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Does Product Design Really Determine 80% of Manufacturing Cost?

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Karl T. Ulrich
Scott A. Pearson

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MASSACHUSETTS
INSTITUTE OF TECHNOLOGY
50 MEMORIAL DRIVE
CAMBRIDGE, MASSACHUSETTS 02139

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Massachusetts Institute of Technology
Sloan School of Management
Cambridge, Massachusetts 02139

Abstract

Many design researchers and practitioners motivate their work with the claim that 80% of the eventual manufacturing cost of a product is determined by the product design. The meaning of this assertion has not been well defined, nor has much empirical evidence been presented to support it. This paper addresses the question of how much product design influences the manufacturing cost of a product. In doing so, we define the research question formally, we develop a methodology for answering the question, and we provide a specific answer, under a particular set of assumptions, for a class of high-volume, electromechanical consumer products — automatic drip coffee makers. Our methodology includes *product archaeology*, the use of the product artifact as a source of data, and manufacturing cost modeling. We find that for coffee makers, the variation in manufacturing costs attributable to differences in product design is slightly smaller in magnitude than the variation in costs attributable to differences in manufacturing systems, for a specific range of assumed manufacturing system parameters.

Acknowledgments

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* Address all correspondence to this author at MIT Sloan School of Management, 50 Memorial Drive, Room E53-390, Cambridge, MA 02139, email: ulrich@mit.edu.

1. Introduction

Countless product design and development researchers motivate their work with references to studies that reveal that product design determines 80% (or some large percentage) of the manufacturing cost of a product; we have used such references many times ourselves. However, few references are made to the original studies and little explanation is given for what such a result might really mean. For example, a widely used engineering design text by Ullman (1992) displays a table showing that the design of the product influences 70% of its manufacturing cost. The table in Ullman's text is drawn from an article in *Manufacturing Systems* (Miller 1988). The information in the article is derived from an internal Ford study. When we tracked down the Ford study, a Ford employee said, "Oh, that was just an informal survey, I wouldn't base too much on it." Another reference, used to support the claim that design determines 80% of cost, describes a study in which engineers at Rolls Royce analyzed 2000 part drawings and discovered that 80% of the *cost reduction opportunities* required changes to the part design (Symon and Dangerfield 1980).

The belief that design determines 80% of the manufacturing cost of a product has become part of the folklore of product design and development research and practice (we use 80% for convenience, although the quoted figure varies from 70% to 90%). The belief is intuitive, compelling, and is an irresistible introduction to a paper or talk. The belief, if true, has profound implications for manufacturers. It suggests that product design is a much bigger lever on manufacturing cost than other factors, such as plant location or operations management practices. Consider, however, what "design determines 80% of manufacturing cost" might really mean.

One widely held interpretation is that once a product is designed, regardless of the way the manufacturing system is designed and operated, the minimum possible manufacturing cost is 80% of the maximum possible manufacturing cost. There is a basic conceptual flaw in such a definition. How can there be a maximum manufacturing cost? Imagine, for example, the rise in cost of a molded plastic product as injection molding yields decline from 99% to 1% due to poor choices of production process parameters.

There is also a basic logical flaw in the argument that if the minimum possible manufacturing cost is 80% of the maximum possible manufacturing cost then product design is a critical activity of the firm. The flaw arises from the assumption that much of the 80% of the cost of the product is under the control of the product designers. Consider, for example, a firm designing and producing electrical components that for fundamental physical reasons must contain a certain amount of gold. The manufacturing cost of the component may be largely determined by the cost of the gold. While in this case the design of the product does impose a lower bound on manufacturing cost corresponding to the cost of the gold, the product designers have little control over the cost. For this firm, trading on the gold market, and not product design, may be the critical activity.

This paper addresses the question of how much product design influences the manufacturing cost of a product. In doing so, we define the question formally, we develop a methodology for answering the question, and we provide a specific answer for a class of high-volume, electromechanical consumer products — automatic drip coffee makers. The methodology we present is not intended for academic inquiry only. Rather, we believe the methodology is useful to firms attempting to understand the relative leverage they can achieve through their design and manufacturing efforts.

The methodology consists of two basic steps: (1) use *product archaeology*, or the study of the product artifacts in the marketplace, to determine the design content of a group of products satisfying the same set of requirements, and (2) use a cost model to explore how the differences in design content relate to differences in manufacturing cost for a set of different manufacturing scenarios.

