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

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Design for manufacturing (DFM) has been promoted as a way to enhance product development and production system performance. Current DFM practices encourage the minimization of the number of parts in a design through the physical integration of several geometric features in the same part. While this part integration often reduces the manufacturing cost of the product, it also can extend product development lead time, because complex parts typically require tooling with large lead times. This paper presents an economic model that makes explicit the trade-off between lower unit costs and longer product development time. This model is applied to a particular example in a field study of the application of DFM to Polaroid cameras.

(*Product Design; Product Development; Design-for-Manufacturing; Design-for-Assembly; Lead Time; Product Cost; Cost Modeling*)

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1. Introduction

One of the most widely promoted product 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. Many firms—including Ford, Digital Equipment Corporation, Motorola, and NCR—have adopted DFM methodologies in one or more product development efforts (DFMA 1990; Miller 1988; Coleman 1988). The benefits of DFM have been extolled in professional journals and the business press (Port 1989; Whitney 1988) and DFM is part of the curriculum at many engineering and business schools (Eppinger et al. 1990).

In this paper we argue that when product development time is critical, current DFM methodologies do not adequately reflect the economic implications of detail design decisions. Strict adherence to current DFM methodologies tends to direct product development teams to combine and integrate parts (Ulrich 1989), resulting in designs containing relatively few complex parts rather than many simple parts. This part integration leads to longer tooling lead times than would a design with simpler parts, and these longer lead times can incur economic penalties larger than the manufacturing cost savings that may result from the application of DFM.

The ultimate goal of design decision making can be viewed as the maximization of the net economic benefit to the firm of the development, production, sales, and follow-on support of a product or line of products. Making the product easy to manufacture, or reducing the total manufacturing cost, is one important part of this maximization, but product revenues are also critical. In this study we focus on discrete mechanical and electromechanical products. Our approach is to estimate, with a simple model, the impact of different design alternatives on the net economic benefit to the firm of a product. We do this in order to better understand existing design practice and to prescribe better design strategies. In addition to presenting a general model, we apply it to a particular product, Polaroid Cameras, in order to illustrate quantitatively the relationships among DFM, lead time, and profits. To generalize our results, we highlight potential pitfalls in current DFM practice and suggest several new DFM heuristics, which are often valid in time-critical environments.

This paper is divided into three remaining sections.

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Section 2 provides background on DFM, illustrates the relationship between DFM and lead time, and presents the model linking lead time to economic benefit. In §3 we report on a field study applying the model to the specific case of Polaroid Cameras. Finally, in §4 we discuss the implications of our work and suggest improvements in DFM practice.

2. DFM, Lead Time and Product Success

There are many incarnations of DFM, but most methods can be divided into two categories: those focused on reducing the cost of individual piece parts, and those aimed at reducing the cost of assembling a collection of parts. The DFM methodologies focused on piece part cost tend to be incremental in nature: given a basic part geometry, how can the part be modified to reduce fabrication costs? Parts are typically evaluated against a collection of design rules. For example, a design rule for sheet metal parts is that holes be located no closer than one hole diameter from the edge of the part, so that no extraordinary measures must be taken to prevent the punch from deforming the edge of the part (Trucks 1987). The DFM methodologies focused on assembly cost (often called *Design for Assembly or DFA*) are oriented toward evaluating and improving a proposed design concept and can lead to major changes in the number of parts in an assembly and in the arrangement of these parts. The focus of this paper is the assembly-related DFM methodologies because they influence the way the geometric features of a product are allocated to individual parts and therefore have the greatest impact on part complexity. In the balance of the paper we refer to the assembly-related methodologies by the general term DFM.

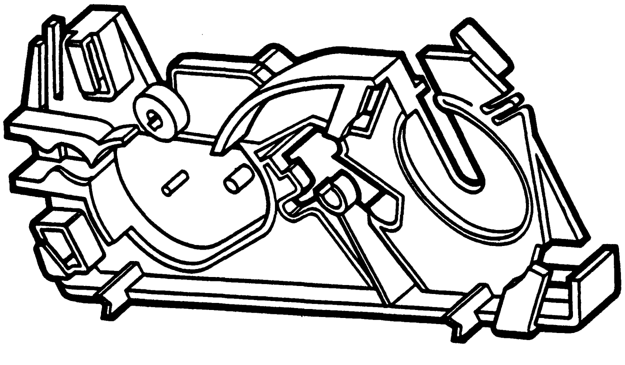
Although assembly-related DFM methodologies have been developed and promoted by several different organizations, they rely on the same basic idea—reducing the number of parts in a design and reducing the time required to orient and insert each part will result in lower assembly costs. The methodologies provide a way of assessing whether each part in a proposed assembly is theoretically necessary and approximately what the orientation and insertion time for a part will be. For example, one method for determining whether a part is theoretically necessary is the Boothroyd-Dewhurst questions (Boothroyd and Dewhurst 1988; Boothroyd 1988): (1) Does the part have to move relative to the assembly? (2) Does the part have to be of a different material from its neighboring parts for fundamental physical reasons (e.g. electrical insulation)? and (3) Does the part have to be removed for disassembly, access, or repair? If the answer to all of these questions is *no*, then in theory the part can be physically integrated with neighboring parts.

DFM tends to lead to geometrically complex parts because the methodology encourages the combination and physical integration of all parts that, in theory, do not have to be physically distinct. The resulting parts, while few in number, incorporate many geometrical features. In high-volume production these parts are typically fabricated with *net-shape* processes like injection molding, stamping, forging, or casting. For example, Figure 1 shows the left side-frame from the IBM Proprinter. The part is injection molded and implements several different design functions (Newman and Krakinowski 1987). Several studies suggest that in high-volume settings it is less expensive to fabricate one complex part than to fabricate and assemble several simple parts (Dewhurst 1988). Proponents of DFM argue that in addition to direct cost reductions, this part integration has other indirect benefits such as lower overhead costs and better reliability (Daetz 1987).

Complex parts like the left side-frame on the Proprinter require complex tools. For plastic parts the tools are injection molds, and for complex sheet metal parts the tools are stamping dies. For many products, such

Figure 1 The Left Side Frame from the IBM Proprinter.

An example of the application of DFM resulting in a complex multi-functional part.

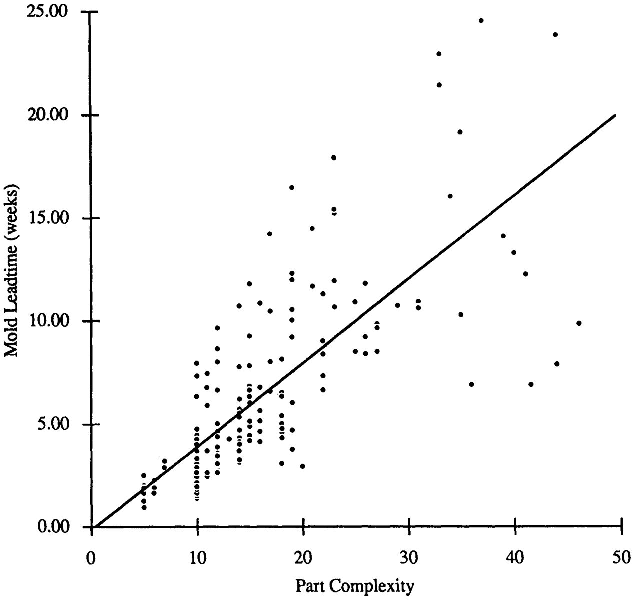


as automobiles, small appliances, and power tools, the procurement time for tooling largely determines the time that will be required to bring a product from the detailed design stage to volume production. Injection molds may require three to six months of fabrication time; large stamping dies, like those for automobile body panels, may require over 12 months to procure (Clark and Fujimoto 1991).

