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A Framework for Including the Value of Time in Design-for-Manufacturing Decision Making

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WP #3243-91-MSA February 1991

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ABSTRACT

Design-for-manufacturing (DFM) has been promoted as a way to enhance product development and production system performance. Current DFM practices exploit substantial part integration to minimize the materials and labor costs of a product. DFM techniques, however, often lead to long tooling procurement times because of the complexity of the resulting parts. We present a cost model that explicitly includes the economic cost of time. Using this model we show that violating DFM guidelines in order to reduce part complexity can lead to a net improvement in product development and production system performance for high-volume products in time-critical markets. We illustrate how the cost model can be applied in practice by reporting on a field study of design decision making for Polaroid cameras.

key words: product design, design for manufacturing, lead time, design decision making, cost modeling for design.

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1. INTRODUCTION

This paper addresses the question of how product development lead time relates to design-for-manufacturing (DFM) decision making. In this introduction, we present background material on design for manufacturing, outline the research questions we address, explain our approach, and preview the key results. In the next section we present a conceptual framework for understanding design-for-manufacturing decision making. The framework is articulated as a simple cost model. We then report on a field study of Polaroid cameras in which we show how the model can be applied in an industrial setting. Finally, we present our conclusions.

1.1 Design for Manufacturing

One of the most widely promoted engineering design philosophies of the past decade is *design for manufacturing* or *DFM*. Broadly stated, the goal of DFM is to make a product easy to manufacture during the design phase of the development process. The benefits of DFM have been extolled in professional journals and the business press [Port89, Whitney88] and DFM is part of the curriculum at many engineering and business schools [Eppinger90]. There are many incarnations of DFM, but the most common can be divided into two groups: the use of *design rules* and the use of *assembly-driven* methodologies.

Examples of design rules are: minimize the number of discrete parts in the design, minimize the number of unique part numbers in the design, eliminate adjustments at final assembly , and eliminate fasteners [Daetz87, Trucks87]. Some of the rules are more narrowly focused on part features and may, for example, specify that holes punched in sheet metal parts should be located at least two hole diameters away from the edge of a part. The rules are a codification of production expertise into a concise form and are easy to communicate. There is significant anecdotal evidence that the use of these guidelines is effective in producing low-cost and high-quality designs [Gager86].

Assembly-driven design methodologies rest on the assumption that a focus of attention on improving the ease of *assembly* of a product will improve the designs in other ways. Although there are many variants, the basic methods behind this approach are to evaluate the ease with which a collection of parts can be assembled and to give the overall assembly an objective score based on this evaluation. These methods have come to be known as *design for assembly* or *DFA* [Boothroyd88a, Boothroyd88b]. The primary strengths of these methods are: they provide objective metrics that allow two designs to be compared, they are intuitive and relatively easy to learn and use, and they are effective in directing engineering attention at production issues [Miller88].

Strict adherence to current DFM methodologies tends to direct product development teams to combine and integrate parts [Ulrich89]. The resulting designs therefore have relatively few complex parts rather than many simple parts. The parts are likely to be snapped together rather than screwed together, and springs and latches are likely to be molded or formed as an integral part of a larger part rather than being implemented as discrete parts [Dewhurst88]. For example, the part shown in figure 1 is the left side frame from the IBM Proprinter, one of the most loudly heralded instances of DFM practice [Newman87]. The part is a complex injection molding incorporating springs, bearings, structural support, electrical ground, and motor mounts all into a single part. As a result of this design discipline, the Proprinter can be assembled in three minutes without any tools or fasteners (versus 30 minutes for its Epson counterpart), and it has 25% of the parts of its predecessor [Dewhurst87]. Many firms— including Ford, Digital Equipment Corporation, Motorola, and NCR— have adopted design-for-manufacturing methodologies in one or more product development efforts [DFMA90, Miller88, Coleman88].

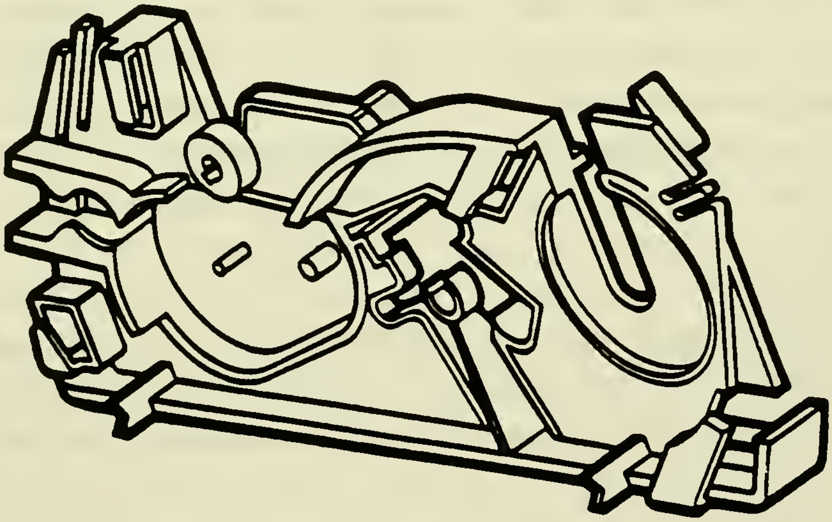

Figure 1: IBM Proprinter left side frame: an example of a part resulting from design-for-manufacturing methodologies.

1.2 Research Questions

Given the publicity of the DFM practices at many firms, we were puzzled to observe that several highly successful firms were not adhering to widely promoted DFM guidelines. For example, despite dozens of articles in journals and the business press, the extreme adherence to the design methodology exhibited by the IBM Proprinter was not adopted by its successful competitor Epson. The Honda Accord and the Mazda 626 each have over 20% more parts than the Ford Taurus. Sony adheres to DFM principles in their least expensive Walkman products, but grossly violates them in their newest, most-expensive models[1].

There are several possible explanations for these observations. First, some of these successful firms may not yet have learned to use DFM, and perhaps once these methods are adopted the firms will be even more successful. Second, these firms may have explicitly considered DFM methodologies and decided that they do not provide desirable results. Third, the design practices in these firms may have evolved, without explicit analysis, towards effective product design strategies that are significantly different from those prescribed by DFM.

We hypothesize that current DFM methodologies are misleading under certain sets of conditions. In particular, we hypothesize that when short product development times are critical or when product volumes are small, current DFM methodologies do not adequately reflect the economic implications of detail design decisions. We claim that current DFM guidelines emphasize the unit variable costs of a product (component costs, labor costs, and production equipment usage) but ignore the implications of design decisions on lead time. We hypothesize that under conditions of time criticality or when product volumes are small, minimizing the unit variable cost of the constitutive piece parts and of the product assembly may be unwise, and may in fact be at odds with product development speed.

1.3 Approach

Ease of manufacturing is ultimately measured by total manufacturing cost. Our argument is that DFM practices do not adequately substitute for minimizing total manufacturing costs under a particular set of conditions dictated by the context in

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[1] These observations were made by examining these products disassembled. The products included the Epson personal computer printer line, the Sony Walkman line, the Ford Taurus, the Mazda 626, and the Honda Accord sedan. We anticipate reporting on this product *archeology* in more detail in another paper.

which the product is developed and sold. This minimization is complex because the cost implications of design decisions are not measured well by traditional cost estimation techniques; these techniques ignore the impact of the design decisions on the overhead functions of the firm and on the speed with which the product can be introduced to the marketplace.

Our approach is to estimate, with a simple model, the magnitude of the different costs that make up the total manufacturing costs in an attempt to better understand existing design practice and to prescribe better design strategies. We define manufacturing costs quite broadly to include the costs of product development and the economic value of lead time.

In addition to developing a general model, we apply it to a product, Polaroid Cameras, in order to illustrate a methodology for design decision making and to demonstrate that existing DFM practices can be misleading under certain conditions.

Because of the complexity of design for manufacturing decision making, we are not able to offer definitive prescriptions for all design situations. Rather, we give an example of a methodology for determining such results for a particular business context, we highlight what we believe to be pitfalls in current DFM practice, and we provide some new design heuristics which are often valid for high volume product design in time-critical environments.

