Proceedings of
The 1996 ASME Design Engineering Technical Conferences and
Computers in Engineering Conference
August 18-22, 1996, Irvine, California

96-DETC / DTM-1610

DESIGN FOR VARIETY:
A METHODOLOGY FOR UNDERSTANDING THE COSTS OF PRODUCT PROLIFERATION

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ABSTRACT

This paper further develops the previously introduced concept of Design for Variety (DFV). Our study seeks a tool that enables product managers to estimate the cost of introducing variety into their product line. This will help them to maximize market coverage while maintaining required profit margins. Variety incurs many indirect costs that are not always well understood or are difficult to capture. These costs are often not considered by people making the decision about introducing variety. Our DFV model attempts to capture these indirect costs through the measurement of three indices: commonality, differentiation point, and set-up cost. These indices will allow the decision makers to estimate some of the generally unmeasurable costs of providing variety. We conclude this paper by discussing our validation plans for testing the model in industry.

1. INTRODUCTION

In the past decade, Design for Manufacturability (DFM: Hinckley and Barkan, 1993) has significantly improved the product quality and profitability of US manufacturing companies. Two widely used DFM methods are Quality Function Deployment (QFD: Hauser and Clausing, 1988) and Design for Assembly (DFA: Boothroyd and Dewhurst, 1983). QFD provides a powerful tool in clarifying customer needs and translating them to design and manufacturing requirements. DFA enables engineers to create designs which are manufacturable at low cost. Despite the improvements in product quality, many companies are now realizing that applying DFM to a single product is not enough. By applying DFM methodologies to a single product, engineers may produce designs which optimize the cost of producing that product, but which sub-optimize the costs of producing all of the products together. Our goal is to develop a methodology which accounts for this interaction among the different varieties offered, and aids the product manager and engineers in making decisions about design issues affecting variety. Many companies today see this variety issue as a key to profitability.

DFV refers to product and process design that meets the market demand for product variety with the best balance of design modularity, component standardization, late point differentiation, and product offering. Our research is developing a systematic design methodology that leads to a wide coverage of customer preferences, while reducing the manufacturing cost, shortening the production cycle, and enhancing product line flexibility.

The key strategy in DFV is to identify the "standard" model and to utilize the methodology to design the products and processes that lead to short in-process time, low inventory, and low logistics costs. The concept of "late point identification" (Steiner, 1994) tells designers to implement the variety towards the end of the manufacturing process and standardize elements that require long lead times. Ulrich and Eppinger (1994) point out that as functions per component increases, volume related costs decrease, while complexity related costs increase. Variety also impacts costs related to life-cycle service (Eubanks and Ishii, 1993) and recycling and reuse (Ishii et al., 1994). Hence, the goal of DFV is to estimate at the early stages of design the cost of providing variety.

The motivation for the research has been driven by interest from many different companies into how they can properly manage variety. The authors have been working with manufacturers of industrial electronics, automobile components, and consumer appliances to develop these methods of determining variety costs. The first cost model (Ishii et al. 1995) gave a simple representation of variety and a very rough measure of variety complexity. Feedback from industry-provided student projects that used our model lead us to enhance our measure in three key areas: commonality, differentiation point, and setup cost.

This paper describes this recent enhancement effort for measuring variety complexity. In section 2 we explain the significance of variety complexity in detail by citing examples from industry. The summary of our previous effort in capturing the cost and importance of variety comprises section 3. Section 4 presents the enhanced measure of complexity and representation of variety. We outline the on-going validation plan in section 5, followed by concluding remarks.

2. WHAT IS THE COST OF VARIETY?

2.1 Scope of Variety

First, let us determine the scope of what constitutes "variety." One can consider product variety at different levels: the entire company, a specific factory, or an assembly line. In our current research, we are mainly focused on variety "seen" by a particular assembly line. Another issue to consider is whether the decisions to be made are strategic or tactical.

Strategic variety decisions are those that affect the number and scope of the variety offered to the customers. This is variety in the product that is noticeable to the customer. At the strategic level, the product manager is deciding what types of products to offer. A company should make such decisions based on whether the additional revenue realized from the introduction of the new variety will be more than the increased costs of providing it. These decisions involve the interaction of marketing and product design.