The paper is organized into six remaining sections. In section 2 we provide the conceptual framework for our study and we define the "80 percent" problem formally. In section 3, we describe our research approach. Section 4 describes the product archaeology methodology as applied to the coffee maker domain. Section 5 describes the manufacturing cost model. Section 6 details the results and Section 7 is a discussion of the results and their implications.

2. Conceptual Framework

Figure 1 is a simple input-output model of a manufacturing system. The system utilizes equipment, information, tooling, energy, supplies, services, and a workforce to transform raw materials and purchased components into finished goods and any associated waste products.

Costs may be incurred in procuring these resources and in disposing of the waste products. Over a long time period, the unit cost of producing finished goods can be thought of as 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.

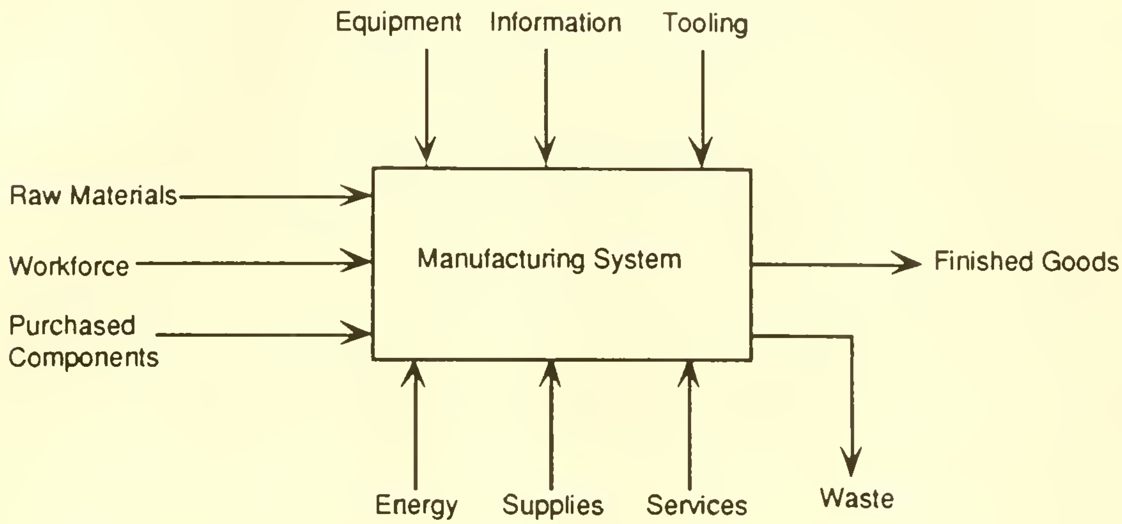

Figure 1: Some inputs and outputs to the manufacturing system.

This simple concept is complicated in practice by at least three challenges: (1) allocating resource consumption when different product lines are made within the same system, (2) determining the rate of consumption of resources lasting much longer than the time period under consideration (e.g. depreciation of capital equipment), and (3) deciding what to include within the boundaries of the "system" (e.g. distribution or manufacturing R&D). Also note that unit production cost is only one of the elements determining the long-run profits of the enterprise; sales price and sales volume are obviously critical factors as well.

For a particular set of product requirements, both product design decisions and decisions about the manufacturing system contribute to determining the resource consumption of the manufacturing system and therefore the ultimate cost of manufacturing the product. Designers have substantial latitude in determining the characteristics of a product. Even assuming a core technological concept for a product, design still involves decisions about how to decompose a product into components (e.g. one big complex part vs. many simple parts), how to fasten those components together (e.g. screws vs. snap fits vs. adhesives), materials (e.g. polypropylene vs.

polycarbonate), and part production process selection (e.g. molding vs. machining). These decisions in turn constrain the manufacturing activities required to produce the product. Conversely, even given a particular product design, manufacturing managers and engineers possess substantial latitude in determining the characteristics of the manufacturing system. By manufacturing system, we intend not only the basic layout of the plant and choice of process technologies, but the management practices as well. They can choose different site locations, different make-buy arrangements, and different operations management practices.

More formally, for a given set of product requirements, R, assume n different product design alternatives, D_i (i= 1 to n). Also assume m different manufacturing system alternatives, M_j (j=1 to m). R, M_j and D_i can be thought of as vectors of attributes. (In most cases, there will be infinite choices of design and manufacturing alternatives, but for simplicity we assume a finite set.) The combination of a design and manufacturing system determine a manufacturing cost. We define C_{ij} as the unit cost of manufacturing design D_i on manufacturing system M_j. Table 1 illustrates this concept.