1.4 Key Results

The key result from our research is that for many types of parts there is a fundamental trade-off in design decision making between lower unit variable costs and the benefits of product development lead time. We found, for example, that in one case the use of four screws instead of snap fits for a plastic enclosure can yield a greater than million dollar improvement in the performance of the manufacturing system. This benefit is achieved, despite an increase in the assembly and material costs of the product, because eliminating the complex geometry of a snap fit allows the product to be brought to market more quickly. Interestingly, this particular design decision directly contradicts the most popular design-for-manufacturing methodologies in current industrial practice.

We show that in general DFM practices are uniformly valid only for high-volume products whose lead time is not critical. As product development cycles become shorter and product volumes decrease, firms must adopt different product design tactics from those used in an environment of high volume, long-life-cycle products. In time-critical environments, we propose that no single part in the product should be substantially more complex than the remaining parts in order to minimize tooling procurement times and therefore overall product development lead time. This guideline may in some cases contradict conventional DFM guidelines.

2. CONCEPTUAL FRAMEWORK

Our research methodology is to model the cost implications of design decision making. We attempt to model costs more accurately than is typical industrial practice, including several terms that are not normally incorporated explicitly in practice. Given this model, we attempt to provide insight into how product attributes and particular design strategies relate to cost.

Our cost model is

$$C = V(m + l + p) + F + S + D + T \qquad (1)$$

where C is the total manufacturing cost of the product over its lifetime (\$); V is the lifetime product volume (units); m, l, and p are the unit materials, direct labor, and production resource usage costs (\$/unit); F is the product-specific capital cost (\$); S is the *system costs* (\$); D is the development costs (\$); and T is the *time costs* (\$)[2]. Each of these terms, except for product volume, is directly influenced by the attributes of the product.

The first two terms on the right hand side, $V(m + l + p) + F$, are the traditional expression for product cost [Winchell89, Ulrich90]. The expression consists of the unit variable cost of the product times the product volume plus the required product-specific capital cost. The volume is simply how many units will be made. The materials term consists of component purchase costs or raw materials costs. The labor term consists of direct production labor like assembly labor or machine operator labor. The production resource usage term might consist of the cost of machine time on a general purpose machine like a milling machine. (This term is based on the assumption that certain capital-intensive production resources are in effect *rented* to

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[2] One additional complexity that must be introduced in applying this model is the time value of money. In practice, each term might be expressed as the present value of the corresponding spending at different points in time. In our case study, we will do the present value calculations, but for explanatory purposes, the simpler cost expression is sufficient.

work on a product.) The product-specific capital cost in most cases represents tooling costs and includes items like injection molds, stamping dies, and test fixtures.

The last three terms in the cost expression, *S*, *D*, and *T*, are not normally an explicit part of product cost modeling. These terms are the system costs, development costs, and time costs. We define system costs as the costs of the system that supports the direct production activities. System costs are normally included in production overhead and include functions like purchasing, production supervision, quality engineering, industrial engineering, and receiving. In general, system costs depend on the product design, the production policies, and to some degree on product volume. Many design-for-manufacturing heuristics encourage minimizing the number of parts in a design in order to minimize the complexity of the system supporting product assembly [Sackett88, Gager86, Miller88]. The system cost term in the cost model is an attempt to capture these benefits.

Development costs are the costs incurred by the engineering and manufacturing organization in transforming the product concept into a functioning product and process. Development costs include engineers' salaries, prototyping and testing costs, and production start-up costs.

Time is a product development resource with economic value. In order to capture the cost of product development time, we define ***T*** as a function that determines the cost of a specified product development lead time. The magnitude of *T* with respect to development time is an indication of the importance of time in a particular product development setting. Time costs result from lost sales, shifting of revenues later in time, reduced ability to include recent technology in the product, and decreased learning rates [Gomery89]. Time cost is not normally thought of as a manufacturing cost, and is not normally explicitly computed in industrial practice. Because we are interested in how lead time and design for manufacturing interact, we have included the time cost as a term in our cost expression.

Our model attempts to capture manufacturing costs but does not include issues of product quality or of life cycle costs like warrantee costs, disposal costs, or product liability costs.

2.1 Model Insights

Even given this simple expression for total product manufacturing cost, some interesting insights for design emerge. Consider two factors that influence the cost expression, product volume and the criticality of time. If product volume were extremely high and product development time were not very important, then the cost expression could be simplified to be $V(m + l + p)$. On the other hand, if product volumes were low and time were extraordinarily important, then the cost expression could be simplified to be T. These two cases can be thought of as extreme regions of a product space described by two dimensions, product volume and time-criticality. Figure 2 is a plot of time-criticality versus product volume for several product categories. For the purposes of the plot, time criticality is approximated by *the frequency of the product development cycle* (cycles/year) for the fastest competitor in a particular market. For example, the development cycle frequency for toys is approximately 1.0 (one cycle each year), while the frequency for commercial aircraft is approximately 0.1 (one cycle every 10 years). We therefore argue that the development of toys is more time critical than the development of commercial aircraft.

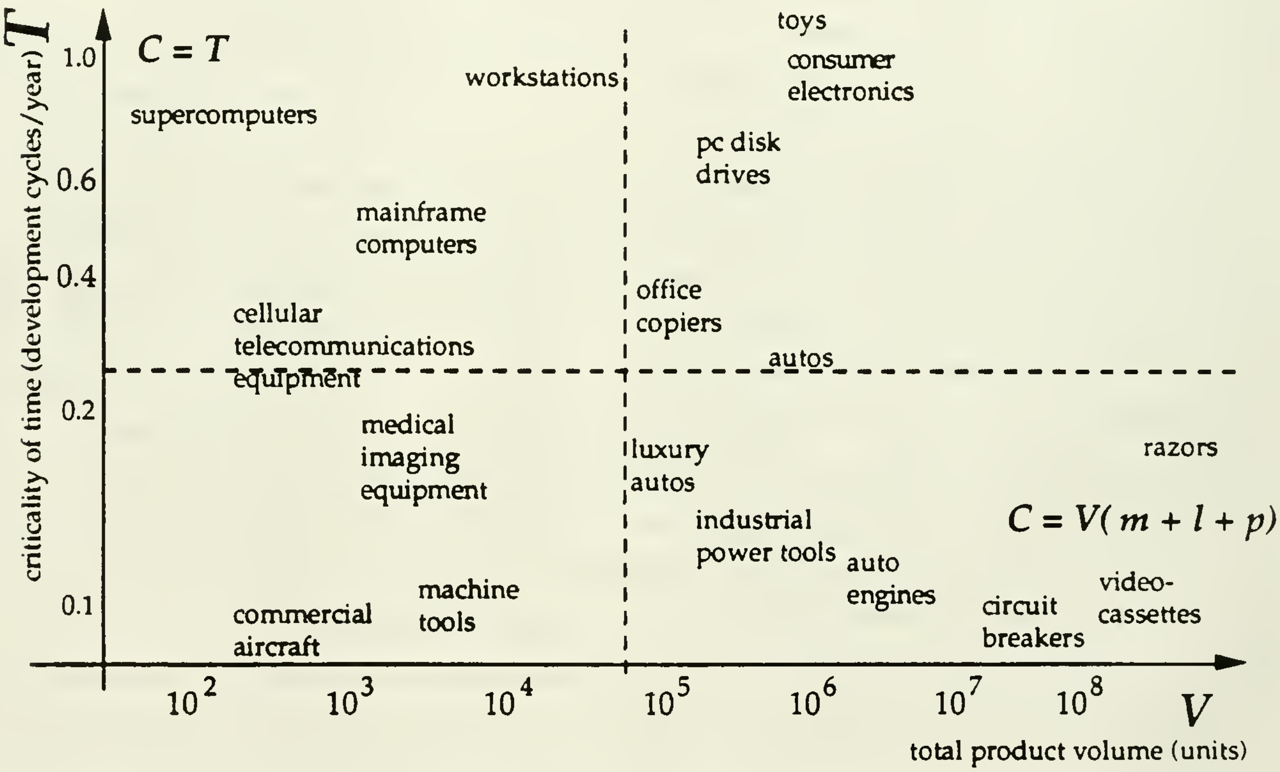

Figure 2: Plot of time criticality versus lifetime product volume for different product classes. In this plot, time criticality is approximated by the frequency of the product development cycle for the fastest competitor in the industry.