Tactical variety decisions are made at the level of the design engineer and involve decisions that affect the manufacture of the product, but which are not obvious to the customer. This involves the use of different parts or processes for the product. For example, should a new frame be designed for the new line of computers? Or should the designers use the current frame that has higher material costs than a redesigned frame would have? These decisions require close collaboration between product design and manufacturing.

Thus, we view DFV as a practice that truly requires concurrent engineering. From the engineer's viewpoint, DFV extends DFM to include marketing, service, and other product life-cycle issues that significantly impact profit.

2.2 Design for Variety in Industry

The topic of product variety has attracted a great deal of industry attention in the past several years. Hewlett-Packard (HP) has focused on efficient manufacturing of product variety as part of their global effort on streamlining supply chain (Davis and Sasser, 1995). The key point of their strategy is the postponement of differentiation. Davis and Sasser cite HP's successful redesign of laser jet printers. They now install localized modules including power supplies at worldwide distribution centers rather than at HP's factory in the US. Since different countries require distinct power supplies, this change in design eliminated the need for HP to produce localized printers in the US and allowed differentiation much closer to the customers. HP reports enormous savings due to the streamlined supply chain, reduced parts' inventory, documentation costs, and service logistics costs.

Matsushita Electronic Industries is vigorously pursuing what they call the "fan" type manufacturing line (Nikkei Kogyo Shinbun, July 13, 1995). They report halving the manufacturing cost of their surveillance camera line. In their DFV effort, they reduced the number of distinct products from over 200 to 96 and implemented late point differentiation. They standardized the camera housing and printed circuit board, and postponed the differentiation until the last step in the assembly process. Matsushita considers DFV to be one of their key manufacturing strategies for the next decade and is applying the same philosophy in other products such as portable tape recorders.

Automotive components and systems suppliers face the same challenge. The Nippondenso assembly line in Aichi, Japan produces over 250 different instrument panel meter consoles in a single line. Part of the line handles over 2000 distinct meter console "backsheets". Their previous manufacturing line required 800 sheet-punching dies and 160 setups per day. In redesigning their product line they identified the outside profile of the backsheet as the most expensive variety factor. Nippondenso now cuts the outside profile with a laser, which provides flexibility with lower setup costs and thus lowers the cost of variety. Coupled with other DFV improvements dealing with switchover costs, they were able to decrease the number of dies and setup time. In sum, they identified cost driving factors in design and manufacturing and generated alternatives that would reduce the cost of providing variety.

Ishii et al. (1995) cite the GE Appliances case in which GE engineers reduced cycle time by almost one-third. They analyzed refrigerator variety, particularly the door systems. They combined focused customization (eliminating variety that does not bring profit) and late point differentiation designs to achieve improvements in manufacturing costs.

The authors learned that all these companies, while being able to generate improved designs by trial and error, are seeking a more systematic method to manage variety: maximizing market coverage yet containing the cost of providing variety. In particular, they expressed the need for a measure for variety complexity that guides the early stages of design and manufacturing decisions.

2.3 What is Done Currently?

Generally, when a product manager wants to determine if it is profitable to have more variety within a current or future product line, they look at the direct costs of increased variety. Will it require more capital equipment or more training of personnel? How many hours of engineering time will it require to make new drawings, analyze the new design, run certification or qualification tests, etc.? Will any suppliers have to be added? The consideration of indirect costs is more difficult, however. Costs that are difficult to determine include those costs associated with changes in:

- raw material inventory
- work in process (WIP) inventory
- finished goods inventory (FGI)
- post-sales service inventory
- reduction in capacity due to set-ups
- increased logistics of managing the variety

While a detailed analysis may be able to determine many of these costs, managers and engineers generally do not have the time or the resources to do such an analysis. What is needed is a method to quickly estimate the costs of introducing or reducing variety. Such a tool will help focus the decision makers on where variety can be added profitably and where it should be avoided.