We define the *design range*, DR_j , as the range of the manufacturing costs of D_1 through D_n made with manufacturing system M_j. We define the *manufacturing range*, MR_i , as the range of the manufacturing costs of D_i made with manufacturing systems M_1 through M_m.

For a given set of design and manufacturing alternatives, we can now compare the design ranges with the manufacturing ranges. If the set of designs represents the range of possibilities we can consider in a product design and if the set of manufacturing systems represents the range of possibilities for the manufacturing system, then we have a way of comparing the latitude in manufacturing cost determined by our choice of design to the latitude in manufacturing cost determined by our choice of manufacturing system. If, for a particular context, the design range is much larger than the manufacturing range then we would conclude that product design is an important area of focus for the firm. Conversely, if the design range is small relative to the manufacturing range, we would conclude that a focus on the manufacturing system would be more appropriate. Although a confounding factor in any resource allocation decision is the required investment to achieve each of the alternatives under consideration. Also note that in general a product development organization does not simply choose a design from a set of fully specified alternatives. Rather, an organization chooses a design approach and chooses the level of skill and resources to be applied to the design effort in the hope that they will achieve a particular level of design performance.

Table 1: Unit cost, C_{ij}, arises from a choice of design, D_i, and a choice of a manufacturing system, M_j. The manufacturing range, MR, is the range of costs for the same design made in different manufacturing systems. The design range, DR, is the range of costs for all the different designs assuming the same manufacturing system.

	M_1	M_2	M_3	...	M_m	
D_1	C_{11}	C_{12}	C_{13}		C_{1m}	MR_1
D_2	C_{21}	C_{22}	C_{23}		C_{2m}	MR_2
D_3	C_{31}	C_{32}	C_{33}		C_{3m}	MR_3
.						
.						
.						
D_n	C_{n1}	C_{n2}	C_{n3}		C_{nm}	MR_n
	DR_1	DR_2	DR_3		DR_m	

We can now express the 80% question as: For a particular set of design and manufacturing system alternatives, what is the design range as compared to the manufacturing range? This conceptual framework addresses the two major weaknesses in the popular interpretation of the 80% statement. First, the set of manufacturing systems under consideration is explicit, so that the worst-case manufacturing cost is defined by the assumed worst-case manufacturing system. Second, we isolate the leverage available through design by working with the *range* of costs rather than the absolute value of the costs. In doing so the design with the minimum manufacturing cost becomes the reference against which other designs are compared.

An important assumption embedded in the framework is the independence of designs and manufacturing systems. We assume any design can be made with any production system and that there are no special synergies between particular designs and particular manufacturing systems. If there were such synergies, the design range and manufacturing range would be exaggerated by the high cost of producing a design on a mismatched manufacturing system. In this paper we analyze products made with very conventional process technologies: injection molding, stamping, and manual assembly. We do not, therefore, face the problems associated with treating design and manufacturing decisions independently. For product designs exploiting unique process technologies, the coupling between design decisions and manufacturing capabilities must be considered when the design range and manufacturing range are interpreted.

3. Research Approach

At least three questions arise from the conceptual framework we present: How does one determine the set of design alternatives for a particular set of product requirements? (After all, if one knew the set of alternatives, one would simply choose the best one.) How does one determine the set of manufacturing system alternatives? and How can the design alternatives and manufacturing system alternatives be used to estimate manufacturing costs? In this section we present our approach to these three questions and discuss our choice of an example domain of application. Although we take the perspective of researchers in this work, we contend that the methodology we present is appropriate for use by manufacturing firms as well.

How to determine the set of design alternatives

Within our conceptual framework a discrete set of designs is used to represent the latitude a firm possesses in designing a new product. We use the product designs currently available in the marketplace to approximate the set of alternatives available to a firm designing a new product. This approach requires that there be a relatively large number of products and firms competing in the marketplace from which we can infer the expected characteristics of a new design. The approach also assumes that the range of capabilities and design effort among the different firms represents the distribution of capabilities and design effort that could be exhibited in a new design. In taking this approach we explicitly exclude radical departures from the practices of the existing firms in the marketplace. Radical design approaches might be classified as *advanced development* rather than product design.

