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IMPROVING PRODUCT QUALITY AND PRODUCTIVITY USING BETTER GUIDELINES FOR CONCEPT DESIGN

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Abstract

The remarkable effectiveness of Japanese practices has led to a growing interest in the United States in the development and application of rules and methodologies which attempt to capture design experience. U.S. companies have found unexpected benefits and pitfalls in the application of these rules and methods. In this article, the authors critically examine one of the most widely accepted rules of Design for Manufacturability (DFM): minimize the number of parts. An examination of 240 assemblies and subassemblies has shown that rigid adherence to this rule can lead to unnecessarily complex parts and assembly.

Quantitative insights derived from this study have led to a better design goal: minimize and simplify assembly operations. This new rule, which should not be rigidly interpreted, tends to reduce part count, while having the benefit of assuring improved assembly. Another significant advantage of the new design rule is that it results in lower product defect rates as demonstrated by correlations observed for a wide range of products from two different manufacturers. This research links quality to the product concept, enabling a new approach to improving quality at the earliest stages of design.

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INTRODUCTION

Although many design axioms espouse simplicity [1][2][3], we currently do not have any fundamental standards useful in evaluating the relative simplicity or complexity of a design. In the absence of accurate measures of complexity, design decisions are generally based on empirical guidelines which are often accepted without question. Because of an implicit trust in such rules, designers occasionally misapply rules or overlook significant opportunities for simplifying a design concept. The end result is that resources are wasted in development and production and companies may miss important opportunities for competitive advantage.

Our interest in the study of complexity has been further motivated by the potential link between complexity and defect rates. Although such a relationship is intuitively sound, it has not been previously quantified [4]. We suspected that oversimplified measures of complexity contributed to the difficulty in linking defect rates to product complexity.

These concerns prompted our search for a sound method of measuring product complexity. In the process, we have critically examined the impact of one of the most widely accepted rules of Design for Manufacturability: Minimize the number of parts. In addition, new opportunities for improving product quality and defining a quality improvement strategy has been revealed.

QUANTIFYING COMPLEXITY

Excess Emphasis on Quantity Measures

A traditional approach to measuring complexity has been based on factors such as the number of parts or assembly operations. However, this approach to assessing complexity is not entirely satisfactory because there can be significant differences in the complexity of the parts, or assembly operations. From this it follows that a complete description of complexity requires two fundamental elements:

A. the number or quantity of factors contributing to the complexity of the system (n), and

B. the measure of the difficulty of producing or executing each of the elements (d_i for the ith element).

A common weakness in efforts to define a better complexity standard has been the singular focus on **quantity measures** such as the number of parts or assembly operations in a product. These simple measures are attractive because they can be easily and accurately counted. However, this approach to assessing complexity neglects the relative difficulty of executing or achieving each element. For example, a bolt and an engine block each count as one part, but the complexity of the engine block differs significantly from a bolt.

Using Design for Assembly to Quantify Complexity

Part and assembly complexity are separate elements contributing to the total product complexity. Although we have not been able to identify a technique for measuring part complexity, Design for Assembly (DFA) methodologies, such as the Boothroyd Dewhurst Method [5], provide a possible means for assessing assembly complexity. These methodologies, which utilize databases derived largely from time-and-motion studies, provide estimates of the time required for a range of representative assembly processes. Using these methods, an estimate of the nominal time needed to perform most assembly operations such as part handling, insertion and securing can be readily compiled. In general, for every factor that increases the difficulty of an assembly action or the complexity of the assembly interface, there is an increase in the estimated time of execution. Thus, the estimated assembly time per operation provides an approximate relative comparison of the difficulty or complexity of dissimilar assembly activities.