DFM focuses on minimizing unit variable costs and so is a wise strategy for products whose manufacturing costs are dominated by unit costs and product volume. This is certainly the case for products residing in the far lower right corner of Figure 2. For example, razors may have volumes of more than a billion units and a development cycle frequency of once every 6 years. For such products, extreme adherence to DFM is clearly an appropriate strategy; minimizing the unit variable costs will minimize the total manufacturing costs.

For products residing in the upper left corner of Figure 2, current DFM practices are likely to be misleading. Getting the product to market quickly dominates design decision making. In the high-performance computer market, arriving to market two months late is sometimes worse than not arriving at all. This suggests that minimizing unit variable costs at the expense of time will lead to suboptimal performance.

Design objectives for the other two quadrants of figure 2 are less clear; trade-offs among several competing factors make design decision making more complex. In the lower left corner, the trade-offs are likely to be among capital cost, development cost, and system costs, although unit variable costs may also be important. Design tactics likely include the use of standard components, the sharing of modules across a product line, and machined or cast parts rather than molded or stamped parts.

The upper right corner is the quadrant upon which we focus. This is the most turbulent battleground in product development. This quadrant includes consumer electronics, some automobiles, photocopiers, personal computers, and some workstations. These products are associated with industries in the United States that have looked to DFM as part of a plan to regain competitiveness. They are also associated with (largely Japanese) firms that have enjoyed remarkable growth and success in the past decade. In this quadrant time and unit variable costs are both important.

2.2 Implications for Design

For high-volume, time-critical products, making wise design decisions requires an understanding of the relationship between design details, lead time, and unit variable costs. In many cases, there is an inverse relationship between lead time and unit variable costs. For example, the IBM proprinter part (figure 1) reduces unit variable cost because the integration of several functions into a single part minimizes the number of discrete parts that must be assembled and produced. However, the part requires an extremely complex injection mold which may take 4 - 6 months to procure. Automobile development also provides several examples. A one-piece tail lamp lens reduces unit variable costs by lowering assembly labor, but is one of the longest lead time items in automobile development. The same is true of large sheet metal body panels, complex one-piece instrument panels, and large bumper fasciae. For parts produced by processes requiring precision tooling, like molding and stamping, in general there is a strong correlation between the size and complexity of a part and the lead time required to procure the tooling for the part. This implies that DFM strategies that result in complex parts will also result in long tooling lead times.

Given this reality, several new design heuristics emerge. One heuristic is to distribute product complexity across a variety of parts, rather than concentrating product complexity in a single part. This strategy reduces overall lead times because tooling for several parts can in general be procured simultaneously. Figure 3 illustrates this idea for two hypothetical design scenarios. Using current DFM methods, design one has a single complex molded part to which three very simple parts attach. The elapsed time between design and production start-up is determined by the lead time for the complex part. The second design distributes the complexity of the product among six simpler parts. This strategy requires additional material and assembly resources, but results in overall lead time savings. Implementing this strategy may involve dividing a complex part into several simpler parts or replacing molded-in snap fits with screws.

Another heuristic is to select faster process technologies for parts that determine lead times. For example, simple sheet metal parts can be made on laser sheet metal machines with very little production tooling. This suggests that time-critical subassemblies should be designed, where possible, from sheet metal parts rather than from injection molded plastic parts. This appears to be part of the reason some automobile firms use sheet metal for instrument panel structures rather than using a complex injection molding. Again, this heuristic contradicts current DFM practice, which encourages the use of multi-function injection molded parts.

We have not discussed these issues with engineers at Epson, Honda, Mazda, or Sony, but we believe that time criticality is one of the reasons that these firms have not fully adopted the DFM methodologies that have been promoted in the United States.

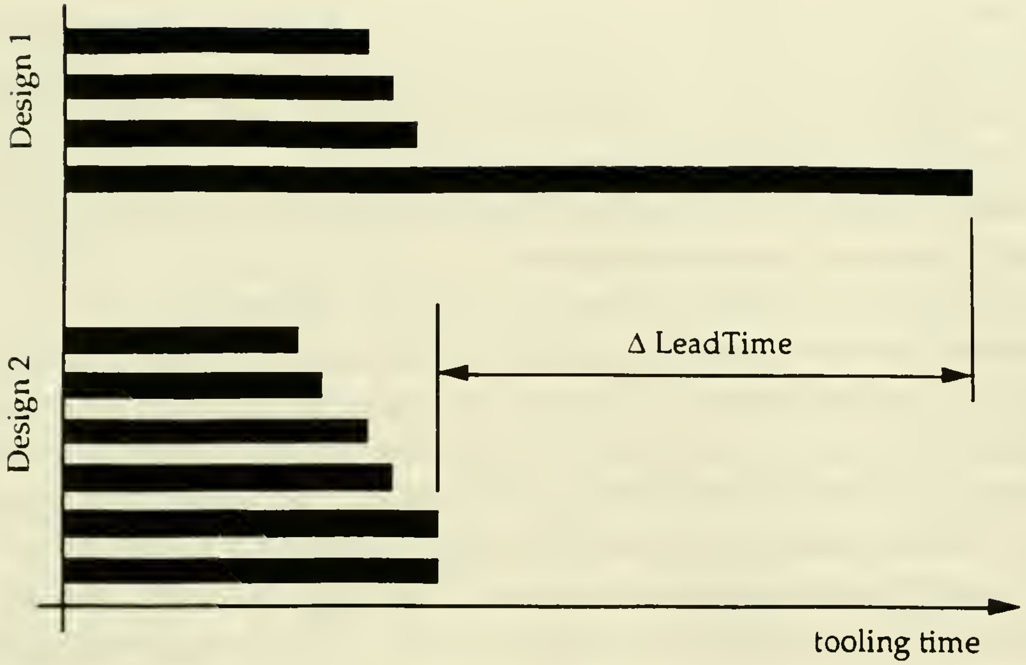

Figure 3: The impact of distributed part complexity on product development lead time.

3. FIELD STUDY: POLAROID CAMERAS

We have explored these design implications in a field study at the Polaroid Corporation[3]. One of us (Sartorius) spent seven months on site in the product development and production organizations at Polaroid studying design decision making. We have used the information collected in this study to estimate the magnitude of the terms in our cost model as a function of design decisions. The primary motivation for this section is to illustrate how the relatively abstract ideas in our conceptual framework can be made concrete in order to support design decision making. We have also taken the results of our analysis and implemented them in a spreadsheet model for design decision making.

Polaroid is a manufacturer of a wide variety of consumer and industrial electromechanical photographic products and film products. We have focused on one of Polaroid's consumer cameras (figure 4). The units sell for between $50 and

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[3] Polaroid has been generously cooperative in this research effort and has agreed to allow us to use one of their products and assembly plants as the major example in this paper. In order to protect their proprietary cost information, we have disguised the data we present. The qualitative relationships among cost figures and the general conclusions of the research are the same with the actual and disguised data.

$100 at volumes of approximately one million per year. The cameras have a product life cycle of five years or less and are assembled from components in a plant largely dedicated to a single product line. Polaroid utilizes a mix of automated assembly and manual assembly in the camera production facility. The product itself has historically been an assembly of injection molded plastic parts, parts machined from metal, stamped sheet metal parts, circuit board assemblies, optical parts, cables and wiring, and various bought components like motors, switches, and displays.

Since the current consumer cameras are evolutionary in nature, soon after a new product is conceived, Polaroid product development professionals can list the major camera subsystems and their basic configuration. Given this system definition, the major focus of the product development effort is on implementing the product concept such that the camera gets to market quickly, functions as conceived, is reliable, and meets the manufacturing cost goals of the program. It is in this stage of the development process that DFM is typically applied, and so we have focused our attention here.

Consumer cameras are high-volume, moderately time-critical products and fall into the lower half of the upper right quadrant of figure 2. One of the reasons the Polaroid case is interesting is that the product has been moving towards increased time criticality over the past few camera models. Studying this case illuminates the design issues associated with shifting from a unit variable cost focus to a focus that includes time.

