“The Virtual Integrated Design Method.”

by

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Abstract

Quality Function Deployment proposes to take into account the "voice of the customer," through a list of customer needs, which are (qualitatively) mapped to technical requirements in House 1. But customers do not perceive products in this space, nor do not make purchase decisions in this space. Marketing specialists use statistical models to map between a simpler space of customer perceptions and the long and detailed list of needs. For automobiles, for example, the main axis's in perceptual space might be categories such as luxury, performance, sport, and utility. A product's position on these few axes determines the detailed customer requirements consistent with the automobiles position such as interior volume, gauges and accessories, seating type, fuel economy, door height, horsepower, interior noise level, seating capacity, paint colors, trim, and so forth. Statistical models such as factor analysis and principal components analysis are used to describe the mapping between these spaces, which we call House 0. Furthermore, utility functions used to determine market share are auxiliary functions that are often based in perceptual space. Conjoint analysis is often used to capture the product preference and potential market share. This research draws from the formal mapping concepts developed by Nam Suh and the qualitative maps of Quality Function Deployment, to present unified information and mapping paradigm for concurrent product/process design. We call this approach the Virtual Integrated Design Method that is tested upon data from a business design problem.

The Virtual Integrated Design Method

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INTRODUCTION

Communication between the functional areas of business is essential for new product success, but can be difficult in a lean organization because time and personnel resources are limited. International competition, short product model life, and rapidly changing customer expectations are moving firms to be more responsive, even as they become lean organizations. The need for communications between marketing and engineering is especially acute because customer needs must be linked to engineering specifications in order to design a successful product. As a general rule marketing and engineering do not always communicate and the result is that "the voice of the customer" in product design is lost. Without a means to transfer knowledge, expertise cannot be combined across all the functional areas and the firm's ability to develop and produce successful products suffers. The failure of engineering and marketing to communicate increases the chances of a product launch disaster. In a study of marketing and engineering managers, Griffin and Hauser found that product development programs with more integration between marketing and engineering had a greater success rate than product development programs with less integration. The more successful firms (profitable firms) worked on marketing and engineering tasks together (1).

Two methodologies have been used in an attempt to formalize the relationship between the different design domains. One is descriptive the other is prescriptive. The first method, Quality Function Deployment (QFD), is descriptive and qualitative (2). QFD assists product designers to explicitly identify customer requirements, relate them to objective engineering characteristics, identify tradeoffs, and evaluate the characteristics of a potential product relative to competing products. The QFD methodology that we discuss here uses a four house approach to product design.

The second method is Suh's Axiomatic Design (3,4). Axiomatic Design identifies mathematical dependencies linking product function to customer needs, product form to product function, and manufacturing process to product form. The dependencies are modeled quantitatively as linear functions. Because the mappings are linear and one-way (customer requirements => functional requirements => functional form => manufacturing processes), the Axiomatic Design process places restrictions on both the design form and the design process. Essentially, the customer requirements, functional requirements, and form drive the linear process. If the product design process does not allow this mapping, the process must be changed to follow the Axiomatic Design approach. This may not be feasible in practice and may be cost prohibitive.

In the next sections, we describe these two methodologies in more detail. Then we describe an enhanced QFD methodology that overcomes the limitations of both QFD and Suh's Axiomatic Design. Next, a case study application of a portion of the new methodology is presented. The final section provides an assessment of the enhanced QFD method and identifies remaining issues in implementation.

EXISTING DESIGN METHODOLOGIES

Quality Function Deployment / Four House Approach

Quality Function Deployment (QFD) is a direct translation of the Japanese term for this design process. The intent is to follow the propagation (deployment) of customer needs (quality) to decisions on the design of the product and its manufacturing process (function). The propagation is represented by a series of qualitative maps between customer needs, product performance requirements, product design, process design, and process control. These maps are represented by matrices, but the relationships in the matrices are qualitative, not quantitative, so there is no assumption of linearity as in Axiomatic Design. These maps are usually called houses, because a roof-shaped grid of variable dependencies is used to augment the qualitative relationships captured in the body of the house (a matrix).

The First House, known as the House of Quality (HOQ), links the customer needs to the technical requirements. Customers rank the customer requirements on a 1-9 importance scale. The design team then uses these customer requirements to select the technical requirements, taking into account any interactions between them.

