing Parameters Corresponding to a Low, Medium, and High-Cost Economic Environment**

	Low	Medium	High
Assembly and Operator Labor Cost, including benefits (US$/hr)	2.00	11.00	20.00
Supervisory Labor Cost, including benefits (US$/hr)	3.00	16.50	30.00
Tool Making Cost, Shop and Labor (US$/hr)	38.00	38.00	45.00
Days Operation per year	250	240	220
Hours per Day	18	16	16
Facility Cost (US$/m²/yr)	19.00	25.00	34.00

All values are derived either from data supplied by the U.S. Bureau of Labor Statistics or from analogous systems described in Mody et al. (1991).

In turn, each of the terms is modeled as follows (all variables are expressed as hyphenated versions of the labels in Tables 2, 3, 5, A1, and A2):

$$C_{\text{assembly}} = \frac{\text{assembly-content} \times \text{assembly-labor-cost}}{\text{assembly-productivity} \times \text{assembly-yield}},$$

$$C_{\text{purchased-parts}} = \frac{\text{total-purchased-parts}}{\text{sourcing-efficiency} \times \text{purchased-parts-yield}},$$

$$C_{\text{molded-parts}} = \frac{C_{\text{plastic}} + C_{\text{molding}}}{\text{molded-part-yield}},$$

where

$$C_{\text{plastic}} = \text{plastics-use} \times \text{polypropylene-cost} \times (1 - \text{plastic-regrind-rate}),$$

$$C_{\text{molding}} = \text{molding-processing-time} \times \left(\text{base-machine-rate} + \text{machine-capacity-rate} \times \text{molding-machine-requirements} + \frac{\text{operator-labor-cost}}{\text{molding-machines-per-operator}}\right),$$

and

$$\text{base-machine-rate} = \frac{r(1+r)^n}{(1+r)^n - 1} \times \frac{\text{base-molding-machine-cost}}{\text{days-per-year} \times \text{hours-per-day} \times \text{equipment-utilization}},$$

$$\text{machine-capacity-rate} = \frac{r(1+r)^n}{(1+r)^n - 1} \times \frac{\text{molding-machine-capacity-cost}}{\text{days-per-year} \times \text{hours-per-day} \times \text{equipment-utilization}},$$

and where r is the cost of capital and n is the useful life of the machines.

$$C_{\text{sheet-metal-parts}} = \frac{C_{\text{metal}} + C_{\text{stamping}}}{\text{stamped-part-yield}},$$

where

$$C_{\text{metal}} = \text{sheet-metal-use} \times \text{mild-steel-cost},$$

$$C_{\text{stamping}} = \text{sheet-metal-processing-time} \times \left(\text{base-press-rate} + \text{press-capacity-rate} \times \text{sheet-metal-press-requirements} + \frac{\text{operator-labor-cost}}{\text{stamping-machines-per-operator}}\right),$$

and

---

[5] The research described in this paper was supported by the National Science Foundation as part of a Strategic Manufacturing Initiative Grant. E. Yung Cha gathered much of the data on component prices and wage rates. We are grateful for the many people at Tredegar Molded Products who generously provided time, data, and insights at various stages of this project; in particular Carl Peasley, Guy Vachon, and Doug Miller. The staff of Product Genesis, Inc. contributed to this research by evaluating the industrial design of the products in our data set. We also acknowledge helpful comments by Erik Antonsson, Sara Beckman, David Ellison, Steven Eppinger, Marshall Fisher, Stephen Graves, John Hauser, Chris Kemerer, Richard Locke, Marcie Tyre, John Wesner, and Bin Zhou. Avi Seidmann and several anonymous reviewers also provided useful help and guidance.