In order to determine the attributes of the set of designs, we analyze the actual physical products available in the marketplace. We call this approach *product archaeology*— the study of industrial practices by measuring characteristics of the physical product itself. Product archaeology is similar to the *competitive benchmarking* some firms perform when analyzing their competitors' products (Camp 1989). In fact, the methodology was inspired by a visit to the General Motors Vehicle Assessment Center where dozens of competitors' products are disassembled and displayed for analysis. Through the use of product archaeology we can directly observe factors like the number of parts and the number of fasteners, and we can use established estimation techniques for determining other factors 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, Henderson and Clark 1990, Sanderson and Uzumeri 1992), we know of no 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 highly reliable. Unlike the human subject of an interview, the product cannot forget and cannot misrepresent facts. Second, the data are readily available. Research on dozens of manufacturers' products can be performed without permission, access to the company, or travel. 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.

How to determine the set of manufacturing system alternatives?

The set of manufacturing systems in our conceptual framework represents the set of alternatives a manufacturer would have in setting up and operating a manufacturing system. If this analysis were performed within the context of a specific firm, the set of alternatives might represent the different possible operating conditions for the firm's existing plants and any new plants under consideration. These systems might be characterized by, for example, wage rates, available raw materials prices, and expected processing yields. As mentioned in the introduction, there is no theoretical upper bound on manufacturing cost, so the range of manufacturing systems should represent the best and worst systems that could reasonably be considered for a new product. For the purposes of this paper, we will make assumptions about the operating parameters of a set of manufacturing systems based on the literature and our previous research.

How to combine a design alternative and a manufacturing system alternative to determine a manufacturing cost?

We use a cost model to estimate a manufacturing cost for a particular design produced by a particular manufacturing system. 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). The model can be more or less sophisticated, but must capture the impact of the major differences in design factors and in manufacturing system factors. For example, one aspect of the model might be assembly cost. The model might take the estimated assembly content of a product and apply an assembly productivity factor and a labor cost factor to estimate the assembly cost. The assembly content is derived from the design, while the productivity and labor cost factors are characteristics of the manufacturing system.

Example Domain: Coffee Makers

We use an example to illustrate the methodology and to make the conceptual framework specific. We chose automatic drip coffee makers as the product for our study for three main reasons. First, there are many coffee makers that implement the same set of product requirements. Each model in our sample is designed around the same brewing process and, according to *Consumer Reports*, delivers coffee that is of equal quality (Consumer Reports 1991). This allows us to avoid differences in manufacturing costs due to differences in product requirements. Second, coffee makers are relatively simple. The components of coffee makers are large enough to examine easily and 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 anticipate that this diversity will be associated with a wide range of approaches to design.

We believe that the design of coffee makers involves many of 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.

The specific models and manufacturers for our sample are shown in table 2. For reference purposes, we list the retail price of each coffee maker (adjusted for differences in features, such as clocks and timers), the market share of the manufacturer, the number of units sold by each manufacturer each year in the United States, and the country in which the product is made. Figure 2 shows one of the coffee makers from the sample.

Table 2: Basic information about the coffee maker manufacturers and models. Market share data is from [Appliance 91].

	Country of Manufacture	Adjusted Retail Price	1991 U.S. Mkt. Shr. (% units)	Units Sold in 1991 (000's)
Black and Decker			21	3275
DCM90	US	18.50		
DCM900	US	25.00		
Mr. Coffee			27	4211
International	China	21.20		
SR-12	China	25.50		
Accel	US	26.60		
Expert	US	33.30		
N.A.P.			7	1092
Norelco 663	US	21.90		
Proctor Silex			18	2807
A6278	US	16.60		
A8737	China	23.20		
Regal			4	624
Regal	US	24.90		
Toastmaster			<1	<156
Toastmaster	Taiwan	18.70		
Braun			9	1404
KF400	Germany	32.50		
KF650	Germany	35.00		
Krups			5	780
130	Germany	47.90		
150	Mexico	43.30		
178	Germany	50.00		
Rowenta			<1	<156
FG22-O	Germany	40.60		
FK26-S	Germany	43.10		