In a typical situation, the marketing staff collects the data from customers and competing products. Often the HOQ is created with participation from the engineering staff. The design team then decides on a set of performance targets for the subsequent product design. The HOQ is one step in the overall process of QFD. The HOQ links the customer needs to the technical requirements. Such a link is essential to relating product characteristics to customer needs in a way that assists engineers in designing the product. The final task for this First House is to rank and select the target values for the technical requirements, which will be called the technical characteristics.

Next, the technical characteristics are linked to physical attributes--part characteristics or product features. QFD's approach to this task is to use a house diagram again. Technical characteristics such as speed become the rows of this Second House (Part Matrix) while part characteristics such as motor type, rotor diameter, etc., become the columns. Again, the relationship is described qualitatively using symbols similar to those in the First House.

Next, product features, (for example, motor type) become the rows of the Third House (Process Planning Matrix) while manufacturing process design parameters (such as the r.p.m. of the copper armature machine) become the columns. Again, the relationships are qualitative and subjective.

Finally, in House Four, the manufacturing process design parameters become the rows and production requirements (such as process control, operating training, and maintenance) become the columns. These relations can be examined in forward and reverse directions, but, again, they are subjective and qualitative.

There are at least five specific problems with this process (6):

1. Targets that are set based on the information contained in the HOQ alone are unrealistic. Using only customer and competitor information to set targets can result

in targets that can never be achieved in practice, leading to time-consuming iterations until an achievable specification is reached.

2 The manner of describing the *coupling* between the design variables in the HOQ does not adequately reflect the tradeoffs that must be made in a real design problem and can lead to highly inappropriate and undesirable designs. The roof of the HOQ cannot represent the complex coupling between the technical requirements because it requires the classification of the coupling into one or two categories (positive or negative). In reality, the design variables may be coupled differently with respect to different design variables and, hence, using a binary classification is usually an oversimplification.

3. The subjective ranking of customer requirements, technical requirements (1-9), and measures of performance are misleading and can cause a unending circle of inappropriate, infeasible product designs. Using subjective ratings for customer and technical requirements may not represent the reality of the design problem and can result in targets that can never be achieved in reality.

4. In each House of QFD, the row and column relations are established only qualitatively without any formal methodology. The interrelationship between customer requirements and technical requirements (body of the matrix) is totally subjective and most likely does not reflect the true tradeoffs and interaction in a real design problem.

5. QFD does not consider other product risks such as market share, contribution margin, or potential profit calculations.

Suh’s Axiomatic Design

Suh divides product/process design into four domains as shown in Figure 1 (4). The first is the customer domain where the customer needs are expressed as customer attributes(CA). The second is the functional domain, which has transformed the customer attributes into a set of functional requirements (FR). Once the FRs are chosen they are mapped in the physical domain as a set of design parameters (DP*s*) which together become the product design. Next, a manufacturing process for the product is designed in the process domain that is characterized by process variables (PV).

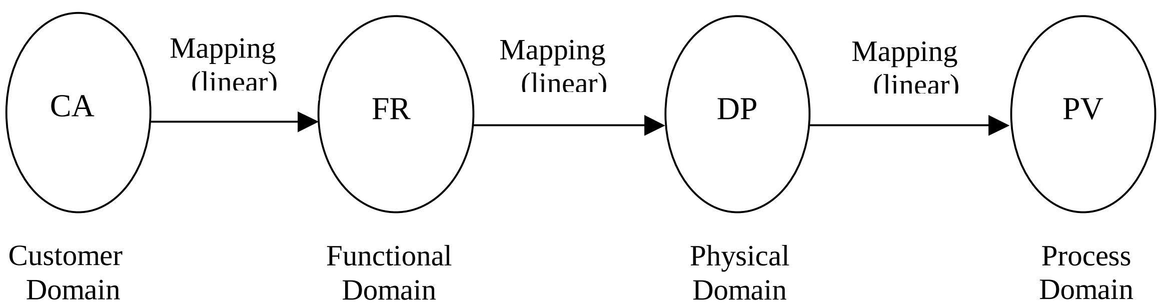

Figure 1. The design spaces of Axiomatic Design (4).