The link between the difficulty of a task and the manual execution time is firmly rooted in experience. Nine different Predetermined Motion Time System (PMTS) methods have evolved from the observation that specific human actions require a quantifiable time for execution [6]. Fitt's law also confirmed that manual execution times consistently increased for increased positioning accuracy, resistance to motion, and part handling difficulty [7]. These patterns led us to believe that *manual* execution times, as estimated by DFA methodologies, were potentially an exceptionally good measure of assembly complexity.

Time - An Ideal Standard

Time is an almost ideal standard of complexity. Time is a simple standard with a common international value that is readily understood. Time can be easily and accurately measured. Unlike cost, time is a stable standard that does not fluctuate from one period to another. One of the most valuable characteristics of a time based standard is that it provides a common standard which enables comparisons of dissimilar activities. To determine the assembly complexity for any complex product, we can simply sum the assembly time estimates for each individual operation. The cumulative assembly time reflects the combined complexity of the individual operations, allowing us to compare the relative difficulty of many simple operations to fewer difficult operations. Thus, the metric of time spans both quantity and difficulty measures of assembly complexity. A standard, such as time, which can interchangeably measure dissimilar attributes is said to be fungible.

We have observed through comparison that the DFA and PMTS database times are reasonably consistent. In addition, we have shown that many teams evaluating the same product using a common DFA method consistently estimated the number of assembly operations and the total manual assembly time. These observations support the conclusion that DFA times are an acceptable standard of assembly complexity.

MEASURING ASSEMBLY COMPLEXITY

To gain a better understanding of product complexity and validate the DFA complexity metric we reviewed DFA evaluations for 240 assemblies. The products studied covered a broad range of electro-mechanical devices drawn from existing or proposed products. The DFA studies were performed by graduate students participating in the Design for Manufacturability (ME217) class at Stanford.

The Link between Simple Complexity Measures

The observed relationship between the number of assembly operations and the number of parts for the 240 assemblies examined is shown in Figure 1. The equation for the linear least squares fit given in the figure shows that there is an average of five assembly operations for every four parts in a product. At least one assembly operation is required to insert each part in a product. However, some assembly operations such a spot welding, soldering, or reorientation do not involve the addition of a part. As a result, the number of assembly operations must always equal or exceed the number of parts in an assembly.

Figure 1 shows that there is a relatively strong link between the part count and operation count in a product. However, the relationship between the part and operation count is not equally constrained. As illustrated by the horizontal arrow in Figure 1, the part count can be reduced through redesign without reducing the number of assembly operations. On the other hand, the ability to reduce the number of assembly operations given a constant number of parts is limited as shown by the vertical arrow in Figure 1 which can not extend into the shaded region. Once the operation count has been reduced to the level of the part count, further reduction in the number of operations requires a reduction in the part count illustrated by the diagonal arrow in Figure 1. Thus, minimizing the number of operations forces a reduction in the part count, but reducing the part count does not require any change in the operation count.

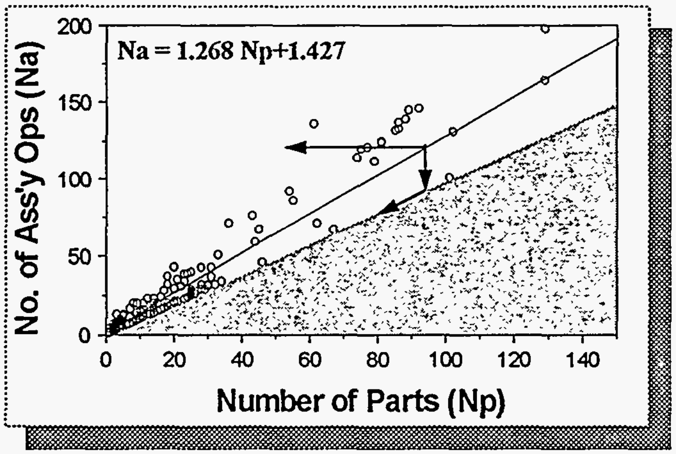

Figure 1. The Number of Assembly Operations (N_a) per assembly versus the number of parts per assembly for 240 assemblies. It is impossible to have valid observations in the shaded area. The equation for the solid line given in the figure, is a linear least square fit and has a correlation coefficient (r) = 0.977 [8].

