A FRAMEWORK FOR INCLUDING THE VALUE OF TIME IN DESIGN-FOR-MANUFACTURING DECISION MAKING

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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].

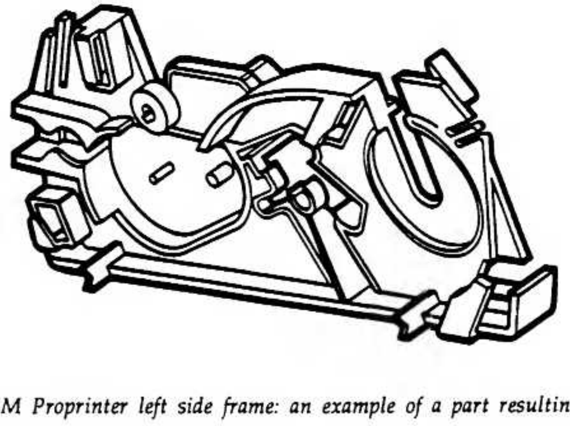

Figure 1: IBM Proprinter left side frame: an example of a part resulting from design-for-manufacturing methodologies.

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

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

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