Design Axioms

There are two design axioms: The Independence Axiom and the Information Axiom. They may be stated as follows (3, 4):

The Independence Axiom (Axiom One)	Maintain the independence of the FRs. Axiom One states that during the design process, as we go from the FRs in the functional domain to the DPs in the physical domain, the mapping must show that the design with the minimum information content is the best design.
The Information Axiom (Axiom Two)	Minimize the information content. Axiom two states that among all the designs that satisfy the Independence Axiom (Axiom One), the design with minimum information content is the best design. The term "best" is used in a relative sense, since there are potentially an infinite number of designs that can satisfy a given set of FRs. In an acceptable design, the DPs and the FRs are related in such a way that a specific DP can be adjusted to satisfy its corresponding FR without affecting other functional requirements. Thus, the best design is a functionally uncoupled design that has minimum information content. This relationship may be represented mathematically (equations 1 and 2). Also, the minimum information content (minimum design complexity) of the design is achieved by selecting the design parameters and manufacturing processes that meet the independence axiom most efficiently.

Mathematical Representation

The mapping process between the domains can be expressed mathematically in terms of the characteristic vectors that define the design goals and design solutions. The set of functional requirements (FRs) that define the specific design goals constitute a vector in the functional domain. Similarly, the set of design parameters (DPs) in the physical domain that are the "hows" for the FRs also constitute a vector DP. The relationship between these two vectors can be written as:

$$(\text{FRs}) = [A]\ (\text{DPs}) \tag{1}$$

where [A] is the design matrix that characterizes the product design. For the design of processes involving mapping from the physical domain to the process domain, the design equation may be written as:

$$(\text{DP}) = [B]\ (\text{PV}) \tag{2}$$

where [B] is the design matrix that defines the characteristics of the process design and is similar in form to [A] (3,4). The methodology is linear, and the matrices [A] and [B] are not assumed to be invertible. As a consequence, the design method specifies a sequential process that moves from customer attributes to functional requirements to design parameters to process variables. We say that the method is prescriptive rather than descriptive because it enforces a procedure that differs from current practice--most design processes iterate between these domains rather than progressing unidirectionally through them.

Related Mapping Paradigms

Nearly thirty years ago, Bose developed a new approach to high fidelity speaker design that is evident in his company's products today. To develop a scientific approach to loudspeaker design he investigated the phenomena of audio reproduction by examining the fundamental nature of problems that involve physical devices, physical measurements, and human perception. Bose considered three abstract spaces (Figure 2).

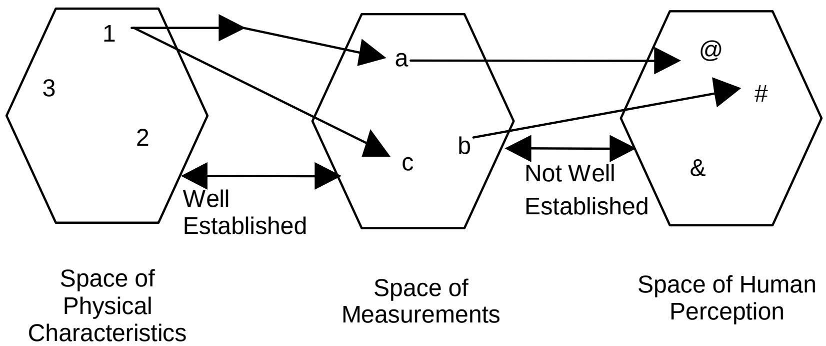

Figure 2. Bose's design spaces (7,8).

The first is the space of physical characteristics. For example, point one might represent the geometry, mass, and stiffness for a particular speaker cone. The second is the space of measurement. Each point in this space represents a specific physical measurement (e.g., frequency response) that can be made on a device such as a speaker from space one. The third space is that of human perception. Points in this space represent different human perceptions of the same music or speech signals passed through different speaker designs. The link between the physical characteristics and the electronic measurements of speaker performance can be predicted to a certain extent by simulation models, but the link between these measurements and the customer perception of the sound quality produced by the speaker is not so well defined.

Nearly ten years later, RCA Laboratories conducted tests to develop statistical models linking the second and third spaces (8). Properties in three different domains were tested for a videodisk playback system: physical factors affecting the stylus-disc interface (physical space), measurements of the signals generated by the player (measurable space), and measurements of consumer perception of the quality of the resulting picture and sound program.