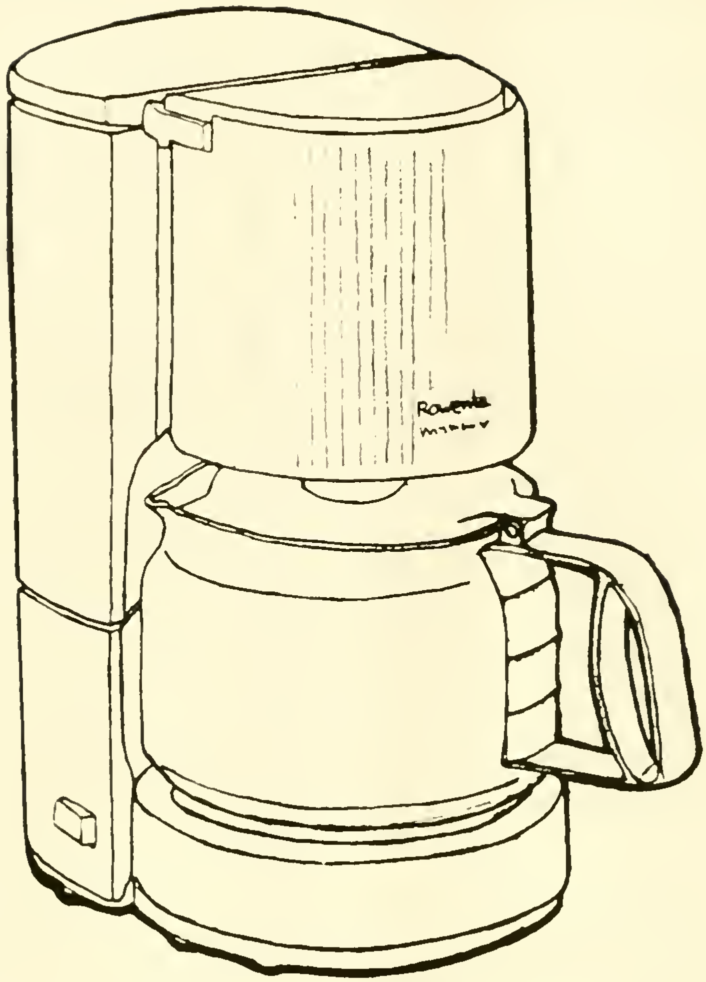

Figure 2: An example coffee maker from the data set, the Rowenta FG22-0.

4. Using Product Archaeology to Determine Design Content

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

We disassembled each product and created a bill of materials (BOM) and a feasible sequence of assembly operations. An example BOM is included in Appendix A. Four metrics can be observed directly from the BOM and the piece parts: the total number of parts, the number of part numbers (unique parts), the number of plastic molded parts, and the number of fasteners (includes screws, nuts, and clips).

The parts fabricated by 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 included 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 million units per year. (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. The quoted prices drop by about 10% as quoted production quantities double— a 90% "learning curve".)

The metrics we estimated are shown in table 3. A summary of each estimation technique is listed. (The details of these estimation techniques are in [Pearson 1992].)

The net result of the product archaeology and associated estimation is the "design content" for each product. This design content can be thought of as the D_i's in our conceptual framework. Table 4 shows the values of all of the design metrics for each of the coffee makers.

Table 3: The design metrics derived from the 18 coffee makers through the use of product archaeology. All metrics are estimates.

Estimated Metrics	Units	Estimation Method
Assembly Content	hours	Boothroyd-Dewhurst method for manual assembly (Boothroyd and Dewhurst 1988, 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 US prices from [Serjeantson 1992]).
Sheet Metal Processing Time	hours (x 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 (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 US bulk resin prices from [Rauch 1991]).
Molding Processing Time	hours (x 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).
Tooling Lead Time	weeks	Estimated time for critical-path tasks on most complex injection molded part. Time for each task derived from mold fabrication time estimate above (Pearson 1992).

Table 4: Design content for coffee makers. All metrics, except part counts and material masses, are estimates

	Assembly Content (BDI hours)	Total Purchased Parts (US$)	Sheet Metal Use (eqv. kg mild steel)	Sh. Metal Processing Time (hours x 1000)	Sh. Metal Press Req'ts (KN-hours)	Sh. Metal Tooling Fabrication Time (k-hours)	Plastic Use (equiv. kg polypropylene)	Molding Processing Time (hours x 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	1.102	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	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	6
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
average	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

5. Modeling Manufacturing Costs

We adopt the basic cost model represented in equation 1. Following is a brief explanation of how each term is modeled. Appendix B gives the specific algebraic expressions relating the manufacturing system parameters and the design parameters from the product archaeology to the terms in the cost model.

$$C = C_{assembly} + C_{purchased\text{-}parts} + C_{molded\text{-}parts} + C_{sheet\text{-}metal\text{-}parts} + C_{tooling} + C_{supervision} + C_{inventory} + C_{facilities} + C_{energy} \quad (1)$$

Where, for example,

$$C_{assembly} = \frac{\text{assembly-content x assembly-labor-cost}}{\text{assembly-productivity x assembly-yield}} \quad (2)$$

and assembly-content is in units of Boothroyd-Dewhurst hours, assembly-labor-cost is in dollars per hour, assembly-productivity is a non-dimensional 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 efficiency and assembly yield are characteristics of the manufacturing system.