Tooling for most net-shape processes is fabricated by sequential material removal operations. For example, injection molds are first *roughed out* with a milling machine. Then, for detailed geometries, electrodischarge machining is used to create each feature. Finally, the molds are polished to create the required surface finish. When multiple geometric features are integrated into the same tool, these features are created sequentially. In contrast, if these features had been embodied in separate parts, separate molds could be procured in parallel. (Appendix A is a more detailed explanation of injection mold making, a prototypical net-shape process.) For this reason, the application of DFM resulting in the integration of geometric features in a single part extends the lead time required to procure the tooling required to create those features. Although the relationship between part complexity and mold lead time is not simple enough to model with a simple expression, the nature of the relationship is indicated by Figure 2, a scatter plot of the estimated mold lead time versus part complexity for all of the injection molded plastic parts in 19 different consumer coffeemakers.

Figure 2 **Scatter Plot of Estimated Mold Lead Time versus Part Complexity for All of the 136 Injection Molded Parts in 19 Consumer Coffeemakers.**[1]

The best-fit linear relationship is also shown. The correlation is significant to the 0.01 level.



Because the size and geometric complexity of a part contributes to determining the time required to procure the associated tools, the largest and most complex parts in a product tend to determine the critical path of tooling procurement and in turn the lead time from design to product introduction. The increased tooling lead time that is often associated with the application of DFM can have large economic consequences. Next we present an economic model integrating the revenues and costs associated with a product and show how these terms are influenced by the application of DFM and by lead time.

Relating DFM and Lead Time to Product Economics

The net present value of the profit a firm derives from the sale of a product (Π) can be expressed as

$$\Pi = \int_0^{\infty} e^{-rt}(Q(t)(p(t) - c(t)) - F(t) - S(t) - D(t))dt \quad (1)$$

where r is the continuous discount rate, $Q(t)$ is the rate of unit sales, $p(t)$ is the unit price or revenues obtained from the sale of a product, $c(t)$ is the unit variable cost of production (e.g. direct materials, labor, etc.), $F(t)$ is the rate of spending on design-specific fixed costs (e.g. molds), $S(t)$ is the rate of spending on system costs (e.g. production overhead and support functions), and $D(t)$ is the rate of spending on product and process development.

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[1] This plot is derived from a related study we performed. We developed a mold lead time estimation tool and applied it to all of the plastic parts in 19 consumer coffeemakers. The part complexity metric is the sum of the complexities of the regions of the part corresponding to the mold cavity and to each of the mold actions. The complexity of a region of the part is in turn the product of the *size* of the region and a subjective 1 *to* 4 *rating of feature complexity*. This study is described in detail in (Pearson 1992).

The terms $Q(t)$, $p(t)$, $c(t)$, $F(t)$, $S(t)$, and $D(t)$ are all potentially functions of time. Product development lead time influences these terms in two ways: *when* the costs and revenues begin and end, and what the *magnitude* of the terms is over time.

This model includes several simplifying assumptions: issues of taxation and accounting practice relating to depreciation are not explicitly modeled, the model focuses on a single product without considering an entire product line or a sequence of products, and costs irrelevant to the DFM issue (e.g. general and administrative expenses) are excluded from consideration. The profit expressed by Equation (1) is relevant to product design decisions, but because it excludes some fixed costs, will yield a numerical value greater than the actual net profits realized by the firm.

The most commonly acknowledged primary influence of DFM in the context of this model is to reduce the magnitude of $c(t)$. This increases the contribution from each unit sale and therefore contributes to increasing Π. There are also commonly acknowledged secondary effects, the details of which depend on the specific product context. DFM may result in a decrease in the magnitude of $S(t)$ because many of the system costs of production are associated with ordering, tracking, inspecting, and handling parts (Daetz 1987). The magnitude of $F(t)$ may increase with increasing application of DFM to handle the increased complexity of the tooling for some of the parts. The magnitude and duration of $D(t)$ may increase when DFM is practiced because of the product and process design effort required to integrate parts.

The central argument of this paper is that, in addition to these direct influences on costs, DFM may incur revenue-related economic consequences arising from the effect of DFM on product development lead time. In the context of the model, increased lead time has four main consequences:

(1) *Shifting of Revenues in Time*. The simplest and least controvertible effect of increased lead times is the shifting of when revenues occur. The economic importance of this effect is reflected by the discounting term e^{-rt} in the economic model. Even if the magnitude of $Q(t)$ is constant over the time period in which the product is sold, if the beginning of sales is shifted later in time, the net present value of these sales is diminished.

(2) *Changes in Price*. In many industries, the price that can be obtained for a product diminishes with time. In some highly volatile industries, such as workstations, memory chips, and consumer electronics, price may change by several percent each month (Hager and Gross 1991). This effect arises from interactions among competitors continually introducing improved products. Obviously if the magnitude of $p(t)$ is reduced because of an increase in lead time required to transition a product from design to market entry, then the contribution from unit sales is reduced.

(3) *Changes in Sales Volume*. Although sales volume, $Q(t)$ is likely to be coupled to price, it is also directly influenced by the lead time to market entry. This influence most frequently arises from potential customers satisfying their needs with competitors' products. For example, a recent delay in the introduction of an IBM workstation was estimated to lead to a loss of \$100 M in revenue out of total annual revenues of \$700 M (Markoff 1991) and leaves the company vulnerable to a loss of sales to competitors (Carroll 1991). This influence is also important when the market for a product exhibits seasonality; missing the season has a dramatic negative influence on sales volume.

(4) *Changes in Development Costs*. The research of Clark and Fujimoto (1991) suggests that longer lead times are associated with larger product development costs. One possible explanation for this is that in a complex project, a single sequence of activities (the critical path) paces the entire project. The lead time of the entire project can be lengthened by relatively small increases in the work content of the project if this work is added on the critical path. Because salaries constitute the majority of product development costs, lengthening the time the project team is engaged in a project raises the overall development costs of the program.

When these lead-time effects are considered, the economic influence of DFM is more complex than has been traditionally acknowledged. The wisdom of applying current DFM methodologies in product development depends critically on how these issues play out quantitatively in a particular product context and market environment. If we can estimate the lead time associated with different detailed design choices, the model allows us to make the economic tradeoffs associated with DFM explicit by estimating the relative magnitude of the effect of lead time on each of the terms. This analysis can be used to support design decision making and to validate or refute DFM heuristics for a particular situation. A procedure for estimating the total economic impact of DFM based on the model is therefore:

(1) Estimate the product development lead time from estimates of the individual tooling lead times of the parts in an assembly.

(2) Estimate the magnitude and timing of $c(t)$, $F(t)$, $S(t)$, and $D(t)$ based on the attributes of the parts and the assembly and on the lead time estimate.

(3) Estimate the magnitude and timing of $p(t)$ and $Q(t)$ based on the influence of lead time on market response.

(4) Using an estimate for r, calculate Π.

Issues Not Modeled

There are higher-order lead time effects as well. We do not model the following issues:

- Short product development lead time is of basic strategic value to the manufacturing firm, allowing a rapid response to the actions of a competitor, a rapid exploitation of technological opportunities, and a rapid response to shifts in market requirements (Stalk 1988).
- Gomory has argued that rapid product development lead time relates directly to the rate at which firms learn and improve their capabilities (Gomory 1990).
- In particular situations, short product development lead time is of specific and immediate economic importance; some firms have cash flow needs that can be addressed by the introduction of a product quickly.
- The speed with which a new product can be introduced also relates directly to market share, which may be of long-term strategic value beyond the immediate increase in unit sales.
- We assume that the basic functionality and quality of the product are not sensitive to DFM, although in some cases the application of DFM appears to increase reliability and to focus the attention of the development team on quality.