Our research continues the important works of QFD, Suh, Bose, and RCA by linking quantitatively the customer needs to engineering design and process variables. We recognize the need to map forward and backward through the model for it to be useful in a real design environment. We also use ancillary models to predict potential market share, cost, and profit.

A FORMAL MAPPING PARADIGM FOR PRODUCT DESIGN

We propose a methodology that is qualitative and quantitative. The new model is a sequence of design spaces linked by formal mathematical models, extending the work of Bose (7) and Barton et al. (8). Since the output vector of one mathematical model is the input vector to another model, the models can be combined to form an integrated design environment. The new methodology includes empirically-based mathematical models relating the measured properties across different spaces, including statistical models relating consumer preferences to technical measures of product performance and models that identify the key perceptual dimensions. Unlike Axiomatic Design, our approach allows non-linear relationships. In addition, the method permits forward and reverse mapping between the different design spaces, which better describes concurrent engineering design practice.

Product design must address multiple objectives. They include market share, profit, and product reliability. These objectives arise naturally in different spaces--market share can be determined from models using information from perceptual space, profit requires knowledge of information from perceptual space (sales price) and manufacturing space (production and distribution cost), and product reliability can be determined from information from design space (materials and form), technical requirement space (product performance requirements), and perceptual space (expected product use and environment). The computation of these objectives requires *auxiliary functions* or maps that may have inputs from one or more spaces.

Figure 3 describes how the design process can be represented as a set of linked spaces. It contains spaces corresponding to QFD's four houses of quality, plus one additional space, which we call "customer perceptual space." This paradigm is a sequence of spaces linked by formal mathematical models. The five houses of our augmented QFD methodology provide a framework for product design. Each house provides a map or set of maps linking two different views of the product, each view in a different space. An integrated design methodology can be developed if it is possible to develop mathematical representations for each of these maps, as illustrated in Figure 4.