2.4 Research Approach

Our research approach to a DFV methodology focuses on the following tools:

1. Measure of the cost of providing variety: the team must be able to estimate the cost of providing variety.
2. Representation of variety: product development teams need a procedure that allows them to identify the key dimensions of variety and concisely document the variety offerings in graphical form. The graph should also indicate pertinent design and manufacturing information that affects variety importance and cost.
3. Measure of the importance of variety: development teams must estimate the importance of variety, i.e., additional revenues that will result by offering a particular variety.

The next section summarizes our first effort in developing this methodology (Ishii et al., 1995). This paper focuses on issues 1 and 2 -- the cost of providing variety and a method for representing variety. Research on measuring the importance of variety to the customer is being explored by other project members within the Industrial Engineering Department here at Stanford.

3. PREVIOUS MODEL OF VARIETY COMPLEXITY

3.1 The Initial Model

A preliminary study (Ishii et al., 1995) revealed three main factors that affect the cost of providing variety: the number of variations, how late in the manufacturing process the variation is implemented, and how "painful" it is to change over from one variety to another. It proposed a very rough measure of cost of variety (Y) on a scale of [0,1]:

$$Y = 1 - D1 \bullet D2 \bullet D3 \qquad (1)$$

where:

D1: number of variations (smaller if number of variations is large)
D2: the stage in manufacturing (smaller if early in the process)
D3: effort required to change over (smaller if the change takes more time).

All three indices (D1, D2, D3) are based on a [0,1] scale.

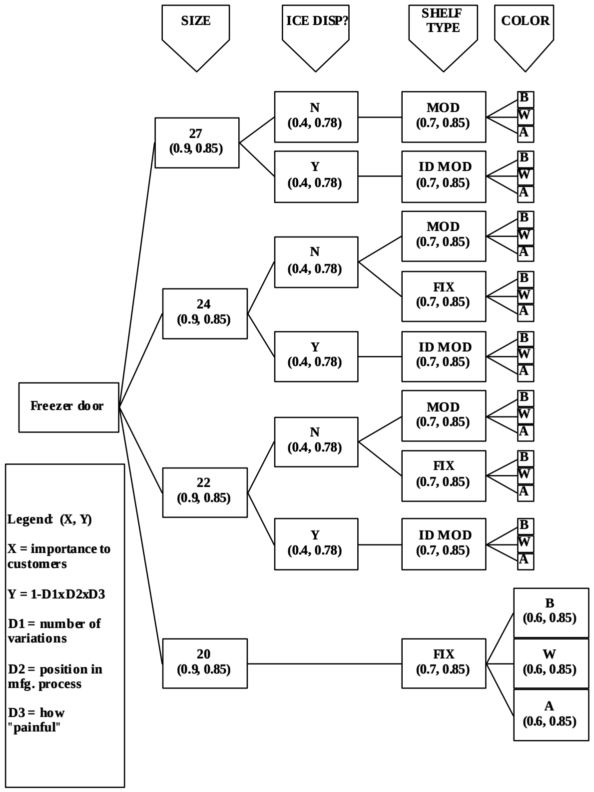


Figure 1. Product Structuring Graph

Figure 1 shows the product structure graph for a refrigerator door. The factor X is a measure of the importance of a variety to the customer. The factor Y is the rough measure of the cost of providing that variety and is determined as discussed above. This information would help the company determine which varieties are expensive to provide, but which have relatively low value to the customer. By plotting these X and Y values on a normalized graph such as that shown in Figure 2, it may help the development team make decisions on the design.

