ELEMENTS OF DESIGNING FOR COST

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Abstract

During recent history in the United States, government systems development has been performance driven. As a result, systems within a class have experienced exponentially increasing cost over time in fixed year dollars. Moreover, little emphasis has been placed on reducing cost. This paper defines designing for cost and presents several tools which, if used in the engineering process, offer the promise of reducing cost. Although other potential tools exist for designing for cost, this paper focuses on rules of thumb, quality function deployment, Taguchi methods, concurrent engineering, and activity based costing. Each of these tools has been demonstrated to reduce cost if used within the engineering process.

Background

For at least the last fifty years, the cost of systems has been driven by performance to ever increasing cost levels - after inflation has been removed. This phenomena was first noted by Augustine[2] and has been well documented by Webb[20]. Figure 1 illustrates this phenomenon.

As a consequence of this trend, Augustine[3] notes that

> In the year 2054, the entire defense budget will purchase just one aircraft. This aircraft will have to be shared by the Air Force and Navy 3 1/2 days per week except for leap year, when it will be made available to the Marines for the extra day.

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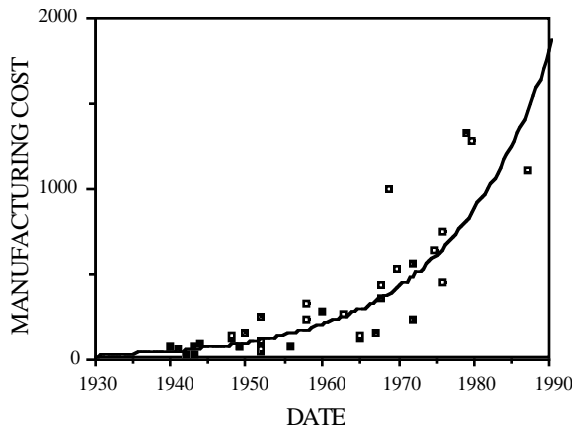**Assistant Professor, Engineering Management

Figure 1
Performance Driven Cost Trend

Yes, we have been obtaining more performance per dollar. Unfortunately, we can no longer afford it. The percentage of Japanese cars on the highway attests to the fact that in many areas we, as a country, are no longer competitive in the world market. Will aerospace be next? The MIT Commission on Industrial Productivity[10] has examined effects and postulated causes of our increasing national uncompetitiveness.

Designing for cost is a necessity if the United States is to retain, and hopefully to increase, our competitive edge in the aerospace industry - one of our last viable national bastions of world class competition.

Designing for Cost versus Design to Cost

Designing for cost has two dimensions, attitude and implementation. Attitude relates to the environment which fosters consideration of cost in the design process. Implementation is the set of processes by which cost is used as a design parameter.

Designing for cost[8] is not design to cost[14]. Designing for cost is the conscious use of engineering process technology to reduce life cycle cost. Design to cost is the iterative redesign of a project until the content of the project meets a given budget. Designing for cost seeks to increase system performance while reducing cost. Design to cost usually reduces performance until the budget is met. Designing for cost seeks to reduce cost as far as possible while meeting customer demands. Design to cost reduces the degree by which customer demands are satisfied until an often arbitrary cost bogey is met. Designing for cost is an engineering driven process. Design to cost is a management driven process. Designing for cost seeks to design the product once and only once. Design to cost is iterative by nature and hence incurs redesign and rework cost. Designing for cost seeks to minimize the life cycle cost to the customer by designing high quality into the product. Design to cost attempts in vain to attain product quality by inspecting quality into the product.

Designing for cost requires designing both the product and the product delivery process for simplicity. Complexity, the opposite of simplicity, increases cost. Designing for cost is thus an integral component of the engineering process. Design to cost is focused on cost and management and only incidentally on the engineering process. Low cost cannot be managed into a product; it must be engineered into a product.

Designing for cost is the orientation of the engineering process to reduce life cycle cost while satisfying, and hopefully exceeding, customer demands.