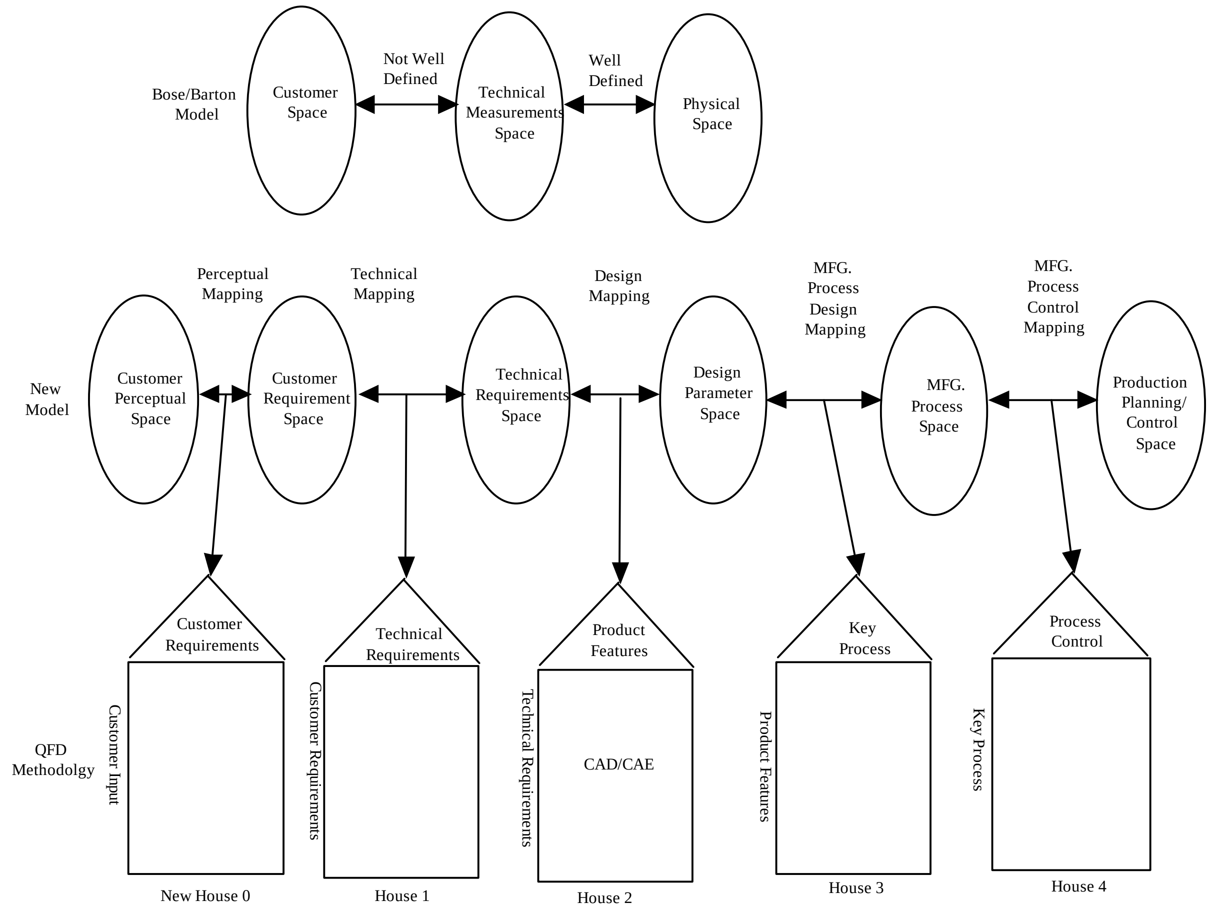

Figure 3. A formal mapping model

(Plus Suh provides mapping between houses 1-3)

Marketing efforts to define a product "position" often manipulate a small set of product characteristics from which detailed customer requirements can be inferred. We call this space *perceptual space.* For automobile design, for example, moving along the *luxury vs. economy* axis in perceptual space has implications for seat quality, interior noise, trunk space, ride quality, and other customer requirements. Generally, perceptual space provides a lower-dimensional space in which strategic decisions about the product features can be made, and in which consumer preference studies can be designed, to construct auxiliary models of expected market share, risk, and sales volume (10, 11).

After the design team identifies the appropriate perceptual space and maps to/from customer requirements, they can identify new product position opportunities using preference models that operate in perceptual space, along with value analysis and cost data from the other houses. These cost and revenue data can be combined to calculate a figure of merit (profit, revenue, market share, etc.).

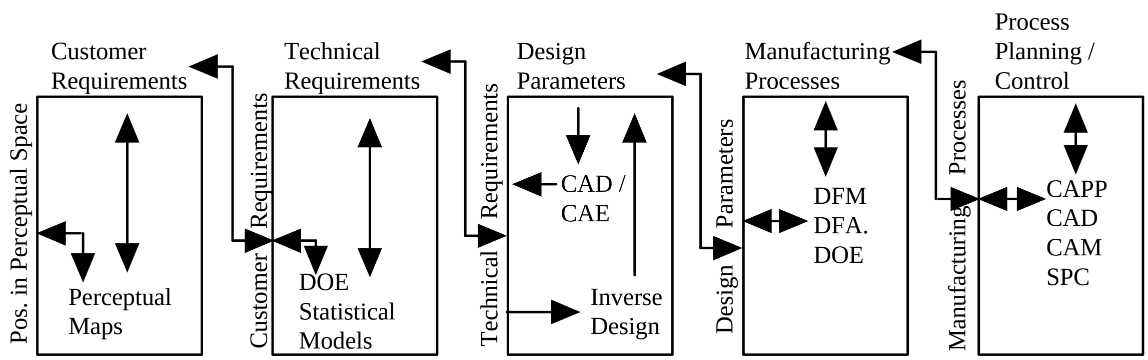

Figure 4. Linking of the five houses of quality (9).

Mapping from Perceptual Space to Customer Requirements Space

Design decisions on product position in perceptual space can be mapped into a customer requirement vector in the customer requirement space. In order to map from perceptual space to customer requirement space, we use the relation

$$X^{\mathrm{T}} = Z^{\mathrm{T}} V^{\mathrm{T}}$$

where X is the customer requirements vector, Z is the product position vector, and V is a matrix of eigenvectors resulting from factor analysis or principal components analysis (9). This is a well-defined mapping from customer perceptual space because the eigenvector matrix V is orthonormal, and $V^{-1} = V^{\mathrm{T}}$ for symmetric orthonormal matrices.

Auxiliary mathematical models and preference measures, both direct ranking (expectancy) and revealed (preference regression), indicate which perceptual dimensions are most important to customers and assist the design team to establish a *target* position for a new product concept.