Using Time to Assess the Impact of Minimizing the Part Count

The strong correlation between part and operation counts might lead investigators to ignore the constraints and assume that minimizing the part count will naturally lead to improved assembly. Assembly time, our selected complexity standard, is the key to determining how minimizing the number of parts influences assembly complexity. In Figure 2 the average assembly time per part is plotted against the number of parts per theoretical minimum number of parts. The "theoretical" minimum number of parts (NM) is an arbitrary Boothroyd Dewhurst value [5] determined for each assembly by those parts essential to the product function that:

1) must be separate to allow movement,
2) must be made of different materials, or
3) must be separate to permit assembly and disassembly.

Thus, the vertical values in Figure 2 represent a "normalized" assembly complexity per part and the horizontal values reflect how successful designers have been in minimizing the part count relative to an arbitrary standard. Interestingly, the dispersion in assembly complexity increases as the number of parts are minimized. *The upward sweep in the data at the left edge of Figure 2 clearly shows that the average assembly complexity per part can increase when the number of parts have been minimized!*

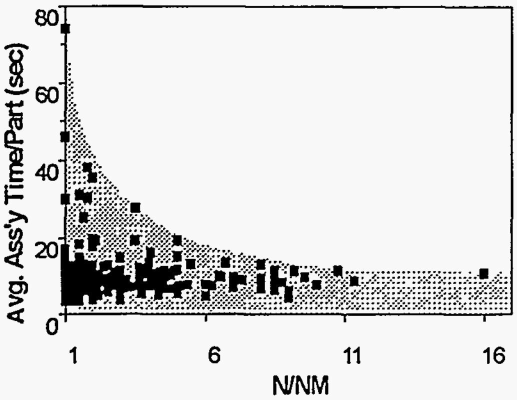

Figure 2.

Average assembly time per part (TM/N) versus the ratio of the part count to the "theoretical" minimum number of parts (N/NM).

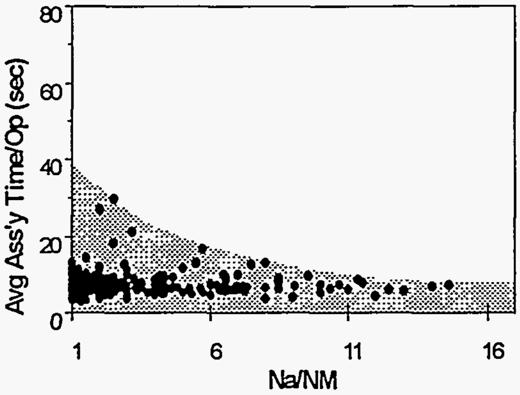

Figure 3.

Average assembly time per operation (TM/N_a) versus the ratio of the operation count to the "theoretical" minimum number of parts (N_a/NM).

Minimizing the Number of Operations

Figure 3 addresses the link between minimizing assembly operations and the assembly complexity per operation. The vertical distribution of the data in Figure 2 is two and a quarter times greater than that observed in Figure 3 based on the ratio of standard deviations. This demonstrates that the assembly complexity per operation is significantly less sensitive to changes in the operation count than assembly complexity per part is to the part count. Thus, minimizing the number of assembly operations has a stronger tendency to reduce assembly complexity. Simplifying each assembly operation provides additional reductions in assembly complexity.

A NEW DESIGN GUIDELINE

Minimizing the number of parts does not assure reduced assembly complexity. In contrast, reducing the number of assembly operations generally requires a reduction in the number of parts while assuring easier assembly. Consequently, a new design rule to "*simplify and minimize assembly operations*" is superior to the generally accepted rule: "*minimize the number of parts*" [9].