<u>The Tool Kit</u>

A number of tools for designing for cost are known. They work! However, most are yet to be discovered. The field is embryonic. The reader is encouraged to help mature the field by adding to the sample of components of the tool kit highlighted by this paper.

Rules of thumb are an important aspect of designing for cost. Unfortunately, rules of thumb are often not based upon historical evidence. This places those rules of thumb into the class of art. Those which can be placed in the class of science have survived the test by evidence. The scientific rules of thumb can be classified as either complete or incomplete. Unfortunately, we can never be certain that a rule of thumb is complete since we can never prove that all factors have been identified and appropriately incorporated. We can, however, hypothesize that a rule of thumb is complete and use

it as such if it has repeatedly been observed to be the case.

Total Quality Management[7] (TQM) is both an attitude[9] and a tool set[12,17]. By empowering people to do their job, they are permitted to create, innovate, and improve the system for delivering the product. This environment draws out the best in workers and provides job enrichment. It also drives decisions down to the level at which they are made with greatest understanding. Although attitude is necessary for greater productivity, it is not sufficient. Tools in the form of processes are also required. Quality Function Deployment[12] (QFD) is a highly structured system engineering process which ranks project activities in terms of customer value. It derives requirements[11], ranks them in terms of customer values, and provides the framework for tracking them - even in a changing customer environment. It also identifies key system parameters which should be optimized using the Taguchi method for parameter design[16]. Both QFD and the Taguchi method are powerful tools from the TQM tool kit.

Concurrent Engineering[23] (CE) is also a combination of attitude and tools. CE is simply getting the right people with the right skills together at the appropriate times within the life cycle to ensure that all the necessary product issues are addressed and resolved. This not to widely used concept has been recognized for many years. Wiener[22] states

> a proper exploration ... could only be made by a team of scientists, each a specialist in his own field but each possessing a thoroughly sound and trained acquaintance with the fields of his neighbors; all in the habit of working together, of knowing one another's intellectual customs, and of recognizing the significance of a colleague's new suggestion before it has taken on a full formal expression. ... We had dreamed for years of an institution of independent scientists, working together ... not as subordinates of some great executive officer, but joined by the desire, indeed the spiritual necessity, to understand the region as a whole, and to lend one another the strength of that understanding.

The final topic to be highlighted in this paper addresses the need for accurate cost data - the necessary foundation of designing for cost. Webster[21] states

> Another - and perhaps more important - reason for the lack of cost consciousness in design is the limited access that designers have to cost information. The management of many companies treats cost as information that is too sensitive to provide to working-level design engineers. It is, therefore, not surprising that the design process has become an inefficient, iterative operation in which attempts are made by management to control costs and optimize cross-functional trade-offs subsequent to the engineering design phase. Engineers must understand the importance of cost as a relevant design factor if projects are to be designed on schedule, within budget, and according to performance and quality expectations. This cannot occur, however, until management fosters the use of cost as a design variable and provides access to needed cost data.

Activity-based cost (ABC) has been developed by accountants in the manufacturing industry to correct previous accounting practices which grossly distort product costs. Cooper[6] states

> Instead of focusing on units produced, activity-based cost systems focus on activities performed to produce products in the manufacturing process. Costs are traced to activities and then to products based on each product's consumption of activities.

Rules of Thumb

Although there are many valid rules of thumb, this paper will only focus on one as an example. A set of rules can be derived from the PRICE H[1] structural manufacturing complexity generator equation[13]

$$Mx = \frac{4.3 \; PLTFM^{0.32} NP^{0.04}(1+(0.06(N-MATUR)))}{1.35 \; PRECI^{0.081} \; MI^{0.024}}$$

where Mx is the manufacturing complexity, PLTFM is the specification or platform level, NP is the number of parts, N is a table which is a function of platform level, MATUR is the maturity level of integration, PRECI is the machining precision, and MI is the Batelle machinability index. Noting that first unit cost is exponential in Mx, analysis of this equation leads to the rules of thumb that to reduce cost one needs to reduce part count, relax assembly tolerance requirements, relax component machining tolerances, use more machinable materials, relax surface finish requirements, and use near net shape raw stock to minimize machining. These rules of thumb equate to keeping the design simple.