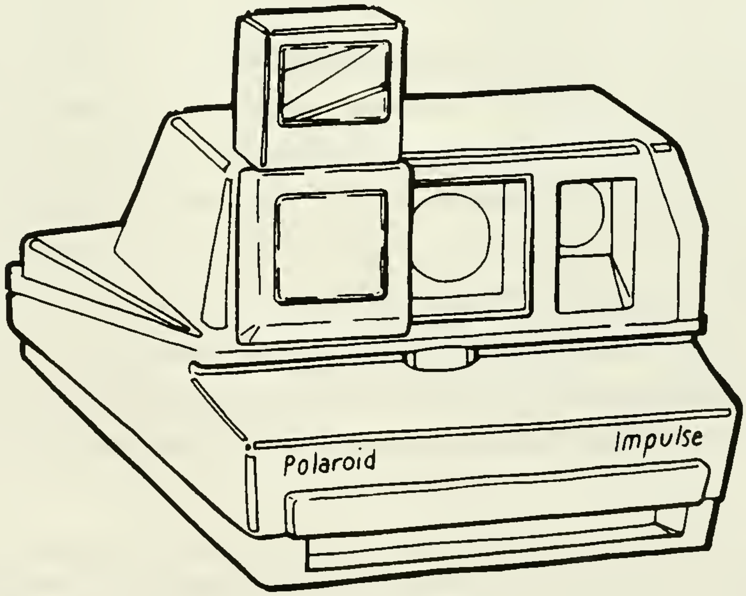

Figure 4: The example camera used in our field study.

3.1 Approach to Analysis

In analyzing design decisions for Polaroid cameras, we have made several focusing assumptions:

We estimate the cost difference *between two design options.* We have suggested that DFM should be a process of minimizing lifetime manufacturing costs. We concentrate our efforts on providing an evaluation of two design options that will allow an engineer to select the most economical course of action. Each option will typically be a collection of several parts in a single assembly. The options do not have to represent the entire product, but may instead represent a particular set of parts on which the detail design activity of the product development team is focused. For example, in considering a camera enclosure design decision, option 1 might be a snap-together design and option 2 might be a design using screws (figure 5). Analyzing differences simplifies the analysis in certain cases and also matches well with the kinds of detail design decisions that seem to arise in industrial practice. The specific attributes that we use to describe the two options relate to the properties of each separate part and of the assembly. These attributes are: the material of the part, the assembly time of the part, the vendor for the part, the purchase price, and, if it is a molded part, a collection of attributes relating to the mold design (like the area of the part footprint and the number of cavities in the mold). All of this information is readily available as a by-product of the detail design process.

We concentrate on parts used in final assembly. Camera production, like production of many electromechanical products, can be thought of in terms of component assembly and final assembly. We concentrate on parts that impact final assembly. Since final assembly is a strictly manual process, this allows us to simplify unit variable cost to include only materials and labor.

We ignore development cost. We assume that the engineering resources required to develop a set of parts are roughly independent of the design details. We make this assumption both because we do not believe that the differences are large in practice and because the relationship between part details and engineering effort is significantly more complex than the other relationships we have modeled.

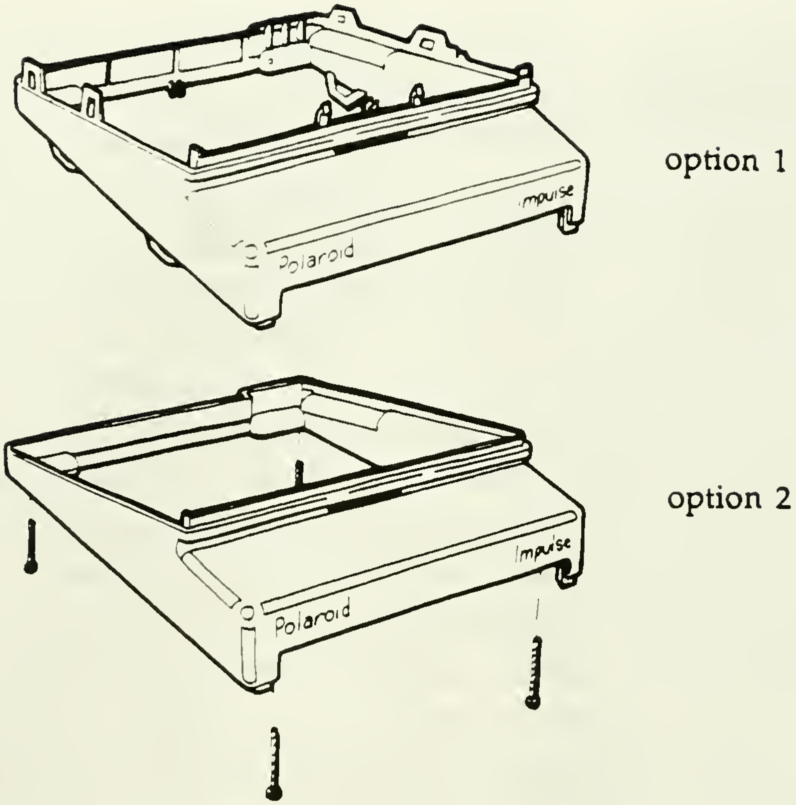

Figure 5: Two options for a camera enclosure design.

As a result of these decisions, the cost model presented as equation 1 takes the following form for the Polaroid case:

$$\Delta C_{1\rightarrow 2} = V(\Delta m_{1\rightarrow 2} + \Delta l_{1\rightarrow 2}) + \Delta F_{1\rightarrow 2} + \Delta S_{1\rightarrow 2} + \Delta T_{1\rightarrow 2} \qquad (2)$$

where each of the delta terms refer to the difference in the term when comparing design option 1 with design option 2.

Estimating the unit variable costs, $V(\Delta m_{1\rightarrow 2} + \Delta l_{1\rightarrow 2})$, and product specific capital costs, $\Delta F_{1\rightarrow 2}$, are relatively straightforward applications of existing techniques and standards at Polaroid, and we therefore do not address these estimation tasks here [Winchell89]. Estimating system costs and time costs is more difficult, and we devote two major subsections to these challenges.

3.2 Estimating System Costs ($\Delta S_{1\rightarrow 2}$)

We define *system costs* as the costs of supporting the assembly of the product. We call them *system* costs because they are the costs incurred by the systems that process information, supply materials, and provide technical knowledge. In the case of the Polaroid assembly plant this support system includes:

- **Manufacturing engineering**— the engineering required to plan the assembly tasks and to design fixtures and work stations for the assembly operations.
- **Industrial engineering**— the engineering required to determine time standards, balance assembly lines, and allocate assembly tasks.
- **Configuration control**— the administrative work involved in coordinating engineering changes to the product.
- **Quality engineering**— the inspection and quality control activities.
- **Vendor support**— the technical interactions with component suppliers.
- **Master scheduling**— the activities coordinating the forecast with the production plan.
- **MRP[4] planning** — the monitoring and order planning activities required to ensure that components are available when needed.
- **Purchasing** — the order placement and expediting activities.
- **Receiving**— the acceptance and verification of purchased components.
- **Materials handling**— the operations associated with delivering components to the assembly areas.
- **Production supervision**— the supervision of workers directly assembling the product.
- **Shipping**— the shipping of the product.

These activities constitute approximately 20% of the total manufacturing cost of the camera, a percentage typical for high-volume electromechanical product manufacturing. One property of system costs, that we observed at Polaroid and believe to be generally true, is that they are almost always directly connected to the number of people involved in system activities. In fact, salaries constitute about 60% of the total system costs at Polaroid, and most of the remaining costs are associated with the telephones, computers, furniture, travel, and office space required by these people. Although these system costs are not fixed, they change slowly— most firms will not lay off half of a purchasing department over the time frame of one quarter, nor will they sell half of a factory. Nevertheless, we argue that although system costs typically change over years and not months, product design decisions should be made and evaluated under assumptions that encourage long-term improvements in manufacturing system productivity. To do so, the connections between the design of

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[4] MRP is a acronym for Materials Requirements Planning, a production management tool that determines when components and subassemblies must be procured such that they are available in the time period in which they are required [Starr89].

the product and the long-run expected system costs of the factory should be made explicit. Our task is to estimate the difference in these system costs between two design alternatives.