Caveats in Applying the New Design Rule

While the new axiom of simplifying and minimizing assembly operations is superior, it must be used with discretion. We have shown in three separate cases involving printer and automotive products that a narrow focus on minimizing the part count has lead to unnecessary part complexity [9]. In a study of Polaroid products and coffemakers, Ulrich et al [10] also observed that simplifying assembly could lead to increased part complexity. Increased part complexity can in turn lead to increased development time and cost.

These observations reinforce the importance of global rather than local optimization. The optimum product should have the minimum combination of *part and assembly complexity*. Currently we do not have a fungible measure of part complexity which enables tradeoffs between part and assembly complexity. However, we propose that the time required to manually execute fabrication operations may prove to be a useful measure of part complexity. Consistent with these views, Ulrich found that the time required to procure injection molds for plastic parts increased in proportion to the complexity of the mold [10]. The time based methods for estimating shop costs suggest that a method of describing part complexity in terms of time could be developed.

COMPLEXITY - A ROOT CAUSE OF DEFECTS

As previously mentioned, our motivation for measuring assembly complexity was to characterize the relationship between product quality and complexity. Intuitively, increased product complexity should result in higher defect rates. Supporting this view, our review of the literature identified numerous studies which showed that increasing task complexity or difficulty increased the frequency of mistakes or defects [8]. Although this relationship is widely recognized, it has never been quantified in general terms [4].

Defect Rates Are Highly Correlated with Assembly Complexity

To test the relationship between DFA measured assembly complexity and defect rates, extensive data were obtained from Motorola [11] and a disk drive manufacturer. Collectively the data reflects defect rates for many tens of millions of parts and assembly operations for a relatively wide range of products in companies with distinctly different quality control strategies. Defect rates on high volume products were sought to average quality performance differences among workers. In addition, by comparing the defect rates for a variety of products within individual organizations we hoped to minimize differences in the quality control philosophy and practice.

As shown in Figure 4 the Defects per Unit (DPU) were found to be highly correlated with a function of DFA estimated assembly time (TM) and the number of assembly operations (N_a). Each point in the figure represents a different product or subassembly. The relationship shown in Figure 4 is remarkable not only for the high correlations (correlation coefficients (r) > 0.95) but also for the observed consistency for data from two different manufacturers.

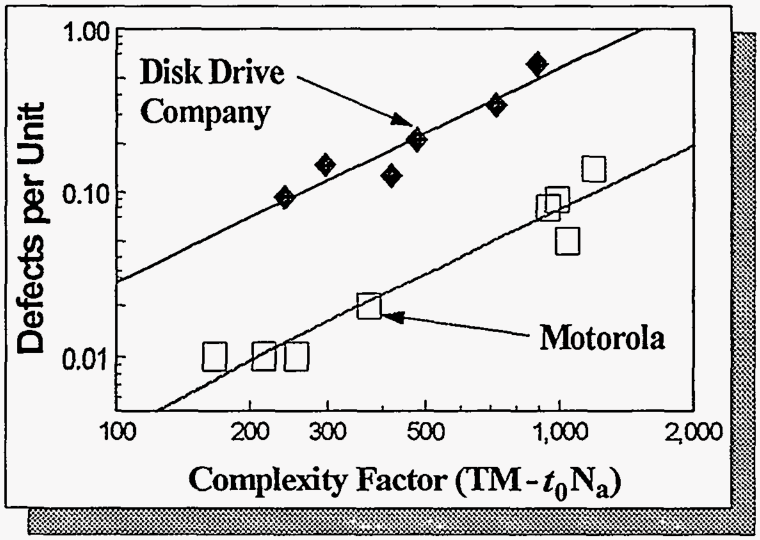

Figure 4. Defects per unit versus assembly complexity for Motorola [11] and a disk drive manufacturer.

Several powerful insights of a general nature follow from the strong correlations demonstrated in Figure 4.