3. Field Study: Polaroid Camera Design

One of us (Sartorius) spent seven months on site in the product development and production organizations at Polaroid studying design decision making. Based on the data gathered during this study, we explore the application of the model to the design of Polaroid cameras. The example is meant to illustrate how some of the terms in the model can be estimated and to demonstrate the significance of the lead-time-related economic effects.[2] Our goal is to make reasonable assumptions in order to estimate the terms in the model. Throughout the analysis the assumptions are identified and in cases where there is significant uncertainty, either several different scenarios are considered or a sensitivity analysis is performed.

Polaroid manufactures a variety of consumer and industrial photographic products. We have focused on one of Polaroid's consumer cameras (Figure 3). The units sell for approximately \$60 at volumes of approximately one million units per year. The cameras have a product life cycle of approximately four years 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.

Because Polaroid consumer cameras are evolutionary in nature, soon after a new product is conceived, the product designers can list the major camera subsystems and their basic configuration. Given this system definition, the focus of the development effort is to implement 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 detail design phase that DFM is typically applied, and so we have focused our attention on this part of the development process.

Example: Mid-cover

Figure 4 shows an example design decision involving a part of the camera enclosure called the mid-cover. The

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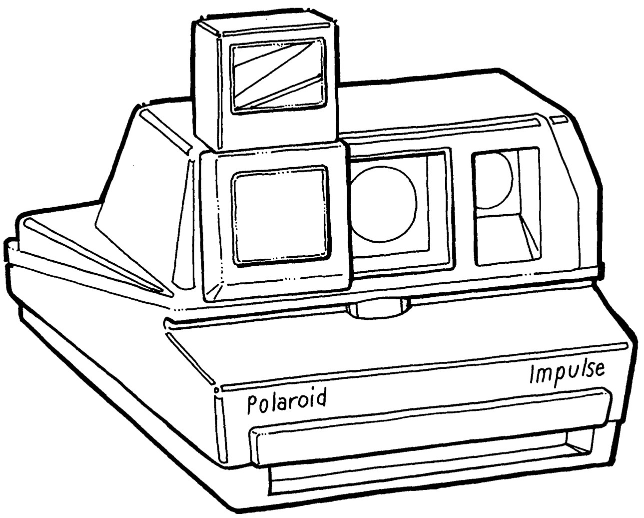
[2] Polaroid has been generously cooperative in this research effort and has agreed to allow us to use one of their products and assembly plants as the major example in this paper. In order to protect their proprietary cost information, we have disguised the data we present. The qualitative relationships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

Figure 3 **Example Product: A Polaroid Camera**



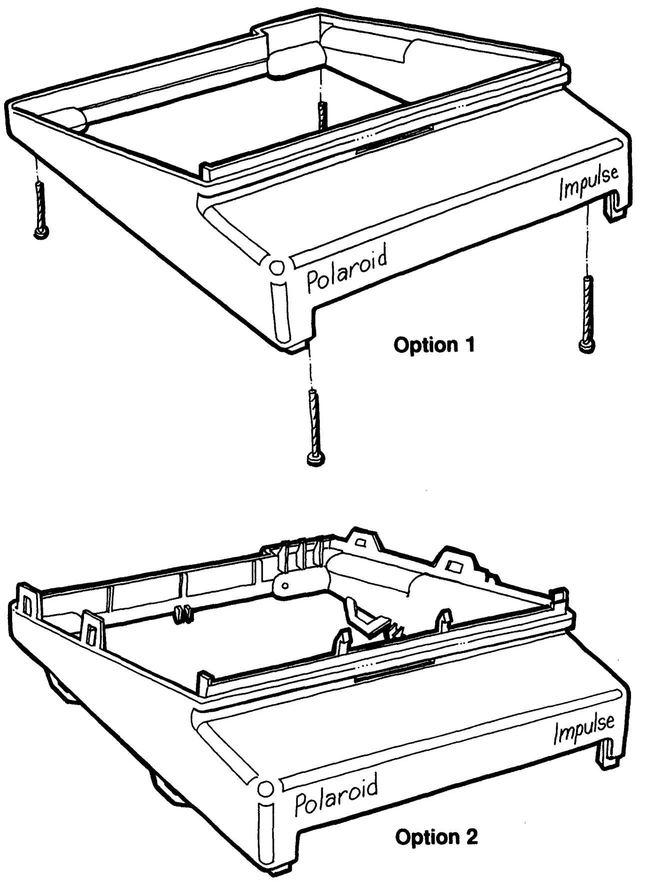
primary difference between the two design options is the fastening technology used to attach the enclosure parts together. Option 1 employs four screws to attach the mid-cover to the rest of the camera (in violation of DFM guidelines). In option 2, DFM is applied to the fastening method; a set of eight snap fits is used to attach the mid-cover to the bottom of the camera and to the top cover. Each snap fit requires two relatively complex mating features—a barbed hook and a rectangular hole into which the hook snaps. The integration of parts that fasten is one of the most common applications of DFM.

In the balance of this section we step through the four-step procedure described in §2 to estimate the economic implications of the two design options. We first estimate the difference in product development lead time between the two options. Then the unit variable costs, design-specific fixed costs, system costs, and development costs are estimated. Next the unit revenues and sales volumes are estimated. Finally, each of these estimates is incorporated into a net present value calculation to estimate the total profits for the two options. The convention we adopt for the estimates is that the time of the design decision corresponds to $t = 0$ weeks and that option 1 would be introduced to the marketplace at $t = 40$ weeks. We assume that for option 1 sales would be constant at 19,231 units per week (1 M units per year) until $t = 248$ weeks (a period of four years).

Step 1. *Estimate the product development lead time from estimates of the individual tooling lead times of the parts in an assembly*. For the mid-cover example, tooling lead time estimates were obtained from one of Polaroid's mold suppliers, Tredegar Molded Products. Two estimators at Tredegar examined the two mid-cover design options and determined that the lead time for option 1 would be 20.0 weeks, and 22.6 weeks for option 2. We summarize the logic behind the estimate of the lead time difference here, and provide a more detailed explanation of injection molding and mold making in Appendix A.

The primary difference in the designs for options 1 and 2 is the eight snap fits. Each of the snaps require electrodischarge machining (EDM) of precise geometry in the mold cavity. Six of the snaps require the addition of insert pins in the mold and the other two more complex snaps require the design, fabrication, and assembly of actions—parts of the mold that retract to allow the part to be removed. Each of the six simpler snaps re-

Figure 4 **Two Options for a Camera Enclosure Design**



quires 30 hours of machining time to the mold cavity while each of the two more complex snaps requires 38 hours of machining to the mold cavity. Machining of features in the mold cavity must be done sequentially, because the mold cavity is a single part and can be worked on by only one machine at a time. This machining is on the critical path for the mold fabrication process. During periods of peak demand, Tredegar operates their machining operations 100 hours per week, so the 256 hours required to create the snap geometry will require at least 2.6 weeks of additional lead time. The molds for the mid-cover are the most complex molds in the camera and are therefore on the tooling procurement critical path. The additional 2.6 weeks of machining time associated with eliminating the fasteners through the use of snap fits therefore adds an additional 2.6 weeks to the development time for the entire product.