Table A2 Assumed Manufacturing Parameters Corresponding to a Poorly Run and Well-Run Plant

	Poorly Run	Well-Run	Source
Assembly productivity	0.80	1.20	Assumption and rules-of-thumb in industry practice.
Assembly yield	0.95	1.00	Authors' observations.
Sourcing efficiency	0.95	1.05	Range of switch prices quoted by four different U.S. vendors.
Purchased parts yield	0.98	1.00	Assumption.
Polypropylene cost ($/kg)	0.92	0.84	Range of international costs in Rauch (1991).
Mild steel cost ($/kg)	0.36	0.33	Range of international costs in Serjeantson (1992).
Molding machines per operator	1	3	Authors' observations.
Molded part yield	0.95	0.995	Authors' observations.
Stamping machines per operator	1	1	Authors' observations.
Stamped part yield	0.95	0.995	Authors' observations.
Equipment utilization	0.50	0.80	Interview with independent U.S. molder.
Span of control	7	10	(Mody et al. 1991)
Inventory level, including raw materials, WIP, and finished goods (expressed in equivalent days of finished goods)	90 days	30 days	(Mody et al. 1991)

The values based only on our observations and assumptions are derived from our prior experience with more than a dozen analogous molding, stamping, and assembly operations in the U.S., Europe, Mexico, and Japan.

$$\text{base-press-rate} = \frac{r(1+r)^n}{(1+r)^n - 1} \times \frac{\text{base-stamping-machine-cost}}{\text{days-per-year} \times \text{hours-per-day} \times \text{equipment-utilization}},$$

$$\text{size-press-rate} = \frac{r(1+r)^n}{(1+r)^n - 1} \times \frac{\text{stamping-machine-capacity-cost}}{\text{days-per-year} \times \text{hours-per-day} \times \text{equipment-utilization}},$$

and where r is the cost of capital and n is the useful life of the machines.

$$C_{\text{tooling}} = \frac{(\text{mold-fabrication-time} + \text{sheet-metal-tooling-fabrication-time}) \times \text{tool-making-cost}}{\text{tool-life}}.$$

$$C_{\text{supervision}} = \frac{C_{\text{assembly}}}{\text{assembly-labor-cost} \times \text{span-of-control}} \times \text{supervisory-labor-cost}.$$

$$C_{\text{inventory}} = \frac{\text{inventory-level}}{\text{days-operation-per-year}} \times C_{\text{variable}} \times \text{inventory-holding-cost},$$

where

$$C_{\text{variable}} = C_{\text{assembly}} + C_{\text{purchased-parts}} + C_{\text{molded-parts}} + C_{\text{sheet-metal-parts}} + C_{\text{supervision}} + C_{\text{energy}}.$$

$$C_{\text{facilities}} = \text{base-facility-size} \times \frac{\text{base-yearly-hours}}{\text{days-operation-per-year} \times \text{hours-per-day}} \times \text{space-utilization-factor} \times \text{facility-cost} \times \frac{1}{\text{production-rate}},$$

where

$$\text{space-utilization-factor} = \frac{3}{(\text{ass'y-productivity} \times \text{ass'y-yield} + \text{equip't-utilization} \times \text{mold-yield} + \text{base-inventory}/\text{inventory-level})}$$

and base-facility-size is 5000 m^2, base-yearly-hours is 4000 hours/year, and base-inventory is 60 days.

The space utilization factor assumes that the required floor space for a given annual production is proportional to the average of the yield-adjusted assembly productivity, the yield-adjusted equipment utilization, and the inventory levels in the plant.

$$C_{\text{energy}} = \text{total-plastic-mass} \times \text{plastic-processing-energy} \times \text{energy-cost},$$

where plastic-processing-energy has a value of 0.75 kw-hr/kg (Busch 1987).

Tables A1 and A2 present the parameter values for each of the different cost scenarios, the results of which are summarized in Table 6.

References

Appliance, "Annual Home Appliance Market Data," A Dana Chase Publication, Oak Brook, IL, September, 1991.

Archer, D., Early Cost Estimation of Injection Molded Components, Masters Thesis, Dept. of Manufacturing Engineering, Univ. of Rhode Island, Kingston, RI, 1988.

Babyak, R. J., "DFM Team Brews Cost-Cutting Coffee Maker; Design for Manufacturing in Black and Decker Corp.," *Appliance Manufacturer*, 39, 11 (1991).

Boothroyd, G. and P. Dewhurst, *Product Design for Assembly*, Boothroyd Dewhurst, Inc., Wakefield, RI, 1989.

Brown, W., "Deflecting Defects; Story of Coffee Maker Points Up Shortcomings of Federal Recall System," *The Washington Post*, H1, May 19, 1991, p. 55.