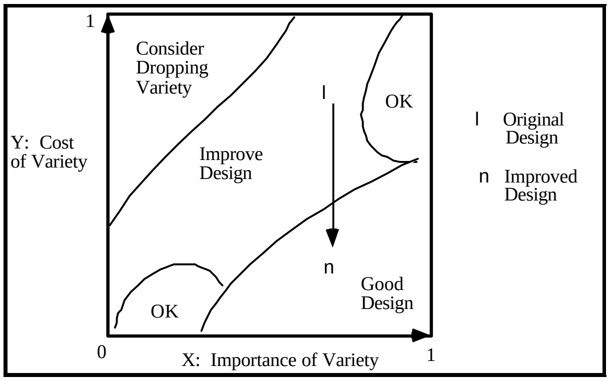


Figure 2: Cost of Variety vs. Importance of Variety

3.2 Industrial Feedback

These tools, the graph and the complexity measure, were used in ME217, a Stanford graduate course sequence in design for manufacturability. Three groups specifically applied the model to: 1) automotive window regulators, 2) heat trace cable connectors, and 3) hard disk drives. The groups indicated that the graph and the measure helped them clarify the variety structure, identify rough cost drivers, and guided them to redesign opportunities. However they saw some serious shortcomings in the methodology.

1. *The use of QFD in estimating the importance of variety is arbitrary and subjective:* other project members are addressing this weakness by applying conjoint analysis (Elrod, et al., 1992) and utility theory (Thurston, 1990).
2. *The complexity measure was too rough and convoluted:* it is useful for identification of cost drivers but was useless in trade-off analysis of detailed design decisions.
3. *The model is useful for a focused product line, but difficult to apply for very complex variety structures:* the refrigerator example had a clearly defined dimension of variety that involved discrete choices. Other products with more convoluted product structures have been found to be more difficult to analyze using this methodology.

The current effort for DFV involves refinement of the measurement indices to more accurately account for the cost of providing variety. As mentioned before, this paper focuses on our effort to enrich the indices and the representation of variety.

4. THE ENHANCED MEASURE OF COST OF VARIETY

4.1 Indices for Measuring Cost of Variety

The core idea of a DFx tool is to use an easily measurable index to act as a proxy for the actual cost drivers for the product. For example, DFA uses the symmetry of the part, angle of insertion, etc., as proxies for the expected labor which will be needed to assemble the part. Similarly, DFV needs indices that designers can use to measure the indirect costs of providing variety. Note that our model does not address direct costs, since we consider them relatively straightforward to determine.

In Ishii et al. (1995), we used the indices of D1, D2, and D3 (number of varieties, differentiation point, and set-up costs) as the proxies for variety complexity. More recently, we have been considering an expanded number of indices. We explored the use of the five indices shown below:

- Degree of variety
- Degree of commonality
- Differentiation point
- Value-added curve (Figure 3)
- Set-up cost

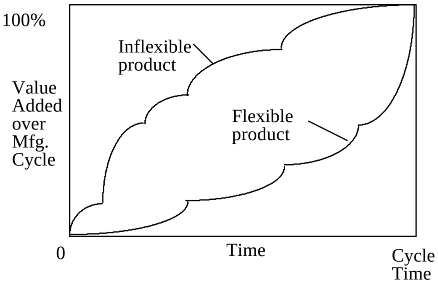


Figure 3. Product cost build-up during the production cycle

After carefully considering these five main cost drivers, we were able to combine them to come up with three indices similar to the D1, D2, and D3 indices of Ishii, but with more detail and information. For these three new indices, the degree of variation is subsumed into the degree of commonality measure, while the differentiation point index includes information on the value added-curves. Hence, our enhanced measures now consist of the following three indices:

CI: Commonality index
DI: Differentiation Point index
SI: Setup Cost index

Our theory is that the different indices are correlated with various indirect costs of providing variety. These indirect costs include items such as inventory holding costs, maintenance of drawings and suppliers, training, learning curve losses, etc. The indices should allow a rough estimation of the indirect costs of providing variety, and thus will help product managers make more informed decisions about how much variety to offer. It will also help engineers understand how to design products and manufacturing systems which will decrease the costs of providing variety.

Table 1 shows some of the costs of providing variety and indicates which indices we feel are correlated with the costs. In the following sections we give a detailed description of these indices.