Two factors add uncertainty to this estimate. First, engineering changes often arise after the part designs have been released to the mold makers. If a large number of changes happens to arise in parts other than the mid-cover, then the mid-cover may no longer be on the critical path. While this issue is difficult to model, engineering changes tend to arise more frequently in complex parts than in simple parts, so on average, engineering changes will accentuate the difference in lead time between complex and simple molds. Second, the production capacity of the mold maker is often limited. Polaroid believes that there are only two mold makers in the United States who have the capability to make the molds for their most complex parts. When all of the camera parts are released for mold fabrication, these limited resources are operated at full capacity. This limit on available capacity exacerbates the tooling lead time differences associated with complex parts.

Although the product development lead time difference between options 1 and 2 is difficult to predict with absolute certainty, we assume a difference in product development time of 2.6 weeks and revisit this assumption when we perform a sensitivity analysis. Based on the 2.6 week estimate, option 1 will be introduced to the marketplace at $t = 40$ weeks and option 2 will be introduced at $t = 42.6$ weeks.

Step 2. *Estimate $c(t)$ (unit variable cost), $F(t)$ (design-specific fixed costs), $S(t)$ (system costs), and $D(t)$ (development costs) based on the lead time and the attributes of the parts and the assembly.* The terms $c(t)$ and $F(t)$ are part of the traditional analysis of product costs done by product development organizations, and so we do not discuss the methods in detail here. A reference explaining traditional cost estimation methods is (Winchell 1989). The unit variable cost, $c(t)$, consists of the materials costs and the labor costs associated with producing each camera. We assume here that there are no significant differences in unit cost due solely to possible differences in production quantities for options 1 and 2. We also assume that the cost remains constant throughout the life of the product, although in general the magnitude of $c(t)$ may vary over time because of learning or other effects. The materials cost for option 1 is \$0.52 for the plastic part (based on Polaroid's existing methods for estimating the price they will pay a molder to provide the parts) plus \$0.02 for each of four screws for a total of \$0.60. The materials cost for option 2 is \$0.52. The labor costs are determined by the assembly time for the two options. The assembly time for option 1 is 20 seconds while the assembly time for option 2 is five seconds (based on Polaroid's industrial engineering time standards). At a labor rate of \$14.00/hour, option 1 costs \$0.08 to assemble and option 2 costs \$0.02 to assemble. The mid-cover component of $c(t)$ for option 1 is therefore \$0.68 and \$0.54 for option 2. If $c(t)$ for the entire camera incorporating option 1 is assumed to be \$40.00, then $c(t)$ for option 2 is \$0.14 less or \$39.86 (for all t).

For options 1 and 2 the design-specific fixed costs, $F(t)$, consist entirely of injection molds. To handle the expected volume of one million units per year, four single-cavity molds will be needed. Due to wear, over the four-year life of the product two complete sets of molds will be required. For option 1, the cost of a single mold is \$79,250 (\$317,000 for a set of molds). For option 2, the cost of a single mold is \$93,250 (\$373,000 for a set of molds). The cost of tooling for the balance of the camera is \$3.5 million for each set of molds, with two sets required over the life of the product. These values were obtained from estimates made for us by Tredegar Molded Products, Polaroid's primary mold supplier, and from the actual purchase orders for the other camera part molds that were eventually put into production. For simplicity we assume the payments for the molds are made at the start of production for the first set and exactly two years later for the second. The net result is that $F(t)$ consists of two instantaneous expenditures: for option 1, \$3,817,000 at $t = 40$ weeks and \$3,817,000 at $t = 144$ weeks; for option 2, \$3,873,000 at $t = 42.6$ weeks and \$3,873,000 at $t = 146.6$ weeks.

Estimating the system costs, $S(t)$, for options 1 and 2 is more involved than the estimates for $c(t)$ and $F(t)$. We define *system costs* as the costs of supporting the assembly of the product. In the case of the Polaroid assembly plant this support system includes the following *activities*: manufacturing engineering, industrial engineering, configuration control (the administrative work involved in coordinating engineering changes to the product), quality engineering, vendor support, master scheduling, MRP planning, purchasing, receiving, materials handling, production supervision, and shipping. These activities constitute approximately 20% of the total manufacturing cost of the camera. Many firms, including Polaroid, use an *overhead rate* on materials costs and labor costs to estimate system costs $S(t)$. While simple to use, this scheme is not accurate enough to distinguish the differences in actual system costs that are likely to occur as a result of subtle detailed design changes like those of the mid-cover example. To cope with this difficulty, we used a variant of the activity-based costing methodology described in (Banker 1990; Cooper 1988; Foster 1990) to estimate the sensitivity of the system cost structure to changes in product design details. We performed the system cost analysis in order to be able to address the claim that one of the major benefits of DFM is a reduction in system costs. The important details of this study are supplied in Appendix B, and we only summarize the results here.

The net result of the activity-based costing analysis is an expression that relates differences in attributes of two design options to an estimate of the difference in annual system costs that will be incurred by the manufacturing system. This overall expression (in thousands of dollars per year) is

$$\begin{aligned}\Delta\text{System-costs} = {} & 2\Delta T_{\text{assembly}} + 16\Delta N_{\text{parts}} \\ & + 128\Delta N_{\text{molders}} + 58\Delta N_{\text{molded-parts}} \\ & + 15\Delta N_{\text{int-vendors}} + 33\Delta N_{\text{int-parts}} \\ & + 39\,\Delta N_{\text{ext-vendors}} + 38\Delta N_{\text{ext-parts}} \qquad (2)\end{aligned}$$

where $\Delta T_{\text{assembly}}$ is the change in the assembly time of the product in seconds, ΔN_{parts} is the change in the overall number of parts in the product (including duplicates of identical parts), $\Delta N_{\text{molders}}$ is the change in the number of vendors of molded parts, $\Delta N_{\text{molded-parts}}$ is the change in the number of unique molded parts, $\Delta N_{\text{int-vendors}}$ is the change in the number of vendors internal to Polaroid, $\Delta N_{\text{int-parts}}$ is the change in the number of unique parts provided by internal vendors, $\Delta N_{\text{ext-vendors}}$ is the change in the number of external vendors of nonmolded parts, and $\Delta N_{\text{ext-parts}}$ is the change in the number of unique nonmolded parts from external vendors.

For the mid-cover, option 2 involves removing four screws. This change removes four parts ($\Delta N_{\text{parts}} = -4$) and one unique part from an external vendor ($\Delta N_{\text{ext-parts}} = -1$). The removal of the screws also removes 15 seconds of assembly time ($\Delta T_{\text{assembly}} = -15$). The net result is an estimated decrease in system cost spending for option 2 of \$171,000 per year. (Note that this analysis confirms the DFM wisdom that reducing the number of parts in a design reduces manufacturing overhead.) Based on the existing Polaroid production system costs, the total rate of system cost spending $S(t)$ for option 1 is estimated to be \$4,000,000 per year (\$76,923 per week) and for option 2 is estimated to be \$171,000 less or \$3,829,000 (\$73,635 per week). We assume that system cost spending remains constant over the life of the product and begins 12 weeks before product introduction and continues four weeks after the end of production.

The development costs $D(t)$ may be influenced by detailed design decisions and lead time in several different ways. First, development costs may be higher for more complex parts. For the mid-cover example, these costs result from more required effort to define the geometric details of the snap and to perfect the fit of the mating parts. Development costs may also be driven by development lead time somewhat independently from the design details. This argument is based on the observation that the product development team often remains intact until the product is launched. If there is a change in the length of the critical path of the project, the time the entire team is retained is changed, regardless of whether or not there are substantial changes in the work content of the project. The precise relationship among development time, lead time, and product design decisions is complex and could be the subject of an entire separate research activity. For this example, we assume that development costs are incurred at a constant rate for the entire development time; longer development times result in proportionally larger development costs (we revisit these assumptions in the sensitivity analysis). Development costs at Polaroid during the detail design phase of the program are approximately \$232,000 per week, so for option 1, $D(t)$ is \$232,000 per week for $t = 0$ to $t = 40$ weeks and zero thereafter, and for option 2, $D(t)$ is \$232,000 per week for $t = 0$ to $t = 42.6$ weeks and zero thereafter.