We use the *current* production system for *current* products as the basis for estimating system costs for a *new* product. Our approach is to estimate the *sensitivity* of the current cost of each system activity to attributes of the current product. Note that the sensitivity approach does not require that the costs of purchasing for a new product be identical to those of an existing product; only that the sensitivity of the purchasing costs to differences in product attributes remain similar. This methodology is essentially a variant of activity-based cost accounting schemes described in [Banker90, Cooper88, Foster90]. Estimating these sensitivities involves 1) dividing the plant system costs into different product-related activities, and 2) estimating how product attributes influence the cost of each of these activities.

In most plants, dividing system costs into activities is made easier by the existence of a department budgeting and spending system. For example, most plants have a shipping and receiving department, a quality control department, and a purchasing department. Two difficulties arise in simply using the department structure as the activity classification for system costs. First, a department will often include several activities that are substantially different in their sensitivity to product attributes. For example, a shipping and receiving department both receives incoming components and ships the finished product. Receiving is highly sensitive to the number of different vendors and components in the product design. Shipping on the other hand is completely insensitive to these attributes. The solution to this type of difficulty is simply to divide the department into two or more subcategories. A second difficulty is that some departments do not relate directly to a production activity. For example, information systems departments support a variety of other departments rather than directly supporting the assembly operation. The solution to this type of difficulty is to allocate the costs of these departments to the other production-activity-related departments on the basis of how much of the department resources they use.

Conceptually this division of the plant system costs into activity-related categories can be thought of as the creation of a collection of autonomous service organizations. Among them is a purchasing organization, a quality organization, and a materials handling organization. Once these categories have been created, the remaining challenge is to determine how the costs of these organizations change with respect to changing product attributes. One way to think about this challenge is in terms of how these organizations would accurately determine a discount or premium for their services when presented with a change in the product attributes.

We estimated the sensitivity of the costs of each of the system activities to the product attributes by interviewing the people who carry out the activities and by then estimating how the magnitude of their effort would change if the demand for the activity changed. For example, imagine that the total purchasing costs for Polaroid were $1 million per year. Further, imagine that there were certain costs that are truly fixed given the current production volume and production policies. An example of one of these costs might be the maintenance contract and leasing agreement for the order entry and tracking software. The balance of the costs are in some way dependent on the product attributes. In the Polaroid case, these remaining costs are directly proportional to the number of people in the department, which in turn depends on the purchasing effort required to support the product.

Based on estimates of the effort expended for each source of parts, we divide the non-fixed purchasing costs into costs for molded parts, costs for non-molded parts, and costs for parts from internal vendors. Based on estimates of the relative magnitudes of the purchasing effort for dealing with vendors as compared with part numbers for each type of part we divide the costs for each of these types of parts into *per-vendor* costs and *per-part* costs. Based on this analysis, we devised the following sensitivity expression (expressed on a per annum basis):

$$\begin{gathered}\Delta \text{ annual purchasing costs} = \\ \$42{,}000/\Delta \text{ no. molded part vendors} + \$3{,}000/\Delta \text{ no. molded parts} + \\ \$6{,}000/\Delta \text{ no. internal vendors} + \$1000/\Delta \text{ no. parts from internal vendors} + \\ \$20{,}000/\Delta \text{ no. vendors of non-molded parts} + \$2{,}000/\Delta \text{ no. non-molded parts}\end{gathered}$$

We performed a similar analysis for each of the system activities to determine the sensitivity of the costs to the product attributes. These sensitivities are shown in table 1. Since all of the sensitivities are linear expressions, the sensitivity of the total system costs to the product attributes is just the sum of the sensitivities for the individual activities. The net result is an expression that allows us to relate the attributes of two design options to an estimate of the difference in system costs that will be incurred by the manufacturing system.

ACTIVITY	% of SYS COSTS	SENSITIVITY EXPRESSION ($000s)	REMARKS
Manufacturing Engineering	15	0	only a small fraction of the engineering costs are directly sensitive to part attributes
Industrial Engineering	2	$3\Delta N_{\text{parts}}$	N_{parts} is a surrogate for number of assembly operations
Configuration Control	5	0	likelihood of an engineering change is not a simple function of part attributes.
Quality Engineering	16	$13\Delta N_{\text{parts}} + 15\Delta N_{\text{molded-parts}} + 4\Delta N_{\text{int-parts}} + 7\Delta N_{\text{ext-parts}}$	includes costs of final inspection as well as lot inspections for different types of parts
Vendor Support	6	$71\Delta N_{\text{molders}} + 7\Delta N_{\text{molded-parts}} + 8\Delta N_{\text{ext-vendors}} + \Delta N_{\text{ext-parts}}$	molders require the most vendor support
Master Scheduling	5	0	does not directly relate to the part attributes
MRP Planning	3	$5(\Delta N_{\text{molded-parts}} + \Delta N_{\text{int-parts}} + \Delta N_{\text{ext-parts}})$	depends only on the number of part numbers in the bill of materials
Purchasing	7	$42\Delta N_{\text{molders}} + 3\Delta N_{\text{molded-parts}} + 6\Delta N_{\text{int-vendors}} + \Delta N_{\text{int-parts}} + 20\Delta N_{\text{ext-vendors}} + 2\Delta N_{\text{ext-parts}}$	described in text
Receiving	9	$15\Delta N_{\text{molders}} + 14\Delta N_{\text{molded-parts}} + 9\Delta N_{\text{int-vendors}} + 9\Delta N_{\text{int-parts}} + 11\Delta N_{\text{ext-vendors}} + 9\Delta N_{\text{ext-parts}}$	analogous to purchasing because order frequency determines receiving frequency
Materials Handling	8	$14(\Delta N_{\text{molded-parts}} + \Delta N_{\text{int-parts}} + \Delta N_{\text{ext-parts}})$	individual parts must be monitored and replenished
Production Supervision	19	$2\Delta T_{\text{assembly}}$	assembly time directly determines the number of assembly workers and therefore the required supervision
Shipping	5	0	once parts are assembled, their attributes do not affect shipping
TOTAL	100%	$2\Delta T_{\text{assembly}} + 16\Delta N_{\text{parts}} + 128\Delta N_{\text{molders}} + 58\Delta N_{\text{molded-parts}} + 15\Delta N_{\text{int-vendors}} + 33\Delta N_{\text{int-parts}} + 39\Delta N_{\text{ext-vendors}} + 38\Delta N_{\text{ext-parts}}$	

$\Delta T_{\text{assembly}}$	change in assembly time (seconds)	ΔN_{parts}	change in total number of parts
$\Delta N_{\text{molders}}$	change in number of molded part vendors	$\Delta N_{\text{molded-parts}}$	change in number of unique molded parts
$\Delta N_{\text{ext-vendors}}$	change in number of external vendors of non-molded parts	$\Delta N_{\text{ext-parts}}$	change in number of unique non-molded parts from external vendors
$\Delta N_{\text{int-vendors}}$	change in number of internal vendors	$\Delta N_{\text{int-parts}}$	change in number of unique internally-supplied parts

Table 1: System costs and sensitivities.

3.3 Estimating Time Costs ($\Delta T_{1 \rightarrow 2}$)

Within the assumptions of the Polaroid case study, our goal is to estimate the economic value of the difference in lead time between two design options. We do this by first estimating the difference in lead time between two design options, and by then estimating the economic value of that time.

Estimating the difference in lead time between two design options

For many high-volume electromechanical products, like cameras, photocopiers, or automobiles, the elapsed time between the detail design activities and volume production is largely devoted to tooling procurement. For cameras, this tooling is almost exclusively injection molds for plastic parts. These plastic parts are often complex multi-function parts. Typical "molded-in" functions include snap fits for easy assembly, cantilever springs, precise optical alignment features, and sliding switch tracks. The incorporation of several complex features into a single part makes the fabrication of the corresponding injection mold difficult, often forcing lead times to over 6 months and mold costs to over $150,000. As an indication of the complexity of an injection mold, figure 6 shows the cross section of a relatively simple mold. The part is a small spool indicated by the solidly filled region in the upper right quadrant of the mold. (A short primer on injection molds is given in the appendix.)