Table 1. Relation between indices and costs of providing variety

Costs of Providing Variety	CI	DI	SI
LOGISTICS COSTS			
Drawing maintenance	√	√	
Supplier maintenance	√		
Expediting	√		
Documentation	√	√	√
IT system	√	√	
Management	√	√	√
MATERIAL COSTS			
Volume discounts	√		
Material handling	√	√	
LABOR COSTS			
Assembly (setups)	√	√	√
Training		√	√
Learning curve losses	√	√	√
HOLDING COSTS			
Raw mtl, WIP	√	√	√
FGI		√	
Field service inventory	√		
End of life buy	√		

4.1.1 Commonality Index (CI)

In the original indices, the "number of varieties" index was directly measured as the number of varieties at a given process (e.g., the number of different colors at the painting process). We felt that this did not sufficiently capture that there may be different "degrees" of variation and that simply counting the number of varieties is not adequate to accurately measure the cost of that variety. For instance, in the original index, a painting process with three different colors would be equivalent to a sheet-metal forming process which produced three different shapes. The question is, would these two processes be equivalent in the impact they have on manufacturing costs? The answer is probably not. The paint process may simply require the purging of the paint gun before switching over to a new color, while the sheet metal process may require time-consuming die switchovers, extra training due to complexities associated with the different shapes, etc. Thus, some method is needed to account for the degree of variation within the process. This is important because it will account for the fact that adding a fourth color may be much cheaper than adding a fourth shape.

In developing a measure for the degree of variation, it became evident that the setup cost index captures part of this. It is tautological, but a high setup cost implies a high degree of variation between the products. However, the setup cost index does not capture all the cost factors. The raw material or sub-assembly inventory holding costs, the logistics in handling various parts, the loss of learning curve effects, etc., are all costs which may vary based on the degree of variation between the different varieties. Another index needs to be used to account for this factor.

We propose the use of what is sometimes called a commonality index (Collier 1981). This is a measure of the percentage of parts that are reused for other product models on that manufacturing line. This index accounts for the utilization of standardized parts and is shown below:

$$CI = \frac{u}{\sum_{j=1}^{v_n} p_j} \qquad (2)$$

$$0 < \mathrm{CI} \leq 1$$

u = # unique part numbers
p_j = # parts in model j
v_n = final # of varieties offered

A lower index number indicates a high degree of standardization. For instance, assume that you had five variants of a refrigerator door, with each variant using ten parts, then the denominator would be fifty (5 x 10). If there were no two parts alike (i.e., there were fifty unique parts), then the CI for the door line would be one (1), which is the "worst" commonality index possible. If on the other hand you only required 25 unique parts to build these five different doors, then the commonality index would be 0.5, indicating a higher degree of standardization.

4.1.2 Differentiation Point Index (DI)

All other things being equal, one wants the differentiation point for a variety to be placed later in the process flow. This will decrease the size of the safety inventory required early in the flow. Any measure that is used should account for the placement of the differentiation point. One possible index (DI) is:

$$DI_1 = \frac{\sum_{i=1}^{n} v_i}{n v_n} \qquad (3)$$

$$0 < DI_1 \leq 1$$

v_i = # of different products exiting process i
n = # of processes
v_n = final # of varieties offered

The denominator normalizes the index between 0 and 1. A lower index indicates that differentiation is occurring later.

DI_1, however, does not account for the time it takes the products to flow through the system. For instance, even if the product is differentiated at the second to last process, if the throughput time between that process and the last process is large compared to the overall throughput time, then there is a much larger effect on costs than the DI_1 measure will show. To account for this, a proposed measure is to weight the DI_1 factor by the throughput time (TPT) from process i to the sale of the product. This is shown below in DI_2.

$$DI_2 = \frac{\sum_{i=1}^{n} d_i v_i}{n d_1 v_n} \qquad (4)$$

$$0 < DI_2 \leq 1$$

d_i = average throughput time from process i to sale
d_1 = average throughput time from beginning of production to sale

However, there is one last factor that must be incorporated into the measure, and that involves the value-added amount that is being "carried". If much value is added early on in the process flow, then early differentiation is going to have a larger negative impact than if most of the value is added towards the end of the process flow. This is incorporated in the following index (DI_3):

$$DI_3 = \frac{\sum_{i=1}^{n} d_i v_i a_i}{n d_1 v_n \sum_{i=1}^{n} a_i} \qquad (5)$$

$$0 < DI_3 \leq 1$$

a_i = value added at process i

DI_3 becomes the index that we use for our model. The denominator indicates the worst possible case, which is where all of the varieties (n) are determined in the first process and all of the costs are incorporated at that point. The numerator reflects to what extent the product structure has moved away from this worst case situation. The lower the number the better. Thus, as DI_3 approaches zero, costs associated with this index (WIP inventory, documentation for the various assembly instructions, etc. -- see Table 1) will decrease.