Step 3. *Estimate the effect of detailed design decisions and lead time on $p(t)$ and $Q(t)$*. For Polaroid cameras, the majority of the product revenues are from film sales. In order to accommodate this factor in the economic model, in addition to the price of the camera we include in $p(t)$ the net present value of the profit contribution from the expected film sales at the time the camera is sold. For the purposes of this example we will use a value of \$150 as the contribution from film sales. If we add \$60 as the price of the camera, the total value of $p(t)$ is \$210. Note that this case is equivalent to a case in which the product price is \$210, and so does not reflect any unique properties of products that consume supplies. Because Polaroid has no direct competitors in instant photography, the impact of lead time on price is not intense (although there are certainly other issues that impact price). We assume that $p(t)$ remains constant at \$210 for all t.

The impact of product development lead time on sales volume, $Q(t)$, is the most uncertain, yet potentially most important estimate in our analysis. As a result, we consider three different cases representing increasingly greater influences of lead time on $Q(t)$. The three cases are: demand is backordered, sales are shifted in time, and sales are forgone.[3]

In the case of backordered demand, customers are assumed to exhibit strong preference for the Polaroid product with great reluctance to satisfy their needs with alternative products. Under these circumstances, the delay in product introduction associated with option 2 will result in backorders for the product. These orders will be filled after the product is introduced as production capacity is available. Under these conditions, the only economic effect of a longer lead time on $Q(t)$ is that some sales are delayed until the product is available. Note that about half of Polaroid cameras are purchased as gift items, and so backordered demand is a very conservative model of the influence of lead time on sales, and we consider this case only as a baseline for comparison. If we assume the factory has an additional 20% available capacity, then the 2.6 week backlog of orders resulting from the delay for option 2 can be satisfied in the first 13 weeks of production, resulting in $Q(t) = 23{,}077$ units/week for $t = 42.6$ to $t = 55.6$ weeks and $Q(t) = 19{,}231$ units/week from $t = 55.6$ to $t = 250.6$ weeks.

The second case, shifting of sales in time, assumes that in effect demand for the product is created by the existence of the product. Only after the product is introduced will customers be aware of the product and purchase it. Similarly, the life of the product is assumed to be the same regardless of when the product is introduced. Based on these assumptions, a change in the time of product introduction only shifts the time when product revenues occur; if product introduction is shifted by one week, the entire revenue stream is shifted by one week. Based on these assumptions, $Q(t)$ for option 1 would be 19,231 units/week from $t = 40$ to $t = 248$ weeks and for option 2, $Q(t)$ would be 19,231 units/week from $t = 42.6$ to $t = 250.6$ weeks.

The third case assumes that there is a window of opportunity for the product, independent of when the product is introduced. Delaying the introduction of the product results in customers choosing other alternatives, and the potential demand is lost forever. If the window is assumed to be open from $t = 40$ weeks to $t = 248$ weeks, then $Q(t)$ for option 1 is 19,231 units/week from $t = 40$ to $t = 248$ weeks and $Q(t)$ for option 2 is 19,231 units per week from $t = 42.6$ to $t = 248$ weeks.

Polaroid marketing managers have thought carefully about these (and other) alternatives in making decisions about product planning, lead time reduction, and when to launch a new product. However, no precise and verifiable models of these effects currently exist for this product. Although there is not complete consensus at Polaroid about which of these cases is closest to the truth, we note that marketing managers believe that the

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[3] A helpful reviewer suggested we consider these three cases.

backorder scenario is much too optimistic and that a combination of the second and third cases is closest to reality. An additional factor that is important in assessing the effect of lead time on sales is the relationship of the new product to the products it replaces. If an existing product is selling extremely well, introducing another product may only cannibalize sales and provide very few increased revenues. In our example, the camera is a substantially new replacement for an aging product with diminished sales and is expected to generate mostly new revenues.

Step 4. *Using an estimate for r, calculate* $\prod$. Tables 1–3 summarize the estimates for each of the terms in the model for the mid-cover example under the three different assumptions for the influence of a delay on sales volume. Note that for modeling simplicity, the cash flows throughout this example have been assumed to be constant over particular time intervals; this allows the net present value (NPV) of these cash flows to be computed by

$$\mathrm{NPV} = \frac{\mathrm{CF}}{r}\,(e^{-rt_1} - e^{-rt_2}) \qquad (3)$$

where CF is the cash flow rate, t_1 is the start time, and t_2 is the end time. In computing the NPV, we use a value of 0.001923 per week (10% per year) for the discount rate r.

The key result for the first case (demand backordered) is that the smaller unit variable costs and lower system costs for option 2 outweigh the increased product development costs and slight delay in receipt of product revenues associated with the 2.6 week longer product introduction time. The net *benefit* of option 2 is $439 k under this scenario. This result supports the conventional rationale for current DFM methodologies: extra effort in product development on reducing unit variable costs through part integration leads to increased unit profits and decreased system costs which in turn leads to higher overall profits.

In the second case the sales volume for option 2 is shifted 2.6 weeks later in time, and the net impact on revenues is punishing. Although, as in the first case, unit variable costs are lower and system costs are lower, the effect on the net present value of receiving the entire revenue stream 2.6 weeks later in time results in a net economic *disadvantage* of $2152 k for option 2.

The third case is identical to the second case except that the sales that would have been made during the

Table 1 Case of Backordered Demand
r = 0.00192/week (10% annual rate)

	Option 1		Option 2		Option 2 − Option 1
Sales Rate, $Q(t)$	19231 units/week	$40 \le t < 248$	23077 units/week 19231 units/week	$42.6 \le t < 55.6$ $55.6 \le t < 248$	
Unit revenues, $p(t)$	$210/unit	for all t	$210/unit	for all t	
Unit variable cost, $c(t)$	$40.00/unit	for all t	$39.86/unit	for all t	
NPV of $Q(t)(p(t) - c(t))$	$518,966,597		$519,276,788		$310,191
Design-specific fixed costs, $-F(t)$ (discrete expenses)	−$3,817,000	$t = 40$	−$3,873,000	$t = 42.6$	
	−$3,817,000	$t = 144$	−$3,873,000	$t = 146.6$	
NPV of $-F(t)$	−$6,428,110		−$6,489,887		−$61,777
System costs, $-S(t)$	−$76,923/week	$28 \le t < 252$	−$73,635/week	$30.6 \le t < 252$	
NPV of $-S(t)$	−$13,265,740		−$12,517,747		$747,993
Development costs, $-D(t)$	−$232,000/week	$0 \le t < 40$	−$232,000/week	$0 \le t < 42.6$	
NPV of $-D(t)$	−$8,932,055		−$9,489,201		−$557,146
TOTAL Π	$490,340,692		$490,779,953		$439,261

Table 2 Case of Shifted Sales
$r = 0.00192$/week (10% annual rate)

	Option 1		Option 2		Option 2 − Option 1
Sales Rate, $Q(t)$	19231 units/week	$40 \le t < 248$	19231 units/week	$42.6 \le t < 250.6$	
Unit revenues, $p(t)$	\$210/unit	for all t	\$210/unit	for all t	
Unit variable cost, $c(t)$	\$40.00/unit	for all t	\$39.86/unit	for all t	
NPV of $Q(t)(p(t) - c(t))$	\$518,966,597		\$516,803,493		−\$2,163,104
Design-specific fixed costs, $-F(t)$	−\$3,817,000	$t = 40$	−\$3,873,000	$t = 42.6$	
(discrete expenses)	−\$3,817,000	$t = 144$	−\$3,873,000	$t = 146.6$	
NPV of $-F(t)$	−\$6,428,110		−\$6,489,887		−\$61,777
System costs, $-S(t)$	−\$76,923/week	$28 \le t < 252$	−\$73,635/week	$30.6 \le t < 254.6$	
NPV of $-S(t)$	−\$13,265,740		−\$12,635,373		\$630,367
Development costs, $-D(t)$	−\$232,000/week	$0 \le t < 40$	−\$232,000/week	$0 \le t < 42.6$	
NPV of $-D(t)$	−\$8,932,055		−\$9,489,201		−\$557,146
TOTAL Π	\$490,340,692		\$488,189,031		−\$2,151,661

first 2.6 weeks are foregone forever and the overall life of the product is reduced by 2.6 weeks. These assumptions lead to a \$7301 k *disadvantage* for option 2. In this case, as in the second case, the change in revenues due to shifted or foregone sales overshadows the other terms in the model.