Mapping from customer requirements space to perceptual space

Target levels in the customer requirements space map to the target levels in the customer perceptual space by using the equation

$$Z^T = X^T V.$$

Thus, the design team can add, delete, or modify requirements in the customer requirements space and then map back to the customer's perceptual space. The reverse mapping may be computed by a projection operation.

Customer Requirements Space vs. Technical Requirements Space

In the customer requirement space, the position vector gives product attribute scores for each customer requirement. From this input vector of customer requirements, the design team determines the technical requirements necessary to meet each customer requirement. The customer needs (dimensions) are linked to engineering characteristics; the technical characteristics of the product provide insight to the design team in setting performance targets without inhibiting creativity. These links have been identified only qualitatively in traditional QFD. Factor analysis, response models based on Design of Experiments, DOE, and conjoint analysis experiments may be used to map from customer requirements to *high level* technical requirements in technical requirements space (where performance is tested) (8, 12). These statistical models will also allow the design team to determine which technical requirements affect key primary perceptual dimensions.

Technical Requirements Space vs. Design Parameter Space

The technical requirements vector in the technical requirements space provides performance targets (metrics) to assist in technical concept testing and candidate product evaluation. This vector must be mapped to the design parameter space, but this mapping is difficult. Recently, however, inverse design techniques have been developed to map from requirements to design parameters (13) and work has been started to develop forward and inverse approximation maps simultaneously (14). In inverse design, technical requirements are given (e.g., lift and drag for air craft wing design) and used to derive design parameter values by applying engineering equations and optimization methods (e.g., values for lift and drag will generate the geometry parameters for the wing). The inverse design methodology gives the design team the ability to map from the technical requirements space back to the design parameter space, a critical capability for customer-driven design that originates in perceptual space.

The reverse map between technical requirements space and the design parameter space is the core of traditional engineering design. An extensive set of specialized mathematical models has been developed in this area. Often, this reverse mapping can be accomplished using a CAD/CAE model (if possible) or engineering equations. Computer assisted engineering (CAE) software typically provides numerical solutions to a set of equations that relate the design variables (physical characteristics) to the performance metrics of the technical requirements used to quantify performance of a product. These models are used to decide whether the designs are feasible, to explore the performance envelope of a design without actually building a physical prototype, and to study the tradeoffs involved in the design.

Design Parameter Space vs. Manufacturing Process Space

Design parameters must be related to the selection of manufacturing materials and processes in order to complete the design and estimate manufacturing costs. Many factors affect the choice of manufacturing techniques; therefore, only the most general of overall guidelines can be specified early in the design of a product. Traditionally, good manufacturing practice has been described in textbooks and in training programs (15). Design for manufacturing (DFM) guidelines have been developed for practically every aspect of manufacture, but they may be broadly divided into four groups --the *general approach* to DFM, the *selection of manufacturing processes*, the *design for particular processes*, and *assembly*. Another recent development also amenable to computer implementation, involves systematically rating a product in terms of manufacturability and then suggesting procedures for improving the rating. This has been applied in particular to design for manufacture (DFM) and design for assembly (DFA) (16, 17, 18). DFA has assumed increasing importance because assembly is so labor intensive--as process costs have decreased because of improved machines and processes so assembly costs as a proportion of the total have increased (15). A recent trend has been to incorporate these guidelines into expert systems for advice on the manufacturability of a design. The design parameter vector must be mapped to the manufacturing process space where the product and component design specifications are related to manufacturing process cost via DFM and DFA tools (16, 17, 18).

The most recent advancement in software for DFA and DFM is Pro/PARTNERS (19, 20) with Bothroyd and Dewhurst. This DFA software provides a tightly integrated layer written in Pro/DEVELOP for generating DFA analysis files. The Pro/ENGINEER link will then use the library to construct future DFA analyses, thereby reducing the steps required to complete the full analysis (19, 20).

Manufacturing Process Space vs. Production Planning and Control Space

After determining the most efficient and cost effective manufacturing processes and generating a process plan, this output vector becomes the input vector to our last space--the production planning and control space. Most existing software programs for mapping between these spaces, including computer-aided process planning (CAPP), material requirement planning (MRP) systems, and enterprise resource planning systems (ERP), do not link strategy to the design function (21).

Statistical processing control (SPC software) by Statistical Analysis Systems (SAS) provides SPC tools for control charts and capability analysis. They are packaged into a point and click environment but do not link strategy to product design (22).