Burt, D. N., W. E. Norquist, and J. Anklesaria, *Zero Base Pricing: Achieving World Class Competitiveness Through Reduced All-In-Costs*, Probus Publishing, Chicago, IL, 1990.

Busch, J. V., "Technical Cost Modeling of Plastic Fabrication Processes," Doctoral Thesis, MIT Dept. of Materials Science and Engineering, Cambridge, MA, 1987.

Camp, R. C., *Benchmarking*, ASQC Quality Press, Milwaukee, WI, 1989.

Clark, K. B. and T. Fujimoto, *Product Development Performance: Strategy, Organization, and Management in the World Auto Industry*, Harvard Business School Press, Cambridge, MA, 1991.

Consumer Reports, "Drip Coffee Makers—Ratings," January (1991), 42–46.

Freeze, K., "Braun AG: The KF40 Coffee Machine," *Design Management Institute Case Study*, Boston, MA, 1990.

Garvin, D., "Quality on the Line," *Harvard Business Rev.*, 61, 5, (1983), p. 64.

Harig, H., *Estimating Stamping Dies*, Harig Educational Systems, Philadelphia, PA, 1976.

HFD-The Weekly Home Furnishings Newspaper, "Proctor-Silex Enlists Retailers in Recall Effort," 64, 37, September 10, 1990, p. 82.

Kaplan, R. S. (Ed.), *Measures for Manufacturing Excellence*, Harvard Business School Press, Cambridge, MA, 1990.

Krafcik, J. F., "The Triumph of the Lean Production System," *Sloan Management Rev.*, 30, 1 (1988), 41–52.

MacDuffie, J. P., "Beyond Mass Production—Flexible Production Systems and Manufacturing Performance in the World Auto Industry," Ph.D. Thesis, MIT Sloan School of Management, Cambridge, MA, 1991.

Miller, F. M., "Design for Assembly: Ford's Better Idea to Improve Products," *Manufacturing Systems*, 6, 3 (1988), 22–24.

Mody, A., R. Suri, J. Sanders, C. Rao, and F. Contreras, "International Competition in the Bicycle Industry: Keeping Pace with Technological Change," Industry Series Paper No. 50, The World Bank, Washington, DC, December, 1991.

Nussbaum, B., "Annual Design Awards," *Business Week*, 3427, June 5, 1995, p. 88.

Ostwald, P. F., *Engineering Cost Estimating*, Third Ed., Prentice-Hall, Englewood Cliffs, NJ, 1992.

Pearson, S. A., "Using Product Archaeology to Identify the Dimensions of Design Decision Making," Master's Thesis, MIT Sloan School of Management and Department of Mechanical Engineering, Cambridge, MA, 1992.

Rauch Guide to the U.S. Plastics Industry, Rauch Associates, Inc., Bridgewater, NJ, 1991.

SEC 10-K Filing, Mr. Coffee Inc., U.S. Securities and Exchange Commission, 1993.

Sanderson, S. and M. Uzumeri, "Managing Product Families: The Case of the Sony Walkman," Research Policy, 24 (1995), 761–782.

Serjeantson, R. (Ed.), *Metal Bulletin's Prices and Data 1992*, Metal Bulletin Books, Ltd., Surrey, UK, 1992.

Suri, R., J. L. Sanders, P. C. Rao, and A. Mody, "Impact of Manufacturing Practices on the Global Bicycle Industry," *Manufacturing Rev.*, 6, 1 (1993), 14–24.

Ullman, D. G., *The Mechanical Design Process*, McGraw-Hill, NY, 1992.

Ulrich, K., D. Sartorius, S. Pearson, and M. Jakiela, "Including the Value of Time in Design-for-Manufacturing Decision Making," *Management Sci.*, 39, 4 (1993), 429–447.

Ulrich, K. T. and S. D. Eppinger, *Product Design and Development*, McGraw-Hill, New York, 1995.

Wall Street Journal, "Black & Decker Division Recalls Coffee Machines," June 21, 1994, p. A10.

Wick, C., J. Benedict, and R. Veilleux (Eds.), *Tool and Manufacturing Engineers Handbook, Fourth Edition, Volume 2: Forming*, Society of Manufacturing Engineers, Dearborn, MI, 1984.

Accepted by Abraham Seidmann; received November 18, 1995. This paper has been with the authors for 2 revisions.