If your organization has kept sufficiently accurate and appropriate data, similar scientific rules of thumb can be derived from that data by statistical techniques[4].

Quality Function Deployment as Modified for Large Systems

In QFD, customer desires are given value which is mapped onto many dimensions. This process is illustrated in Figure 2. Customer desires on the z-axis are related to both system functions on the x-axis and quality characteristics (attributes) on the y-axis. For large systems, the authors have found it is easier to relate the customer desires to system functions first and then use the system functions to derive the quality characteristics. The customer desires and the functions are independently identified by a group using the affinity diagram and tree diagram tools[12]. The group, led by a facilitator, must contain the skills and experience required to define valid customer desires and system functions. Concurrent engineering is thus a tool of QFD.

Having identified the customer desires, the customer desires are then weighted and ranked by the group. Then each function is correlated by the group to each customer desire. A value of 0 represents no correlation, a value of 1 represents a weak correlation, a value of 3 represents a moderate correlation, and a value of 9 represents a strong correlation. The value of each function becomes the inner product of the customer desire value vector and the column vector of correlation values associated with that function. The functions are then ranked. A value threshold may be used to focus attention only on the most important functions as defined by the transformed customer value. As definition of the product becomes more refined, the threshold will be reduced to incorporate the functions with less customer value.

Quality characteristics can be defined by asking how each function can be measured to ensure that the customer will get what they desire. At the top levels of a large system, quality characteristics may be sets of attributes which can only be defined at lower levels. The definition process should be driven down until functions are associated with individually measurable attributes. At this level, requirements can be defined. The quality characteristics are then correlated to customer desires and ranked by a transformation as were the functions. Thus each quality characteristic has a transformed customer value.
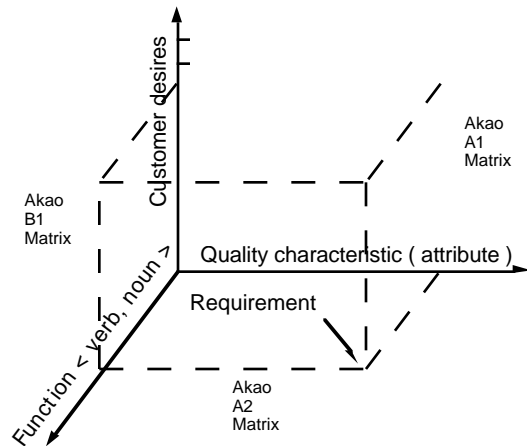

Figure 2
Functions and Quality Characteristics

Following Gause and Weinberg[11], a requirement is of the form <function, attribute, value range> where a function is stated as <verb, noun>. Regrouping by defining a requirement variable as <function, attribute>, we have the requirement <requirement variable, value range>. Equating quality characteristics and attributes, the xy-plane defines the requirement variables. Each requirement variable has a transformed customer value which is the product of the function value, the quality characteristic value, and the correlation value supplied by a group evaluation of each function against each quality characteristic. The requirements can then be ranked and thresholded in terms of customer value. They also provide variables for optimization using the Taguchi method.

The requirements allocation process consists of allocating functions to be performed by subsystems and associating the quality characteristics with the subsystems. This is shown in Figure 3.
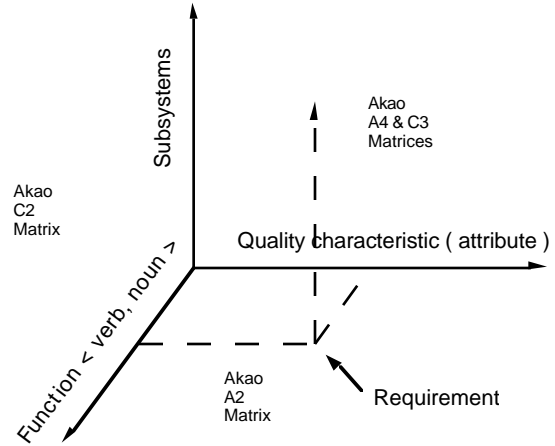

Figure 3
Allocation of Requirements to Subsystems

QFD contains many other dimensions. Two additional dimensions of importance link directly to customer desires. Both new concepts and failure modes are correlated to customer desires and thus take on transformed customer values.