If we assume that the case of back-ordered demand does not reflect reality well, the basic result of the analysis for this particular case is that the impact of the delay on revenues dominates the potential benefits that may be accrued through decreased unit variable costs and decreased system costs. This result is true even

Table 3 Case of Foregone Sales
$r = 0.00192$/week (10% annual rate)

	Option 1		Option 2		Option 2 − Option 1
Sales Rate, $Q(t)$	19231 units/week	$40 \le t < 248$	19231 units/week	$42.6 \le t < 248$	
Unit revenues, $p(t)$	\$210/unit	for all t	\$210/unit	for all t	
Unit variable cost, $c(t)$	\$40.00/unit	for all t	\$39.86/unit	for all t	
NPV of $Q(t)(p(t) - c(t))$	\$518,966,597		\$511,536,397		−\$7,430,200
Design-specific fixed costs, $-F(t)$	−\$3,817,000	$t = 40$	−\$3,873,000	$t = 42.6$	
(discrete expenses)	−\$3,817,000	$t = 144$	−\$3,873,000	$t = 146.6$	
NPV of $-F(t)$	−\$6,428,110		−\$6,489,887		−\$61,777
System costs, $-S(t)$	−\$76,923/week	$28 \le t < 252$	−\$73,635/week	$30.6 \le t < 248$	
NPV of $-S(t)$	−\$13,265,740		−\$12,517,747		\$747,993
Development costs, $-D(t)$	−\$232,000/week	$0 \le t < 40$	−\$232,000/week	$0 \le t < 42.6$	
NPV of $-D(t)$	−\$8,932,055		−\$9,489,201		−\$557,146
TOTAL Π	\$490,340,692		\$483,039,561		−\$7,301,131

assuming that the only influence of increased lead time on sales is to shift the occurrence of product revenues in time (case 2). Appendix C is a sensitivity analysis for the mid-cover example, considering the impact of errors in each of the terms on the results. The sensitivity analysis indicates that although the numerical value of the profits varies widely with the assumptions and estimates that are made, the basic qualitative result is very robust for the Polaroid case. These results are sensitive only to the lead time estimates and to the assumptions linking lead time to sales; the basic results do not change significantly even if there are 50% errors in the estimates for unit costs, revenues, fixed costs, or system costs.

Other Camera DFM Decisions

A distinguishing characteristic of the mid-cover example is that the mold procurement time is on the critical path of the product development effort. The analysis would yield the same basic result for any collection of parts that pace the introduction of the product to the market place. This is because for Polaroid consumer products, a specific instance of part integration arising from DFM influences unit variable costs by only a few cents (the material and assembly costs for a part are on the order of a few cents to begin with). When four million units of a product will be made, these differences in costs are significant; a $0.10 difference in unit costs results in a $400,000 difference in lifetime costs. But, when compared to the influence of changes in development time on revenues for *the entire product*, these unit cost differences for particular parts are small.

As an illustration of the economic impact of DFM on noncritical-path parts, consider another example called the *chute*. In this case, the parts are simple enough such that there is no influence of mold lead time on overall development lead time. Option 1 is two plastic parts assembled with a single screw and option 2 is a single part replacing the three parts in option 1. Option 1 has $0.05 higher unit variable costs than option 2. This difference results from the use of slightly more plastic in option 1 and from the material and labor associated with assembling the two parts with a screw. Each set of molds for option 1 cost $43 k less than for option 2, because the molds are much simpler and have no actions. Because option 1 involves 2 additional parts (one new nonmolded part and one new molded-part) and five additional seconds of assembly time, the sensitivity expression for system costs yields an estimated $138 k per year decrease in system costs for option 2. We assume that the development costs do not change. Because the timing of all of the terms in the model for the two options is identical, the NPV of the economic difference between products associated with each option is equal to the NPV of the differences in variable costs, mold costs, and system costs. The result of this analysis of cost differences is shown in Table 4. The analysis shows that the NPV of the costs for option 2 is $568 k less than for Option 1, suggesting that the application of DFM in this case is a wise economic decision.

4. Discussion

In this section we discuss the generality of the results, the relationship between DFM and product functionality and quality, the organizational impact of DFM, and the possibility of changing the underlying relationships between DFM and lead time.

Generalizing the Results

While we have presented the results of only one field study, the basic characteristics of the Polaroid case are not unique. A similar trade-off between production costs and revenues, arising from the application of DFM, will exist for any product in which (1) a delay in market entry would result in lower product line revenues, and (2) the application of DFM would extend the time required to enter the marketplace. The specific quantitative characteristics of this trade-off depend on the product context. In the high performance computer business, the cost of extended lead time is likely to overwhelm any manufacturing cost savings associated with, for example, creating a complex injection molding integrating enclosure parts. But in a mature market like blank videocassettes, the lead time to replace an existing product is likely to have a negligible impact on sales; manufacturing costs are the dominant issue. Many products fall somewhere between these two extremes. Consumer electronics, automobiles, photocopiers, and small appliances must be brought to market quickly *and* must be inexpensive to produce. For such products, we suggest three new product design heuristics:

(1) *Minimize the complexity of the most complex part*. Because the tooling for the longest lead time part is

Table 4 Chute Example
$r = 0.00192$/week (10% annual rate)

	Cost of Option 2 − Cost of Option 1		NPV of Cost Difference
Unit variable costs, $c(t)$	−\$0.05/unit	for $Q(t) = 19{,}231$ units/week for $40 \le t < 248$	−\$183,165 (costs less for option 2)
Product specific fixed costs, $F(t)$	\$43,000 \$43,000	$t = 40$ $t = 144$	\$72,415 (costs greater for option 2)
System costs, $S(t)$	−\$2,654/week	$28 \le t < 252$	−\$457,695 (costs less for option 2)
Total Cost			−\$568,445 (net costs are less for option 2)

often on the critical path in new product development, this part should not have a substantially longer lead time than the other parts in the product. A design based on this heuristic would distribute the product complexity uniformly among many parts, rather than concentrate the complexity in one part.

(2) *For complex parts, use processes with fast tooling fabrication*. Most choices among material and process technologies involve trade-offs between fixed and variable costs. Machining has low fixed costs but high variable costs. Injection molding has high fixed costs but low variable costs. Decisions about part material and process technology are typically made by assessing the total fixed and variable costs for the expected product volume. We suggest that the tooling procurement time should also be considered in making material and process decisions and that a more expensive process can be justified when product lead time is critical. One specific example of such a decision would be the use of a sheet metal assembly instead of an injection molding in a high-volume product. Sheet metal assemblies can often be designed to be functionally identical to the moldings, but are often less economical in high volume. However, sheet metal tooling requires substantially less time to procure.[4] We suggest that even at high volumes, if lead time is critical, sheet metal may be a more appropriate choice.