1. A new, easily computed quantitative measure of assembly complexity with units of time can be defined. Since this parameter can be computed while the design is in the early product layout stage, it offers an invaluable guide to evaluating alternative concepts and improving product quality while the design is most flexible and easily modified.
2. By creating a company unique database derived from the defect history of existing products it is possible to characterize a company's quality control performance. This performance can then be used to quantitatively predict the probable defect rates of new products in an early stage of design.
3. Complexity analysis can help in assessing the relative importance of the two fundamentally different major sources of assembly defects as enumerated below. These insights contribute to the development of more effective quality improvement strategies, since each source requires a distinctly different method of control.

Two distinct sources of defects

a. **defects arising from the product design** - these defects are consequences of the *complexity of the product design.* Improvement efforts must focus on reducing complexity, which can only be addressed in the early stages of product design.

b. **defects attributable principally to manufacturing process control** - a consequence of mistakes and variation in the manufacturing processes. Improvement efforts focus on quality control.

The remainder of this paper will be devoted to a discussion of these concepts.

A New Quantitative Measure of Complexity

In our study, more than 50 potential relationships between defect rates and various complexity measures were examined. Our own observations reinforce the conclusion that defect rates are poorly correlated with part or operation counts. Thus, minimizing the number of parts or assembly operations will not necessarily reduce the defect rate. In contrast, the relationships illustrated in Figure 4 clearly show that minimizing and simplifying assembly operations will contribute to significant quality improvements, reinforcing the superiority of the new design guideline.

Equation 2, which is the abscissa of Figure 4, constitutes a significant metric of product assembly complexity which best correlates with the observed DPU.

$$C_c = \text{Complexity} = \text{TM} - t_0 \cdot N_a = \sum_{i=1}^{N_a} (t_i - t_o) \qquad (1)$$

In Equation 1, TM is the total manual assembly time and N_a is the number of assembly operations. The constant t_0 represents a threshold minimum assembly time for the simplest assembly operation. This threshold time is about 2 seconds for most applications. Finally, t_i is the DFA estimated time to complete the ith assembly step. Thus, $t_i - t_0$ is the difficulty of the ith operation (d_i) relative to the simplest possible operation. Note in Equation 1 that the magnitude of complexity is expressed in terms of time. Equation 1 is the core of a new general or global metric for relating design attributes and production practices to production defects.

To determine the assembly complexity (C_c) for any product, we can simply sum the assembly time estimates for each individual operation. The cumulative assembly time reflects the combined complexity of the individual operations and provides a common basis for comparing the quantity and difficulty elements of complexity.

In itself, Equation 1 provides a useful measure for evaluating alternative design options and for benchmarking the relative assembly complexity of competing design concepts. Any one of the available DFA methodologies, such as Boothroyd Dewhurst [5], or Westinghouse method [12], that converts the difficulty of operations to assembly times may be used for such evaluations. The procedure is straightforward and involves the following steps.

1. A design is selected for analysis and the manual assembly sequence is defined.
2. For each part and operation in the sequence, the manual assembly operations are listed.
3. A DFA-estimated time for each operation is obtained from the database provided by the particular DFA methodology selected. We have found that the final results are substantially independent of the specific DFA methodology employed, even though the times assigned to individual operations occasionally differ among the several available methodologies. In some circumstances, the DFA database may not adequately cover unique assembly conditions such as excess size, or weight. A customized set of assembly times may be needed in these situations.
4. Total number of assembly operations (N_a) and the total DFA-estimated manual assembly time (TM) are computed. If desired, the total number of parts (N_p) may also be determined.
5. A value of t_0 representing the threshold or minimum time for the simplest operation is selected. A typical value for the minimum DFA database assembly time is about 2 seconds for average size parts. The commonly encountered range of t_0 lies between one and four seconds. The rank ordering of concepts has been found to be relatively insensitive to differences in t_0 within this range of values. This allows the user to focus simply on estimating the total assembly time (TM) and counting the number of assembly operations (Na) as the principal means of determining product assembly complexity.