QFD is an intensive thought process, a system engineering process, and a project management wiring diagram. With a history of between 30% and 70% reduction in cost and schedule for successful projects which use QFD as one of their tools, QFD should be considered an important design for cost tool.

Taguchi Methods

The Taguchi method is one step of an optimization process. Its power comes from the ability to use the method in an experimental environment. One does not need to know a set of equations to perform the optimization. By using orthogonal arrays[18] from the design of experiments[15], orthogonal array based simulation (Figure 4) can determine the values for a set of parameters which provide the best results as defined by the experimenter. By optimizing the signal to noise ratio, where noise includes uncontrollable factors, the system becomes robust to uncontrollable perturbations. This also reduces variation which often permits the use of lower cost components.

In an orthogonal array based simulation, controllable and environmental noise parameters are permitted to have a finite number of levels. In Figure 4, three parameters have 3 levels each. Under conditions of linearity, use of the orthogonal array permits the 3^4 = 81 combinations of controllable parameters to be reduced to 9 experiments. The 2^4 = 16 combinations of environmental noise parameters are reduced to 4 experiments. Thus 36 experiments cover all 1296 possible combinations of parameters.

The experimentation efficiency of the Taguchi method permits an engineer to consider simultaneously the effect of a number of parameters during design. This can improve performance considerably with a small effort. Bush and Unal[5] illustrate this in the design of an aerobrake. Unal and Dean[19] illustrate that the Taguchi method can also be used directly to reduce cost.

Noise Orthogonal Array

	1	2	3	4
N1	1	1	2	2
N2	1	2	1	2
N3	1	2	2	1

Control Orthogonal Array

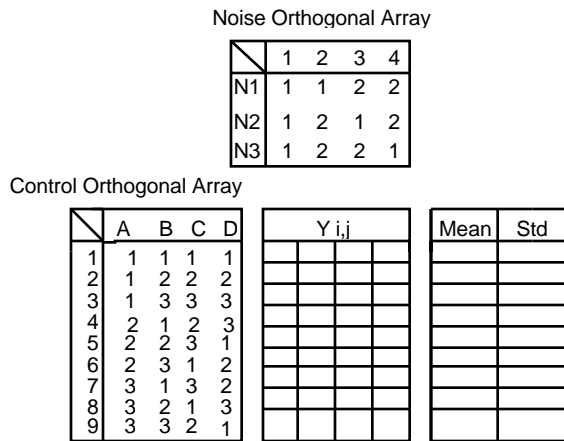|	A	B	C	D	Y i,j			Mean	Std
1	1	1	1	1					
2	1	2	2	2					
3	1	3	3	3					
4	2	1	2	3					
5	2	2	3	1					
6	2	3	1	2					
7	3	1	3	2					
8	3	2	1	3					
9	3	3	2	1					

Figure 4
Orthogonal Array Based Simulation

In general, the Taguchi method relates cost and quality through the quality loss function, is an efficient form of parameter design, is one step of an optimization algorithm which can be performed experimentally, obtains large amounts of design information with a small effort, and can be used to make the system robust to perturbations which can reduce component cost. The Japanese currently claim that 80% of their quality gains come as a result of using the Taguchi method.