We acknowledge that there are several other issues that influence the time required to bring a design into production, including the detailed design time itself and the production start-up time. Neither of these issues is as clearly connected to part design as mold making time. Furthermore, we believe that both design time and production start-up time are both highly positively correlated with the time required to make injection molds and therefore believe that mold lead time is a good surrogate for some of the secondary relationships between part design and overall lead time.

Because injection molds for a collection of parts can be made concurrently, the part with the longest associated moldmaking time determines the lead time for the entire product. If there is a difference between the longest lead time molds corresponding to two design options, then there will be a difference in overall lead time between the two options. So, determining a difference in lead time for two design options is equivalent to determining the difference in lead time between the longest lead time parts in each option. We do this by using a spread sheet model that computes the time required for individual moldmaking activities from the specified part attributes.

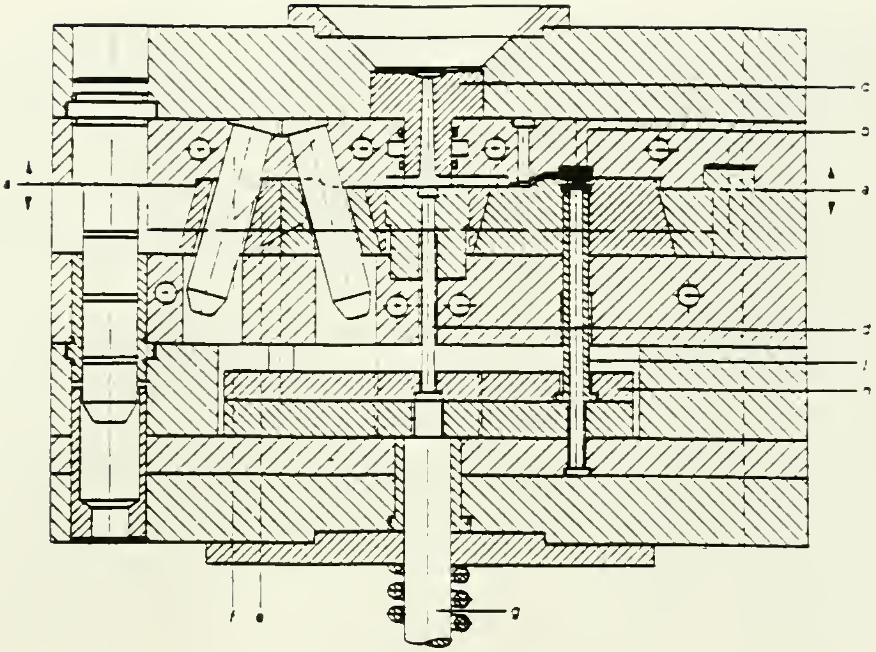

Figure 6: A cross section of an injection mold. The part is indicated by the filled region in the upper right hand quadrant of the illustration.

The injection mold design and fabrication process can be broken down into the simple PERT network shown in Figure 7. This figure illustrates the major tasks and their precedence relations for mold fabrication.

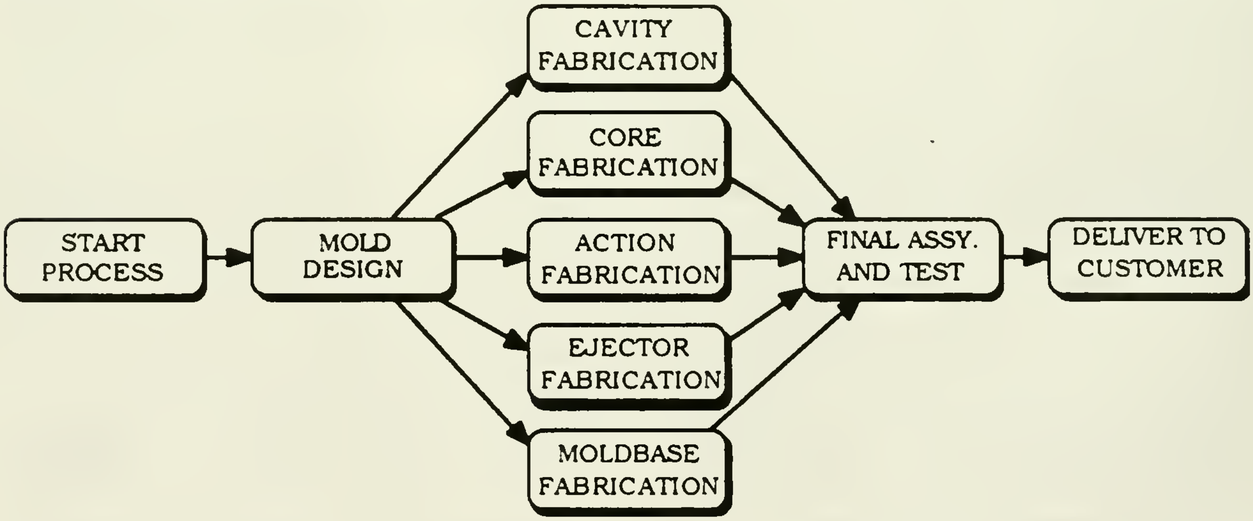

Figure 7: Simplified PERT Network of Injection Mold Design and Fabrication

For each activity in the PERT network, we have developed a relationship between the part attributes and the time required to perform the activity. These relationships are based on the number, type, and size of each feature that must be incorporated into the mold. Once the individual times for each mold making activity are determined, the critical path for the process can be identified and the overall mold making lead time can be determined.

As the number of features required to form a part increases, the complexity and cost of a mold also increase. As a result, the complexity of the part directly determines the amount of time that will be required to procure the molds. For cameras, this is the key connection between part design and lead time. For example, the absence or presence of a hook for a snap fit on a camera enclosure part may result in a one week difference in mold making lead time. This relationship arises from the time required to machine the hook feature into the core or cavity and from the time required to design, fabricate, and assemble a mold action.

Lead time estimates are highly dependent on shop capacity allocation, and we assume that the mold experiences no queueing delays. Our model agrees to within one or two weeks with the expedited lead times quoted for the parts we analyzed (the overall lead times are typically between 4 and 6 months). Since the model is used to compute differences in lead time between two molds, we believe the accuracy is sufficient to answer our research questions.

Assigning a Cost to Differences in Lead Time

Once a lead time difference between two design options has been estimated, the next step is to assign an economic value to the time. The challenge of converting lead time changes to dollars is complicated by the following issues:

- Schedule slip. If the product development program is behind schedule, then the production facility has already been preparing for production and the value of time is at least as great as the cost of maintaining a production facility and work force. These costs can be as high as a million dollars a day for some products.
- Strategic value of lead time. Improvement in lead time performance has long-term strategic value to the company because of the firm's enhanced ability to introduce new technology, to learn, and to exploit more recent market information.
- Critical target dates. Sales of a product will likely depend in some way on *when* the product comes to market. This is particularly true when the team is working toward a key target date like Christmas or a trade show.
- Cannibalization of existing sales. If an existing product is doing well in the marketplace, introduction of a new product could cannibalize sales.
- Actions of competitors. In many markets, the sales of a product depend critically on the recent and anticipated product introductions of competitors.

Despite these complications, we have attempted to estimate the value of lead time in order to compare its magnitude to other types of costs. We believe that some explicit estimate of the value of time is better than assigning no value to time differences, which is current industrial practice. Our approach to estimating this value of lead time is to determine the change in *net present value* of the sales revenues due to their early or late receipt, assuming that sales volume does not change. We view this as a highly conservative estimate, but as an unquestionable lower bound. For Polaroid consumer cameras, most of the expected revenues are from film sales. If at the time of a camera sale, the net present value of the film revenues were $200, and one million cameras will be sold each year for four years, then a one week change in the start of production is worth $1856k (at an 18% annual discount rate). We use this figure as an estimate of the value of product development lead time. Note that this value of time is likely to be valid only for relatively small changes in development lead time. Once the product cycle becomes substantially shorter, issues of cannibalization of existing products make the value of additional shortening much smaller.