(3) *Thoroughly apply DFM in incremental product designs*. The economic penalty for time delays is most severe for the newest products in the most dynamic markets. Many new products are followed by incremental product designs as they mature. These products are likely to be less sensitive to time than the first version of the product and may benefit greatly from the reduced manufacturing costs associated with the application of DFM. A related heuristic is to apply DFM to components or systems that are reused *across* many product generations while concentrating on minimizing the development time of the components and systems that change *between* each generation. An example of this approach is the use of a highly manufacturable tape transport mechanism across several generations of tape players while adopting a fast but relatively costly design for the product enclosures, which change with each model.

Figure 5 is a two by two matrix categorizing DFM strategies according to lifetime product volume and the criticality of development lead time. Most of the recently promoted DFM strategies apply primarily to the lower right cell, where development lead time is not critical and product volumes are very high. While researchers and practitioners have identified product volume as a critical dimension for the applicability of traditional DFM methodologies, development lead time is another important dimension.

Because there are so many design decisions required in developing a new product, we do not expect that the kind of detailed economic analysis that we have performed for the Polaroid examples will be carried out

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[4] Here we refer to simple blanked and bent sheet metal parts and not to drawn parts like those used in automobile bodies.

Figure 5 DFM Strategies Categorized by Criticality of Development Lead Time and Lifetime Product Volume

Criticality of Development Time	LOW	HIGH
HIGH	Example Products High-performance computers Telecommunications equipment DFM Strategy • Avoid tooling with long lead times. • Use standard components. • Minimize production risk.	Example Products Notebook computers Toys DFM Strategy • Minimize the complexity of the most complex part. • For complex parts, use processes with fast tooling fabrication. • Apply traditional DFM to less time-critical parts.
LOW	Example Products Machine tools Electrical distribution equipment DFM Strategy • Avoid expensive tooling. • Use standard components (Other issues, such as maintenance or customization, are likely to be significant.)	Example Products Blank videocassettes Circuit breakers DFM Strategy • Thoroughly apply traditional DFM. • Combine and integrate parts. • At very high volumes, design for automated assembly.
	Lifetime Product Volume	

for every decision. Rather, such an analysis could be carried out for several specific examples to determine the order-of-magnitude sensitivity of product profits to lead time. Based on this analysis, heuristics could then be adopted for making the many routine decisions that are required in product design.

DFM, Functionality, and Quality

Product functionality and product quality have been ignored in our analysis. We assumed that the design team is capable of generating several alternatives that provide equal product functionality. In a recent Polaroid development effort, there was 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 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. In this case the choice between snaps and screws is not simply a time or unit production cost issue; the decision also involves product quality. We know of no clear relationships among DFM, functionality, and quality. We raise these issues to highlight the multifaceted nature of design decision making and to emphasize that there are not yet simple and clear decision procedures for many DFM decisions.

The Organizational Impact of DFM

In some firms, product development time is long *and* unit variable costs are high with respect to their competitors. In some of these situations DFM has been effective in facilitating organizational change and in moving product development teams in the right direction. DFM forces the development team to think about the production process; it brings representatives from different disciplines into the same room, and it forces a consideration of several alternative detail design strategies. These are all useful effects. We acknowledge the usefulness of the current DFM methodologies in forcing firms out of traditional ways of thinking. However, we suggest that the next step is an integrated view of product development that includes the strategic and market implications of the design as well as production costs. Conventional DFM methodologies may inhibit this integration because of their focus on production costs.

An additional organizational issue we have encountered is that distributing complexity across a variety of parts may diffuse the focus of attention of the development team. At Polaroid, some project 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. However, if the penalty for having an unusually complex part is high enough, firms may be able to justify enhanced resources for managing distributed complexity in the development operation.

Changing the Relationship between DFM and Lead Time

The results of our analysis in some ways remind us of traditional operations management results like the Economic Order Quantity (EOQ). 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 JIT focuses on changing relationships that had been traditionally assumed to be fixed. We hope that our results 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 underlying relationships. *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?* 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, which allows them to use fasteners effectively and inexpensively (Fujimori 1990). 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. Product development strategies are critically linked to internal design and production capability. Developing certain capabilities allows the traditional wisdom to be upended. We hope that models like ours will be focusing mechanisms for both product and process improvement and not petrifications of existing manufacturing systems.[5]

Appendix A: Overview of Injection Molding and Mold Making

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.

Figure A1 **A Simplified Representation of an Injection Mold Cross-section**

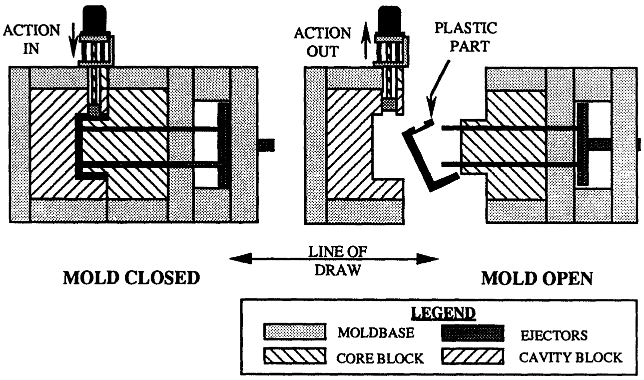
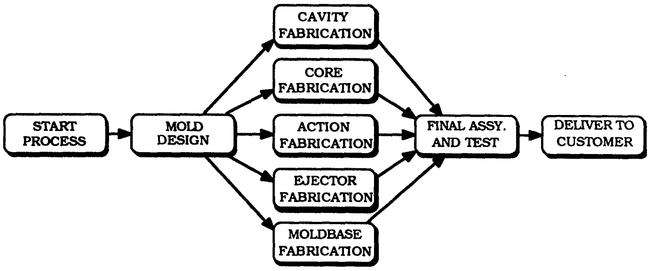


Figure A2 **Injection Mold Design and Fabrication Process**



- *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.
- *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.

The injection mold design and fabrication process is described by the network shown in Figure A2. This figure illustrates the major tasks and their precedence relations for mold fabrication.

Typically either the core or cavity fabrication steps will be on the critical path for the overall mold fabrication. In cases where the maximum possible parallelism in fabrication is carried out, the time required for the critical path determines the tooling lead time. For many low-priority jobs, a single mold maker will complete all of the mold making tasks; under these circumstances the lead time is determined by the total work content of the mold.

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Table B1 System Costs and Sensitivities