Concurrent Engineering

Concurrent engineering is getting the right people together at the right time to identify and resolve design problems. Concurrent engineering is designing for assembly, availability, cost, customer satisfaction, maintainability, manageability, manufacturability, operability, performance, quality,

risk, safety, schedule, social acceptability, and all other attributes of the product.
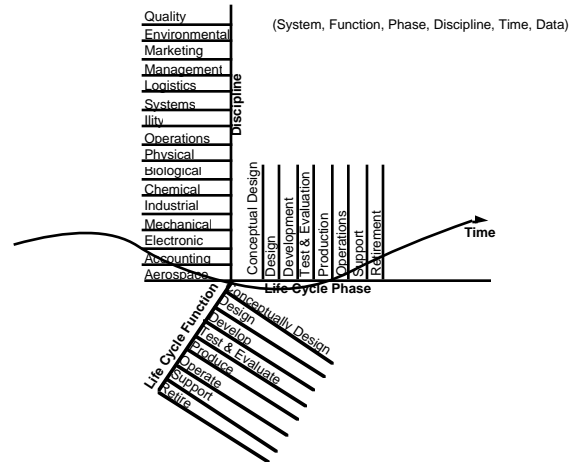

Figure 5
Concurrent Engineering Dimensionality

Figure 5 makes explicit the need to perform each project function for each phase with the appropriate perspectives supplied by various disciplines. For example, the product delivery process should explicitly conceptually design the conceptual design phase, the design phase, the development phase, the test and evaluation phase, and so on. This means that the product delivery team must have experienced perspectives of all phases from all appropriate disciplines at any give time during the product delivery process. That represents a lot of people. It becomes obvious for the sake of efficiency that individuals on the product delivery team should be as interdisciplinary as possible. Generalists with a broad communications base - as opposed to specialists - are the key personnel for the product delivery team.

Activity Based Costing

Not only should the project or life cycle functions be explicitly performed, but also the cost of each of these phases should be gathered for analytical purposes.

The prevalent current attitude within the engineering community is that it costs too much to collect that data. Quite the contrary, the expense to collect the cost data can easily be paid for from the understanding gained of the real causes of cost. Industries which must compete in the world market are realizing that they must have an undistorted view of the cost of each product. Because of large capital investments and overhead functions, direct labor is no longer an appropriate allocation basis for all other costs. It is easy to demonstrate that the direct labor allocation process can completely mask the real cost of a product and create management decisions which

result in greatly decreased profitability when they were intended to increase profitability[21].
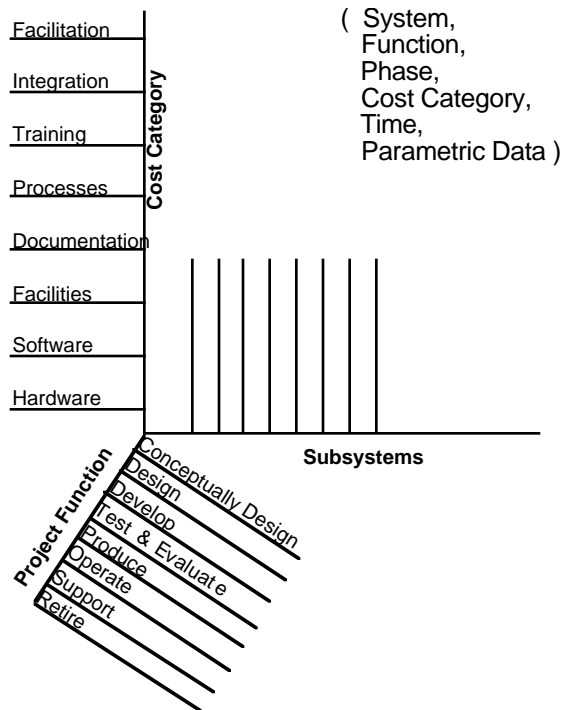

Figure 6
Activity Based Cost Dimensionality

The key to understanding cost, and hence to reducing cost, is the ability to measure cost accurately and to allocate it appropriately to products. Only then can intelligent decisions be made concerning cost. Activity based costing is an effective attempt to move in that direction.

<u>Conclusions</u>

Our research indicates that there are tools by which we can effectively and efficiently design for reduced cost while satisfying, and possibly even exceeding, customer desires. The primary deterrents to designing for cost include a "who cares" attitude toward cost, a lack of cost understanding within the product delivery community, and a lack of knowledge within the product delivery community of tools that can be used to design for cost. A primary need in our country, if it is going to regain the competitive edge, is for management with the vision to lead in designing for cost. Tools are available! Where are the users?

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