Given the ability to determine the relationship between part design and mold making lead time, and the ability to estimate the economic value of that time to the firm, we can now add an estimate of time costs to our cost model.

3.4 Example Design Decision: The Mid-Cover

We have embodied the results of our cost modeling into a spreadsheet for evaluating camera design decisions. Using this spreadsheet model, an engineer or a researcher can investigate some of the major trade-offs among various design alternatives. This evaluation can be performed for any collection of parts representing a design option for parts involved in final assembly. Here, we present the results of our analysis for one decision— the mid-cover design options shown in figure 5.

The primary difference between the two options is the fastening technology used to attach the enclosure parts together. In option 1 a set of eight snap fits is used to attach the mid cover to the bottom of the camera and to the top cover (the fully assembled camera is shown in figure 4). Each snap fit requires two mating parts— a barbed hook and a rectangular hole into which the hook snaps. Option 2 employs 4 screws to attach the mid cover to the rest of the camera. The screws allow much simpler plastic features than do the snaps. Option 2 is a gross violation of current DFM practice while Option 1 is in strict conformance. We estimate the net *benefit* of option 2 over option 1 to be almost two million dollars. All of the costs are expressed as the net present value of the lifetime cost differences between the two options using an 18% annual discount rate, and the product volume is assumed to be 4 million units evenly distributed over a four year period. The results are summarized in table 2 and discussed below.

Cost Term	Description	Cost (k$)
$V \cdot \Delta m_{1 \to 2}$	materials cost	254
$V \cdot \Delta l_{1 \to 2}$	labor cost	204
$\Delta F_{1 \to 2}$	product-specific capital cost	-41
$\Delta S_{1 \to 2}$	system costs	487
$\Delta T_{1 \to 2}$	time cost	-2598
TOTAL	(negative cost implies net benefit)	-1694

Table 2: Summary of cost terms for mid-cover options.

Materials costs. Screws are more expensive to purchase than the extra cost of the plastic in the molded snap fits; they cost about $.02 each. This adds $.08 to the materials cost of option 2, resulting in an additional lifetime cost of approximately $254,000.

Labor costs. The difference in assembly time for the two options is approximately 15 seconds or $0.06/unit at $14.00/hour. This results in additional lifetime labor costs of $204,000.

Product-specific capital cost. The molds for option 2 cost about $24,000 less than for option 1. Two sets of molds will be required over the life of the product, resulting in a lifetime tooling cost savings of $41,000.

System Costs. Option 2 involves adding 4 new identical parts, 1 new part number from an external vendor, 15 seconds more assembly time, and 1 new vendor. This results in a net increase in system costs of approximately $171,000 each year, or $487,000 over the life of the product. The annual cost increases by system activity are: industrial engineering $12,000, quality engineering $59,000, vendor support $9,000, MRP planning $5,000, purchasing $22,000, receiving $20,000, materials handling $14,000, and production supervision $30,000.

Time Costs. The mid cover is one of the most complex parts in the product. If we assume that the molds for the part require the longest lead time, then shortening the mold procurement time for the part will allow the product to be sold sooner. The critical path for mold making for this tool is the sequence: mold design, cavity machining, and mold assembly. Option 2 has a 42 hour shorter design time, a 38 hour shorter cavity machining time, and a 10 hour shorter final assembly time. This results in a net time savings of 90 hours of shop work content. Assuming that all of the machining time could be done with a two shift operation (100 hours/week), but that the shop operates 50 hours per week for design and assembly, the net lead time difference is approximately 1.4 weeks. Assuming the lead time is worth $1856k per week, and that all of the time saved on the mid cover can be translated into shortening the development lead time, the time benefit of the design decision is worth at least $2598k. This analysis is conservative, since it assumes that the mold shop has no capacity constraints and therefore no queueing delays are present in the system. Also, there may be another complex part in the product with a lead time only slightly shorter than the mid cover, in which case the maximum lead time savings would be the difference in lead time between the mid cover and the next most complex part.

The clear result for the mid-cover example is that time costs are large compared to the other costs. If in fact the mold lead time is determining the development lead time, then current DFM guidelines should be violated to avoid the complex geometry of snap fits.

Summary of other examples

Based on exploring five design decisions for cameras, we discovered that the design for manufacturing strategy of minimizing the number of parts in the design appears to be economically sound as long as the parts are not on the critical path of the program. When the options involve critical path parts, the time costs dominate the others and strongly motivate simplifying the plastic part design even if additional parts and/or assembly time are required.

3.5 Discussion of Polaroid Study

Several issues were raised in the course of our case study. Here we discuss the accuracy of our analysis and some of the complications that have arisen in applying the results of the analysis at Polaroid.

Accuracy and Correctness

The specific model we have developed for the Polaroid study can not be assumed to be completely accurate. In fact, even defining accuracy within the context of a cost model of this type is difficult. The problem is that actual costs are incurred at a very aggregated level over some period in the past and we would like to estimate what future costs will be under a different set of conditions. The manufacturing system is much too large and expensive to run model validation experiments. The best one could do is to compare predictions with outcome for the one particular set of design choices that happens to emerge in the next product cycle. Instead we carefully examine the underlying assumptions of our model and attempt to justify each of its constitutive elements. If we believe the assumptions, we should believe the implications of the arithmetic linking the assumptions to cost. The power of models like these is that they facilitate exploratory calculations. Researchers and program managers can test the impact of differing detail design strategies under different sets of assumptions to gain insight into how design details impact manufacturing system performance.

Complications in Implementation

Our analysis was met with great interest at Polaroid. In fact, our results meshed with the intuition of many people in the product development and production organizations. The research was a catalyst for several fruitful debates that raised a variety of complicating, but interesting, issues.

First, product functionality and product quality are ignored by our analysis. We assume that the design team is capable of generating several alternatives that provide equal product functionality. In general our model suggests that part complexity should be distributed across several parts in order to minimize the lead time of the entire product. In a current Polaroid development effort, there has been a prolonged debate about this issue. In one case the debate centered on a major structural part of a camera— using one large and complex part allowed the optics to be precisely and rigidly aligned, while using several parts made alignment more difficult. Functionality and long-term reliability won out over lead time and the team chose to use a single complex part rather than several simpler parts. In another case, the team discovered that snap fits provide better impact resistance than screws because they provide some compliance under impact loads. Again, if impact resistance is a difficult product specification, then snap fits may be the preferred alternative, even if fasteners provide a better solution economically.

An interesting response we have encountered to the results of our analysis is that distributing complexity across a variety of parts diffuses the focus of attention of the development team. At Polaroid, some program managers like to have a single particularly complex part in a product because they know on which part to focus. If there are finite resources for dealing with complex parts (for example a single engineer who can design such parts) this strategy is quite sensible. If the cost of having an unusually complex part is high enough, firms should make managing distributed complexity a high priority skill.

4. CONCLUSIONS AND TOPICS FOR FUTURE RESEARCH

We have proposed a new framework for design decision making that includes the explicit modeling of time and system costs. We draw several conclusions from our experience in applying this framework and also see several opportunities for future research.

4.1 Design Rules Depend on Product Context

The single most important implication of our research is that design-for-manufacturing rules, like most heuristics, can not be generically applied to all detail design decisions. Different business contexts demand different design strategies. We have provided a way of modeling and trading-off some of the most salient factors in design decision making through the use of cost models. We believe that an analysis like ours should be undertaken within a particular business context in order to determine product-specific design guidelines.

4.2 Lead Time Considerations Encourage Distributing Part Complexity

For high-volume and time-critical products, a new design-for-manufacturing rule is to minimize the complexity of the most complex part in the product. Another way of articulating this rule is to distribute the complexity among as many parts as possible. This rule is often valid because: 1) simpler parts lead directly to faster tooling procurement, and 2) the value of time often dominates the other costs. A corollary is that combining parts and eliminating parts (including fasteners) is almost always a valid strategy up to the point when the part becomes the most complex part in the product. The reason that this corollary is generally valid for this product context is that assembly costs and system costs generally decrease with a reduction in the number of different parts in the design while materials costs may remain the same or increase only slightly. These guidelines rest on the assumption that the functionality and quality of the product are not degraded.