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 design and other assumed manufacturing parameters. A baseline of 5000 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.

The cost model does not include much of what would normally be considered plant overhead. There is no estimate of purchasing, shipping, receiving, quality control, materials handling, or senior plant management.

As we mentioned in section 3, the manufacturing system parameters used in the model should represent the range of reasonable alternatives that could be used in producing the product. For an on-going manufacturing firm, these alternatives would represent the set of operating conditions that might be encountered in the existing production facilities of the firm or in any new facilities under consideration. For our purposes, we consider the set of manufacturing system alternatives that may be used by any of the manufacturers in our data set. We know with certainty that these manufacturers make coffee makers in a variety of countries with markedly different wage rates. We do not know with certainty what the other manufacturing parameters are for these systems. Our approach is to base the assumptions about different manufacturing systems on published parameters for analogous production systems in order to make reasonable estimates of the range of manufacturing costs that could be encountered by these different manufacturers.

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). Rather than consider 12 manufacturing system alternatives, we will consider only 6, assuming that several of the manufacturers' plants have quite similar cost structures. The six plants we consider correspond to a well run and poorly run plant in a low, medium, and high-cost economic environment. The manufacturing parameters driven by the economic environment are shown in table 5, while those parameters driven by the way the plant is run are shown in table 6. The parameters we assume to be constant for all the plants are shown in table 7.

Table 5: Assumed manufacturing parameters corresponding to a low, medium, and high-cost economic environment. 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].

	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$/hr)	38.00	38.00	45.00
Days Operation per year	250	240	220
Hours per Day	18	16	16
Facility Cost (US$/$m^2$/yr)	19.00	25.00	34.00

Table 6: Assumed manufacturing parameters corresponding to a poorly run and well run plant. 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.

	Poorly Run	Well Run	Source
Assembly productivity	0.80	1.20	Our assumption and rules-of-thumb in industry practice.
Assembly yield	0.95	1.00	Our 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	Our 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	Our observations.
Molded part yield	0.95	0.995	Our observations.
Stamping machines per operator	1	1	Our observations.
Stamped part yield	0.95	0.995	Our 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)

Table 7: Assumed manufacturing parameters shared across all plants.

Molding machine cost (US$), (Busch 87)	
basic molding machine cost	21383
molding machine capacity cost	+ 59 per kN capacity
Stamping machine cost (US$) [cost information from press vendors]	
basic molding machine cost	30400
molding machine capacity cost	+ 73 per kN capacity
Inventory holding cost	20 % per year (0.055% per day)
Cost of capital	10% per year
Plastic regrind rate	20%
Useful machine life (Busch 1987)	6 years
Energy cost	0.10 $/kw-hr
Production rate	1,000,000 units/year
Tool Life	1,000,000 units

6. Results

Table 8 shows the estimated manufacturing cost of each of the 18 coffee makers for each of the six different sets of modeling assumptions corresponding to a well run and poorly run plant in each of three different economic environments. Table 9 is a detailed breakdown of the estimated cost of one of the models, the Rowenta FG22-0.

The design range varies, in dollars, from $3.08 to $5.59 or, as a percentage of the average cost of products made with a particular manufacturing system, from 45% to 49%. The manufacturing range varies from $4.45 to $10.71 or, as a percentage of the average cost of the product, from 51% to 75%. The lowest cost product is the Rowenta FG22-0 ($5.92 for the well run system in a medium-cost environment). The highest cost product is the Krups 178 ($9.28 under the same conditions).

Table 8: Estimated manufacturing cost for each of 18 coffee makers for each of six different sets of manufacturing parameters.

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

Table 9: Detailed breakdown of estimated costs for the Rowenta FG22-0. These estimated costs correspond to a well run plant in the medium-cost economic environment.