Activity	% of System 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	$3\Delta N_{\mathrm{parts}}$	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	$13\Delta N_{\mathrm{parts}} + 15\Delta N_{\mathrm{molded\text{-}parts}} + 4\Delta N_{\mathrm{int\text{-}parts}} + 7\Delta N_{\mathrm{ext\text{-}parts}}$	includes costs of final inspection as well as lot inspections for different types of parts
Vendor Support	6	$71\Delta N_{\mathrm{molders}} + 7\Delta N_{\mathrm{molded\text{-}parts}} + 8\Delta N_{\mathrm{ext\text{-}vendors}} + \Delta N_{\mathrm{ext\text{-}parts}}$	molders require the most vendor support
Master Scheduling	5	0	does not directly relate to the part attributes
MRP Planning	3	$5(\Delta N_{\mathrm{molded\text{-}parts}} + \Delta N_{\mathrm{int\text{-}parts}} + \Delta N_{\mathrm{ext\text{-}parts}})$	depends only on the number of part numbers in the bill of materials
Purchasing	7	$42\Delta N_{\mathrm{molders}} + 3\Delta N_{\mathrm{molded\text{-}parts}} + 6\Delta N_{\mathrm{int\text{-}vendors}} + \Delta N_{\mathrm{int\text{-}parts}} + 20\Delta N_{\mathrm{ext\text{-}vendors}} + 2\Delta N_{\mathrm{ext\text{-}parts}}$	described in text
Receiving	9	$15\Delta N_{\mathrm{molders}} + 14\Delta N_{\mathrm{molded\text{-}parts}} + 9\Delta N_{\mathrm{int\text{-}vendors}} + 9\Delta N_{\mathrm{int\text{-}parts}} + 11\Delta N_{\mathrm{ext\text{-}vendors}} + 9\Delta N_{\mathrm{ext\text{-}parts}}$	analogous to purchasing because order frequency determines receiving frequency
Materials Handling	8	$14(\Delta N_{\mathrm{molded\text{-}parts}} + \Delta N_{\mathrm{int\text{-}parts}} + \Delta N_{\mathrm{ext\text{-}parts}})$	individual parts must be monitored and replenished
Production Supervision	19	$2\Delta T_{\mathrm{assembly}}$	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%	$2\Delta T_{\mathrm{assembly}} + 16\Delta N_{\mathrm{parts}} + 128\Delta N_{\mathrm{molders}} + 58\Delta N_{\mathrm{molded\text{-}parts}} + 15\Delta N_{\mathrm{int\text{-}vendors}} + 33\Delta N_{\mathrm{int\text{-}parts}} + 39\Delta N_{\mathrm{ext\text{-}vendors}} + 38\Delta N_{\mathrm{ext\text{-}parts}}$	

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

Appendix B: Estimating the Influence of Design Attributes on System Costs

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 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. One property of system costs, which we observed at Polaroid, 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 the product and the long-run expected system costs of the factory should be made explicit. Our task is to estimate the expected difference in 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. We estimated the sensitivity of the costs of each of the system activities to the product attributes by interviewing the people who perform the tasks and by then estimating how the magnitude of their effort would change if the demand for the activity changed.[6]

As an example of this system cost sensitivity calculation, assume that the total costs of the purchasing activity for Polaroid were $1 million per year. Further, assume that there were certain costs that are truly fixed given the current production volume and production policies. An example of one of these costs is the maintenance contract and leasing agreement for the order entry and tracking software. The balance of the purchasing 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 purchasing department, which in turn depends on the purchasing effort required to support the product. Based on estimates by the purchasing department personnel of the effort expended for each source of parts, we divided the nonfixed purchasing costs into costs for *molded parts*, costs for *nonmolded 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 divided 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 in thousands of dollars per year):

$$\begin{aligned}\Delta\text{Purchasing-Costs} = {} & 42\Delta N_{\text{molders}} + 3\Delta N_{\text{molded-parts}} \\ & + 6\Delta N_{\text{int-vendors}} + \Delta N_{\text{int-parts}} \\ & + 20\Delta N_{\text{ext-vendors}} + 2\Delta N_{\text{ext-parts}}\end{aligned}$$

where $\Delta N_{\text{molders}}$ is the change in the number of molded part vendors, $\Delta N_{\text{molded-parts}}$ is the change in the number of unique molded parts, $\Delta N_{\text{int-vendors}}$ is the change in the number of vendors internal to Polaroid, $\Delta N_{\text{int-parts}}$ is the change in the number of unique parts provided by internal vendors, $\Delta N_{\text{ext-vendors}}$ is the change in the number of external vendors of nonmolded parts, and $\Delta N_{\text{ext-parts}}$ is the change in the number of unique nonmolded parts from external vendors. This analysis assumes relatively small changes in the product attributes relative to the product currently in production.

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 B1. Because 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.

Appendix C: Sensitivity Analysis for the Mid-cover Example

The analysis of the mid-cover example suggests that for the case of shifted or forgone sales (cases 2 and 3), the economic penalty for

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[6] 25 interviews with nine different production personnel were conducted by Sartorius and Ulrich from June 1989 to November 1990.

longer development time dominates the other terms in the model. Here we examine the sensitivity of this result to the assumptions we have made in making the estimates. Table C1 shows the net economic benefit of option 2 over option 1 subject to changes in the following assumptions.

- *Sales Distribution*. In §3 we assumed that sales are constant over the life of the product at a level of 1 million units per year. Here we assume two alternatives: (1) two thirds of the sales occur in the first half of the product life and one third occur in the second half, and (2) one third of the sales occur in the first half of the product life and two thirds occur in the second half.
- *Sales Volume*. We assumed the sales volume is one million units per year. Here we consider volumes of 500,000 and two million units per year.
- *Difference in Unit Variable Costs*. In analyzing the mid-cover, we estimated the difference in unit variable costs between options 1 and 2 to be $0.14. Here we consider the cases corresponding to a doubling and halving of this estimate.
- *NPV of Unit Revenues*. We assumed that at the time the camera is sold the camera price plus the net present value of the expected film revenues for the product is $210. Here we assume instead that the unit revenues are either $105 or $420.
- *Difference in System Costs*. We estimated the system cost difference between options 1 and 2 to be $171 k per year with total system costs of $4 million per year for option 1. Here we consider differences twice as great and half as great.
- *Difference in Development Costs*. We estimated development costs to be constant at $232 k per week, and assumed that the additional

Table C1 Results of Sensitivity Analysis Expressed as Net Benefit of Option 2 Over Option 1 ($000s)

(Base case assumptions shown in parentheses.)	Case 1: Backordered Sales	Case 2: Shifted Sales	Case 3: Forgone Sales
Results with Base Case Assumptions	439	−2152	−7301
Sales Distribution (uniform)			
2/3 in first half	403	−2259	−11,209
2/3 in second half	478	−2044	−3,393
Sales Volume (1M/year)			
500,000 units/year	284	−1070	−3586
2M units/year	749	−4315	−14,731
Unit Variable Cost Difference ($0.14)			
$0.07	226	−2364	−7516
$0.28	867	−1726	−6880
NPV of Unit Revenues ($210)			
$105	511	−553	−2452
$420	295	−5349	−17,000
Difference in System Costs ($171k/year)			
$86k/year	160	−2434	−7581
$342k/year	998	−1587	−6742
Difference in Development Costs ($232k/week over difference in lead time)			
Same development costs for Option 1 and Option 2	996	−1595	−6744
Discount Rate (10%)			
5%	593	−977	−7521
15%	306	−3025	−7078
Difference in Lead Time (2.6 weeks)			
1 week	750	−275	−2239
Breakeven Difference in Lead Time	30.5 days	5.4 days	2.1 days

2.6 weeks of estimated lead time for option 2 would result in additional development cost spending at this rate. Here we assume that option 2 incurs no additional development costs at all.

- *Discount Rate*. We assumed the discount rate r to be 10% per year. Discount rates can be justified by a variety of arguments including the cost of capital, opportunities for return on investment in other parts of the firm, or the prevailing rates for external investments. Ten percent is close to the current cost of capital, but is low for a typical internal rate of return. Here we assume discount rates of 5% and of 15%.
- *Difference in Lead Time*. We estimated that the difference in lead time between options 1 and 2 would be 2.6 weeks. Here we consider a difference of only one week. In addition we show the *breakeven* difference in lead time, or the difference in lead time for which the opportunity costs of late product introduction equal the savings expected from the application of DFM in option 2.

As one would expect, changes in the numerical values of the assumptions change the numerical value of the outcome. However, the basic qualitative result of the mid-cover example is relatively insensitive to the assumptions. The application of DFM in option 2 results in cost savings under the backordered-sales case, but incurs large opportunity costs for the cases of shifted or foregone sales.

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