4.3 Better Cost Analysis Tools are Needed for Design Decision Making

Manufacturing cost is ultimately the best measure of ease of manufacture. Unfortunately, most current cost accounting systems are inadequate for product design decision making. These systems generally rely on materials costs, direct labor costs, and sometimes production equipment time as bases on which to allocate the system costs of the firm. To our knowledge, no existing cost systems provide any explicit accounting for the value of time. In our view, adding two simple terms to estimate system costs and time costs would greatly enhance the ability of development teams to make design decisions. Given that detail design decisions often have multi-million dollar consequences, the modest effort required to perform the kind of system cost and time cost analysis that we have done for the Polaroid example seems easily justified. Several firms have begun to apply activity-based costing schemes in their production organizations. A natural extension of these efforts would be to use these schemes for product development decision making and to also estimate a value for development lead time.

4.4 Detail Design is Only Part of the Development Picture

We have focused our attention on one part of the development process, detail design. There are many other opportunities for improvement in the product development process. In fact, there are probably ways to save months of lead time during some of the earlier phases of the development cycle. This possibility does not diminish the importance of detail design, but rather provides for many research opportunities. One area of opportunity that has arisen at Polaroid and at several other firms is the area of product definition during the preliminary phase of product development. By the time the team is addressing detail design decisions, lead time is measured in hours and days and there is tremendous management pressure to get the product to market. At the initial stages of design, the team is still thinking in terms of months and works at a comparatively relaxed pace. In many cases, there are apparent opportunities to eliminate several months of development lead time by making better product definition decisions. If teams had ways of agreeing on what the product was really going to be before they began doing it, then there would be fewer false starts and a smoother detail design phase. We raise these issues to acknowledge that we have not addressed all of the critical issues in improving product development performance and that much remains to be learned.

4.5 Firms Must Develop Diverse Competences as the Environment Changes

The results of our analysis in some ways remind us of traditional operations management results like the Economic Order Quantity (EOQ)— an analysis suggesting an optimal lot size given some specified parameters like set-up times and inventory holding costs [Starr89]. The EOQ mentality was turned on its head by just-in-time manufacturing. It is not the case that the EOQ analysis is false, but rather that the assumptions on which it is based were questioned and changed. We hope that models like ours will suffer the same end. Rather than simply accepting the connections between part design and lead time, or part design and system costs, manufacturing firms should strive to change the rules of the game. *Why does it take so long to make molds? Can the mold making process be changed? Why should our purchasing costs be so sensitive to the number of parts in the product? Can we change that relationship?* We hope that evaluation models like ours will be focusing mechanisms for both product and process improvement and not petrifications of existing manufacturing systems.

Some firms have developed competence in particular areas of manufacturing that have allowed them to operate in different and highly competitive ways. For example, Sony has developed their own robotics capability that allows them to use fasteners very effectively and very inexpensively [Fujimori90]. Because they have developed this expertise, they have been able to lower the costs of using fasteners, which has allowed them greater design flexibility and greater development speed. Once this capability has been developed, they can exploit much shorter product life cycles in an economical way. The important message is that product development strategies are critically linked to internal design and production capability. Developing certain capabilities allows the traditional wisdom to be upended.

Design details are important. In our examples, seemingly trivial details turn out to be of multi-million dollar importance. We have argued that making enlightened design decisions requires careful consideration of the particular business context in which product development occurs— simple heuristics valid for General Motors will not in general be valid for Polaroid. Boeing's design rules will be different from Sony's. For many products, the choice of an optimal detail design strategy revolves not only around issues of unit variable costs but also around time. Designers will optimize their designs according to the evaluation metrics used by the product development organization. Unless these metrics include a measure of the value of time, potential opportunities for product improvement will be missed.

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Appendix: Injection Molds

Figure A1 is a simplified description of an injection mold. The mold consists of five major parts:

- **Core and Cavity**: An injection mold consists of two large blocks of steel (called the *core* and *cavity*) into which every detail of a part must be machined. These major halves of the mold move together and apart in one dimension called the line of draw. The hollow cavity formed when the core and cavity blocks are together is injected with molten plastic under pressure to form the part.
- **Actions:** In order to separate the mold without damaging the part, all depressed or protruding part features machined in the core and cavity sections must be parallel with this line of draw. Parts designed with features not lying parallel to the one dimensional motion of the core and cavity are formed in molds requiring *actions*. By retracting an action from a part surface, the part can be ejected without damage, and conversely the part will not come out of the mold intact if the action is not retracted.
- **Ejector Mechanism:** The ejector mechanism is used to force the part out of the mold when the core and cavity separate. The mechanism usually consists of a set of pins that protrude out of the core or cavity as a result of the mold opening.
- **Mold Base:** The mold base is the structure that supports the remaining mold components. The mold base is also the interface to the injection molding machine.

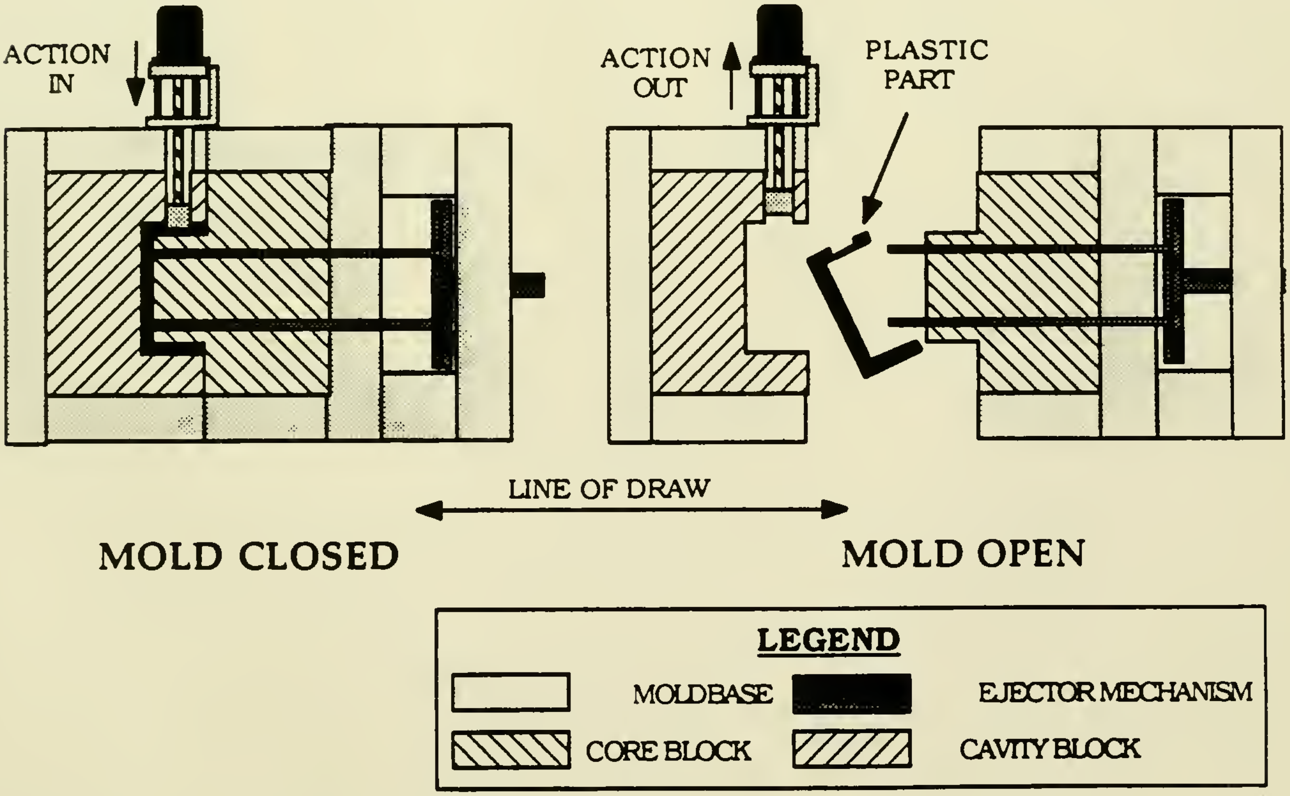

Figure A1: A simplified representation of an injection mold cross-section.