Category	Estimated Cost
Assembly	0.82
Purchased Parts	3.12
Molded Parts	0.85
Sheet Metal Parts	0.12
Tooling	0.60
Supervision	0.12
Inventory	0.13
Facilities	0.09
Energy	0.06
TOTAL	**$5.92**

7. Discussion

Does design determine 80% of manufacturing cost?

In the introduction to the paper, we suggested that the 80 percent question was not well posed. We reformulated the question in terms of the concepts of *design range* and *manufacturing range*. The relative magnitude of the design range and manufacturing range determines the relative impact of design and manufacturing activities on manufacturing cost. In our study, for the industry as a whole, assuming the set of production system parameters in our models, the design range represents an average of 47% of the average manufacturing cost and the manufacturing range represents an average of 65%.

These results will, of course, be different for any particular firm considering a particular set of manufacturing system options. A particular firm's manufacturing range is dictated by the actual set of production system conditions under consideration. In no case would a firm deliberately choose to consider either a design or production system which is substantially worse than their current state.

Consider a small appliance manufacture with two existing manufacturing systems: a well run plant in a high-cost environment and a poorly run plant in a low-cost environment. If this manufacturer were considering entering the coffee maker market, the manufacturing range might be defined by the two existing plants plus a well run plant in the low-cost environment. This set assumes that the firm could invest in improving the performance of their current poorly run plant in the low-cost environment and would not let the other plant's operations deteriorate. Under these conditions, assuming the manufacturing parameters in our study, the manufacturing range would be only 31% of the average manufacturing cost, while the design range would be 48%. Conversely, one can imagine a situation in which a firm with an existing low-cost design might have very little design range and a large manufacturing range.

Industrial design issues

Although the coffee makers are functionally identical, they exhibit significant differences in industrial design, the aesthetic and ergonomic characteristics of the products. We suspect that industrial design influences consumer behavior and therefore firms may be willing to suffer higher manufacturing costs in order to achieve higher levels of industrial design. In a related study (Pearson 1992) we tested the hypothesis that the quality of industrial design is positively correlated with manufacturing cost. 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 consistent with one another. However, there was no significant correlation of either aesthetics or ergonomics with manufacturing cost. We did find that industrial design quality is positively correlated with our estimate of one element of manufacturing cost, tooling cost, and is positively correlated 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 so are probably not significant factors in determining the costs of good industrial design.

Cost vs. price

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 did not include in our study of manufacturing costs. In our related study, we adjusted the retail price for these differences in features. The details of this adjustment are in [Pearson 1992]. Although our cost adjustment procedure is approximate, the hypothesis that cost and price are positively correlated is not supported by our data. Some of the most expensive models have the lowest manufacturing costs, and some of the least expensive models have relatively high manufacturing costs. For example, the Rowenta FG22-0 sells for a feature-adjusted price of $40.60 (unadjusted price is $49.99) while we estimated its cost at $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 estimated its cost at $7.61.

Quality

Perhaps there are differences in manufacturing costs arising from differences in product quality. In this context we intend quality to mean durability, reliability, and robustness, because as we have noted, the quality of the coffee made by the models is uniform. There are not many 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 of the heating elements have basically the same tube geometry, this calcification should occur with equal frequency in all the models. Occasionally the electromechanical components, the thermostat and switch, fail. 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 quality and cost is slight. Also, the products with a public perception of quality, primarily the German products, exhibit costs no higher than average.

Plant location vs. design vs. operations improvement

Given the cost model and the design data, we can explore some of the decisions a firm faces when trying to reduce costs. Within our conceptual framework there are at least three approaches to reducing costs: improvements in design, changes in the economic environment, and changes in production management practices. Consider a firm in a high-cost environment, such as Germany, with a poorly run plant and an expensive design. The firm could move their operations to a low cost environment such as Mexico; they could attempt to improve the efficiency of their production system; or they could improve the design of the product. One of the results of this research is to quantify the benefits available through an improved design.

Consider the specific example of the Krups 178, the most costly design in our study. Assume (for purposes of illustration only) that it were made in a poorly run plant in a high-cost economic environment. We estimate the manufacturing cost under these conditions to be $14.54. Krups could move to a low-cost environment, retaining the same design. If their new plant were poorly run they could reduce their costs to $9.73. If the plant were well run, they could reduce their costs to $8.06. Krups could also redesign their product. Assuming they could achieve a design like that of the Rowenta FG22-0, Krups could reduce their costs to $9.72 in their original plant. If they improved their plant operations at the same time, they could reduce their costs to $6.98. Perhaps they could improve their design, move their plant, *and* improve their operations. Under these conditions they 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 cost reduction through redesign of the product may be an extremely attractive alternative to moving operations to a low cost economic environment.