A Quantitative Predictor of Defect Rates

As shown in Figure 4, there is a remarkable correlation between the Complexity Parameter (C_c), which is based solely on design data, and the actual defect rates for a wide range of products. Each data set in the figure narrowly defines a characteristic quality curve for each company. The separation between these curves most likely reflects differences in the nature of the processes employed and the effectiveness of each company's quality control efforts.

Thus, two types of quality improvement strategies are suggested by Figure 4. A company can reduce its defect rate by either simplifying its product designs or improving its quality control. Product design changes that reduce the complexity factor (C_a) for a specific product shifts the product data point to the left along the company-characteristic curve. A lower defect rate is the consequence of such a change. A second alternative for reducing the defect rate is to improve quality control. Such a change would be the equivalent of shifting the companies characteristic defect rate curve downward.

A New Basis for Quality Improvement Strategies

Each company can determine its own characteristic curve of the type shown in Figure 4 by compiling historic defect data for each product and also determining the complexity factor for related products by the means already described. The plot of these values should form a company characteristic curve for its line of products. By benchmarking and analysis, an appropriate strategy for quality improvement can be deduced. Further, with such a curve available, the likely defect rate for each proposed product design can be estimated. Early identification of potential problems will permit suitable improvements at a time when the design concept and production processes are most readily changes. The benefits in saved time and expense can be very significant.

CONCLUSIONS

To remain competitive, the performance of most products must continually improve while maintaining or reducing cost. To achieve this goal, designers depend upon axioms, equations, concepts, and methodologies which capture and distill the design experience. Although we can model mechanical and electrical problems of remarkable sophistication, we have difficulty describing product complexity and evaluating simplifying tradeoff's during development. As a consequence, poor design decisions are often identified too late in the development and production process to be useful. Illustrating the limitations of the current understanding of design complexity, we have shown that one of the most widely accepted axioms of DFM, *minimize the number of parts*, can lead to increased assembly complexity.

In this paper, DFA estimated times have been introduced as the standard for assembly complexity. Prior research has shown that these times are linked with the difficulty or complexity of the assembly tasks. Time is an almost ideal standard of complexity because it is fungible, temporally stable, and has a common international value. Because time is a fungible measure, it enables tradeoffs between a greater number of simple operations or fewer complex operations. Our research has also shown that the DFA methodologies can be applied with sufficient consistency by a variety of individuals to be a useful standard of complexity.

By using time to evaluate assembly complexity, we have been able to identify a superior design guideline: *minimize and simplify assembly operations.* Even the new rule, however, must be applied with discretion since it can lead to unnecessarily complex parts. This weakness suggests the need for a fungible measure of both part and assembly complexity which enables tradeoffs between these factors. Time, the measure of complexity identified in this report, could potentially be used to assess part complexity.

In this report, we have also shown that product defect rates are strongly linked to assembly complexity. This link enables comparison of the potential defect rates of competing concepts at the earliest stages of design. The correlation between defects and complexity also enables the development of a new metric for assembly complexity which is useful in guiding concept selection decisions by identifying those concepts that will be easiest to assemble, and those concepts that have the lowest potential defect rates.

Based on the observed link between complexity and defects, companies can characterize their quality control performance. Using the characteristic curve which defines their quality control, quantitative estimates of defect rates for product concepts can be made at the earliest stages of design. In addition, the characteristic quality control curves provide a means for benchmarking the quality performance of companies even where they are producing dissimilar products. The large difference observed in the characteristic curves for two companies explains why previous industry-wide efforts to relate defects to complexity have failed. Corporate quality control differences are so great that they obscured the role of complexity in defects.

Finally, the correlation between defects and complexity reveals that there are two separate methods of reducing defect rates: a) simplifying the design, or b) improving quality control. This enables a new approach to defining quality improvement strategies within companies that has the potential of efficiently directing quality improvement efforts.

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