4.1.3 Setup Cost

This measure is similar to the original measure, D3, but it utilizes estimated setup costs rather than set-up times. It also aggregates all the different setups for the product and normalizes it with the expected total direct costs of the all the products being offered. The index measures the percentage cost contribution of setups to the total costs for the products.

$$SI = \frac{\sum_{i=1}^{n} v_i c_i}{\sum_{j=1}^{v_n} C_j} \qquad (6)$$

$$0 \leq SI \leq 1$$

v_i = # of different products exiting process i
c_i = cost of set-up at process i
C_j = total cost (material, labor, and overhead) of jth product

One concern about this index is that the costs of a setup is non-linear. For instance, if there is excess capacity in the factory, including labor, the true cost of a new setup might be considered zero. Thus, this index is dependent on the utilization rates in the factory for both machines and labor. For our current model, this complexity will not be incorporated.

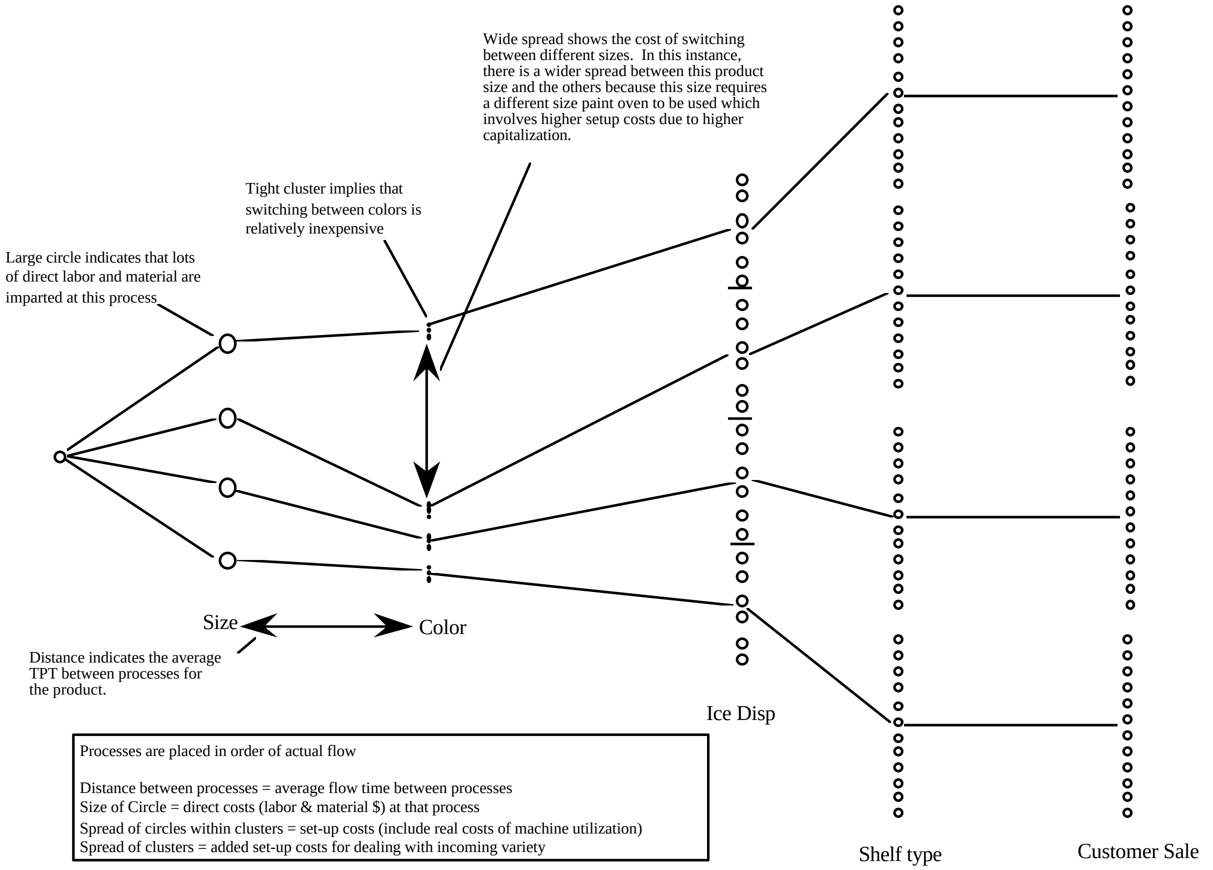
4.2 Cost of Providing Variety

Determination of the variety effects on the cost requires a method to aggregate the various descriptive indices. One can consider the aggregate as a regression of the dependent variable of costs against the indices:

$$\Psi = b_0 + b_1\mathrm{CI} + b_2\mathrm{DI} + b_3\mathrm{SI} \qquad (7)$$

Ψ = indirect costs of providing variety
b_0, b_1, b_2, b_3 = regression coefficients

Direct costs related to providing variety (such as material, labor, and designing costs) are relatively straightforward to determine. It is the indirect costs that our index is trying to capture. The idea is that the regression equation above should give us a method for estimating many of these costs. The equation above might have different coefficients based on the industry, capacity utilization of the factory, etc. Part of our



Wide spread shows the cost of switching between different sizes. In this instance, there is a wider spread between this product size and the others because this size requires a different size paint oven to be used which involves higher setup costs due to higher capitalization.

Tight cluster implies that switching between colors is relatively inexpensive

Large circle indicates that lots of direct labor and material are imparted at this process

Distance indicates the average TPT between processes for the product.

Processes are placed in order of actual flow

Distance between processes = average flow time between processes
Size of Circle = direct costs (labor & material $) at that process
Spread of circles within clusters = set-up costs (include real costs of machine utilization)