Have manufacturers adopted consistent design and plant location strategies?

One might expect that firms operating in high-cost environments would minimize the assembly content of their designs and those in low-cost environments would not. The average estimated assembly time for the five products assembled in China, Taiwan, and Mexico is 0.105 hours. The average estimated assembly time for the seven products assembled in the United States is 0.109 hours. The six products assembled in Germany had an average estimated assembly time of 0.094 hours. Given that the average estimated assembly time for all products is 0.100 hours and the range is 0.086 hours, we do not find the differences among the locations significant.

How to design a low-cost coffee maker

Based on our observations of the 18 models in our study, we can suggest some guidelines for minimizing the cost of a high-volume electromechanical product like a coffee maker. Some of these guidelines are:

- Use inexpensive materials. 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 (by a factor of two or three) polymer. The relative merits of the two materials is covered at length in [Freeze 1991].
- Minimize the use of material. The cost of the materials in a coffee maker is quite significant. Both wall thickness and overall part dimensions should be minimized in order to reduce the use of material. Careful structural design can achieve rigidity while minimizing the use of material.
- Minimize the number of parts. This is a standard design-for-manufacturing guideline. Adherence to this guideline through the consolidation of plastic parts results in less expensive molded parts, because consolidating two plastic parts reduces tooling costs and minimizes the plastic that much be scrapped with each shot of the injection mold. However, note that tooling lead times may be extended if one particularly complex part results from the consolidation of function. (See [Ulrich et al 1993] for a thorough discussion of this issue.) Minimizing the number of parts also, in general, reduces the assembly content of the product.
- Concentrate high-quality surface finishes only where surfaces are visible. Surface finish is one of the part attributes contributing to tooling cost and lead time. The inner surfaces of parts do not have to exhibit high quality finishes.
- Work closely with suppliers to minimize purchased parts costs. From 25% to 50% of the cost of a coffee maker is made up of purchased components.

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 subjectively rate 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 archeology 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.

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Appendix A: Bill of Materials for the Rowenta FG22-0 Coffee Maker

PART	TYPE
Main tank	injection molded polypropylene
Base piece	injection molded polypropylene
Filter cone	injection molded polypropylene
Machine cover	injection molded polypropylene
Tank cover	injection molded polypropylene
Base plate	injection molded polypropylene
Pot cover	injection molded polypropylene
Pot handle	injection molded polypropylene
Pot ring	injection molded polycarbonate
One-way elbow valve	injection molded polycarbonate
Elbow valve	injection molded polycarbonate
Condenser	injection molded polypropylene
Filter baffle	injection molded polypropylene
Heater plate	stamped aluminum
Heat shield	stamped cold-rolled steel
Heater bracket	stamped cold-rolled steel
Heater tubes (4)	purchased, rubber
Heater seal	purchased, silicone rubber
Carafe	purchased (Schott)
Heater	purchased
Circlips (5)	purchased fasteners
Screw (tamperproof)	purchased fastener
Switch	purchased toggle, painted
Power cord	1000 mm, zig-zag strain relief, one spade, one crimp
Wire1	100 mm, two crimps
Wire2	100 mm, one bare, one spade
Wire3	100 mm, one bare, one crimp
Wire4	100 mm, two crimps
Wire sleeves (3)	purchased, Teflon
Feet (2)	purchased, rubber
Check valve- part A	purchased, plastic
Check valve- part B	purchased, plastic
Handle adhesive	purchased, thermoset
Thermostat	purchased
Thermostat nut	purchased
Temperature fuse	purchased

Appendix B: Formulas for Manufacturing Cost Model

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

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

In turn, each of the terms is modeled as follows (all variables are expressed as hyphenated versions of the labels in tables 3, 4, 5, 6 and 7):

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

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

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

where

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

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

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.

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

where

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

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

and

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

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

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

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

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

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

where

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

$$C_{facilities} = \text{base-facility-size} \times \frac{\text{base-yearly-hours}}{\text{days-operation-per-year} \times \text{hours-per-day}}$$

$$\times \text{ space-utilization-factor} \times \text{facility-cost} \times \frac{1}{\text{production-rate}}$$

where space-utilization-factor =

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

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.

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

where plastic-processing-energy has a value of 0.75 kw-hr/kg (Busch 87).