Spread of clusters = added set-up costs for dealing with incoming variety

Figure 4. Graphical Representation of Variety

contribution is to determine if this equation will be valid and at what level we might be able to generalize it.

The variety cost index is a method of "allocating" (e.g., estimating) indirect costs for a planned product. In that sense, it is analogous to an activity-based costing (ABC) system. If a company has a well-developed ABC system, will they need the Index? The answer is -- it depends. The ABC system would have to be well developed to account for such items as supply chain costs and post-sales service costs. In a "perfect" ABC system, our index would not be needed, but very few companies have comprehensive ABC systems. For most companies, our index could be used to help estimate the indirect costs for providing variety.

4.3 Graphical Representation of Variety and Complexity

Schematic representations are often useful in communicating simply and clearly the basic information of a system. Quality Function Deployment (Clausing 1991) and KJ diagrams (Shiba et al. 1993) utilize graphical techniques to enhance the decision making process. Such a tool could be useful for variety discussions between marketing, product design and manufacturing.

The proposed graphical tool is a refinement of the original product structure graph (seen in Figure 1). Where there is a variation introduced into the product, a branch is sprouted. The new graph (see Figure 4) should quickly communicate to the product design team how their product offerings fare with respect to the costs of providing variety. Such a visual aid can help in design review meetings where marketing, product design, and manufacturing negotiate what varieties to offer.

The new product structure graph gives a visual indication of the cost drivers of providing variety. The process flow is shown from the left to right with variations in the product shown in the branches. In addition, the graph shows the following information:

- average estimated flow time between the processes
- setup costs at each process
- the amount of value-added material and labor at each process

The graph indicates the estimated flow time between processes as the horizontal distance on the graph. For this, designers use an educated guess of the average throughput time between successive processes. The setup costs will be the estimates of the costs involved in switching from one variation to another within a process. The graph shows these setup costs in the vertical separation between the circles. Finally, the value-added amount for each process is indicated by the size of the circle.

This representation graphically shows how the costs of providing variety can be reduced.

1) Differentiate as late as possible, indicated by the branching occurring far to the right
2) Shorten the time between the processes, seen as a horizontally shorter graph.
3) Reduce set-up costs, indicated by a tight vertical clustering of circles.
4) Delay the addition of value to the product to later in the process flow, indicated by the largest circles being to the right.

A visual representation of the product can quickly show the team where variety can be added inexpensively, and where adding it could be expensive. Using such a representation in initial meetings can help the team in deciding what variety to offer and help determine where the company should spend their resources in trying to reduce the costs of variety.

5. VALIDATION PLAN

As with other design methods and tools, the true validation is in the competitiveness enhancement attributable to the deployment of the tool. Thus, the essential ingredient of our validation plan is to team with industry to work on commercial examples. For the tools that we have proposed in the previous section, the enhanced product structure graph and the variety cost index, the key questions are as follows.

1) Does the variety cost index reflect the true cost of providing variety?
2) Can design teams easily create the product structure graph?
3) Do the graph and index aid managers and designers in managing variety more efficiently?

Of these questions, the most critical and challenging is the first -- how do we validate the cost index? We intend to use direct collaboration with companies and graduate student projects to achieve this goal.

ME217, Stanford’s design for manufacturability curriculum, provides a rich opportunity for validating various simultaneous engineering methods and tools. Student teams work on industry provided problems related to product competitiveness over a six month period. The last several years have seen an increase in projects that address manufacturability of product families and management of product line structure. As part of this effort, the students will gather cost information (often in normalized form) and attempt to improve the design for reduced cost of variety. For 1996, a domestic electronic instruments' manufacturer and hard disk supplier have defined design for variety projects for the students. These projects will help us calibrate the variety cost index with the actual cost of variety.

More rigorous validation will come from our direct collaboration with industry. We are scheduling workshops in which engineers from industry will use our DFV methodology and compare the variety cost index with actual cost data. The most promising validation method is for industry to provide information on product design and manufacturing specifications with associated cost data, and we will gauge the actual costs against the calculated indices. Participating companies include a domestic commercial aircraft manufacturer, a Japanese automobile component supplier, a telecommunications company, and a semiconductor fabrication equipment manufacturer. Through this effort, we intend to validate monotonicity between our index and the actual cost, and further develop a procedure to calibrate the tool for different product types and individual companies. Our experience with other DFx tools gives us confidence in validating and enhancing this important method of design for variety.

6. CONCLUSION

Over the past few years, two issues have become mantras for corporations throughout the world: “mass customization” and “meeting or exceeding the customer's needs”. Companies have rushed to offer a range of products that covered almost every configuration their target market might want. However, as the number of products being offered by companies grew larger, it became evident that the cost estimates used to determine the profitability of these new product offerings did not fully account for all the costs associated with providing this variety. Increased inventories above what was expected, additional setups, and the complexity of managing the increased variety were not always included in the original cost estimates, and the expected profits did not follow because of these factors. These additional cost drivers were not included because of the difficulty in estimating their effects.

The design for variety (DFV) methodology is a basic procedure for helping managers and engineers understand the true costs of introducing variety into their product line. Through the use of indices that are relatively easy to measure or estimate, we plan on giving the managers a tool to help them make informed decisions about variety.

Over the next few months, we will apply the DFV methodology to a number of industry sponsored projects. Utilizing these projects we will determine appropriate regression coefficients for our DFV index, and analyze the validity of the methodology.

ACKNOWLEDGMENTS

The sponsors of this research include the National Science Foundation and the Stanford Integrated Manufacturing Association. The authors would like to thank Kyle Cattani, Dakai Chen, and Warren Hausman who are our partners in this project in Stanford’s Department of Industrial Engineering and Engineering Management. We would also like to thank our industrial collaborators at GE, Hewlett-Packard, Boeing, Nippondenso, and Matsushita.

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REV 1 - 4/16/96: corrected format errors and changed <= to <