CAPP

In traditional process planning systems the process plan is prepared manually. The task involves interpreting engineering drawings, determining how many cuts should be made or how parts should be assembled, deciding the order in which operations should be executed, and specifying the tools, machines, and fixtures necessary for the production of the finished product. The resulting process plan is, therefore, very much dependent on the skill and judgment of the planner..

The use of computer based decision support systems (CAPP) can reduce the work loads of manufacturing engineers and also help to generate rational, consistent, and optimal plans. An integrated CAD/CAM system can only be developed if there is a system that can utilize both design data from a CAD system and information from manufacturing databases to manufacture the part. CAPP can provide this interface between CAD and CAM (15).

Incorporating Cost and Estimating Costs

The decision to proceed with a new product development project must incorporate costs, benefits, and expenses. It may appear at first that it is difficult to quantify the costs, benefits, and expenses of the various candidate products, but approximation of these dollar metrics in the design phase is important. There are four primary areas to be considered early in new product development decisions concerning cost and benefits:

- *Product Features* determine product performance and set the cost of performance, which is an important determinant of market success. The design team should analyze cost/benefits to help them decide if a new product feature(s) should be added.

- *Product cost* is the total cost of the product over its life cycle. This includes manufacturing, distribution, warranty, and logistical costs.

- *Speed of product development* determines the time to market–from the time the need for the product is realized to the point it is delivered or sold to the customer. This can be critical to the success of the product. It involves all of the company's departments, not just design engineering.

- *Development expenses* are the one-time costs associated with development of the product. Although seldom an overriding concern, these expenses must be justified to upper management early in the design phase.

The goal of identifying and calculating cost cannot be realized by the design engineers alone. Other departments' expertise also needs to be utilized to identify and minimize cost---at the very minimum, purchasing, process planning and, cost engineering (value analysis/value engineering) are also required. It is important to understand that different components of cost are calculated in different spaces. Material costs are calculated using an auxiliary function whose domain is design parameter space. Manufacturing costs are calculated using an auxiliary function in manufacturing process space. Revenue is calculated using pricing and market share auxiliary functions in customer perceptual space.

Selecting Candidate Designs

Ultimately, commercial product designs are based on projected profit. To compute profit, the design team will have to link the process planning and control space to the other four spaces.

Profit and revenue maximization

The design team may perform sensitivity analysis by changing design parameters, recalculating all costs implied by these new design parameters, setting the price (customer input), and then calculating the amount that each candidate product contributes to profit (contribution margin). The next step in the profit analysis is to calculate market share. Our model for market share prediction uses the equation (10):

$$m_n = \frac{\sum_{i=1}^{n} w_i p_{in}}{\sum_{n=1}^{N} \sum_{i=1}^{I} w_i p_{in}} \tag{3}$$

where

I = number of customers in the market study,

N = number of product alternatives for the customer to choose from, including the new product concept,

m_n = market share of product *n*,

w_i = the relative volume of purchases made by customer I with the average volume across all customers indexed to the value 1, and

p_{in} = proportion of purchases that customer *i* makes of product *n* (or equivalently, the probability that customer *i* will choose product *n* on a single occasion).

Confidence interval estimates for market share are discussed by Hsu and Wilcox (11). Finally, this model is based on the notion that each product receives a share of the customer preferences:

$$p_{in} = \frac{q_{in}}{\sum_{n=1}^{N} q_{in}} \qquad (4)$$

where q_{in} is the estimated utility of product *n* to customer *i*(10).

Product design rarely depends solely on profit, at least not on a quantifiable characterization of profit. Other factors such as the development of corporate capabilities, establishment of market presence, etc., are considered (23).

APPLICATION OF THE METHODOLOGY TO THE CONSTRUCTION OF HOUSE ZERO

We applied our model to a case study of the design of a printer/copier scanner for the internet, allowing us to experiment, observe, and learn about the problems encountered in a applied product development project. It provided information and insight concerning the practical implementation of the methodology and its cost effectiveness. Constraints on time, resources, and technology forced us to limit the study to customer perceptual and customer requirements spaces

Figure 5 depicts the company's qualitative map between customer requirements and technical requirements space. House One has 25 customer requirements with 18 technical requirements. Each technical requirement has a performance level (target).

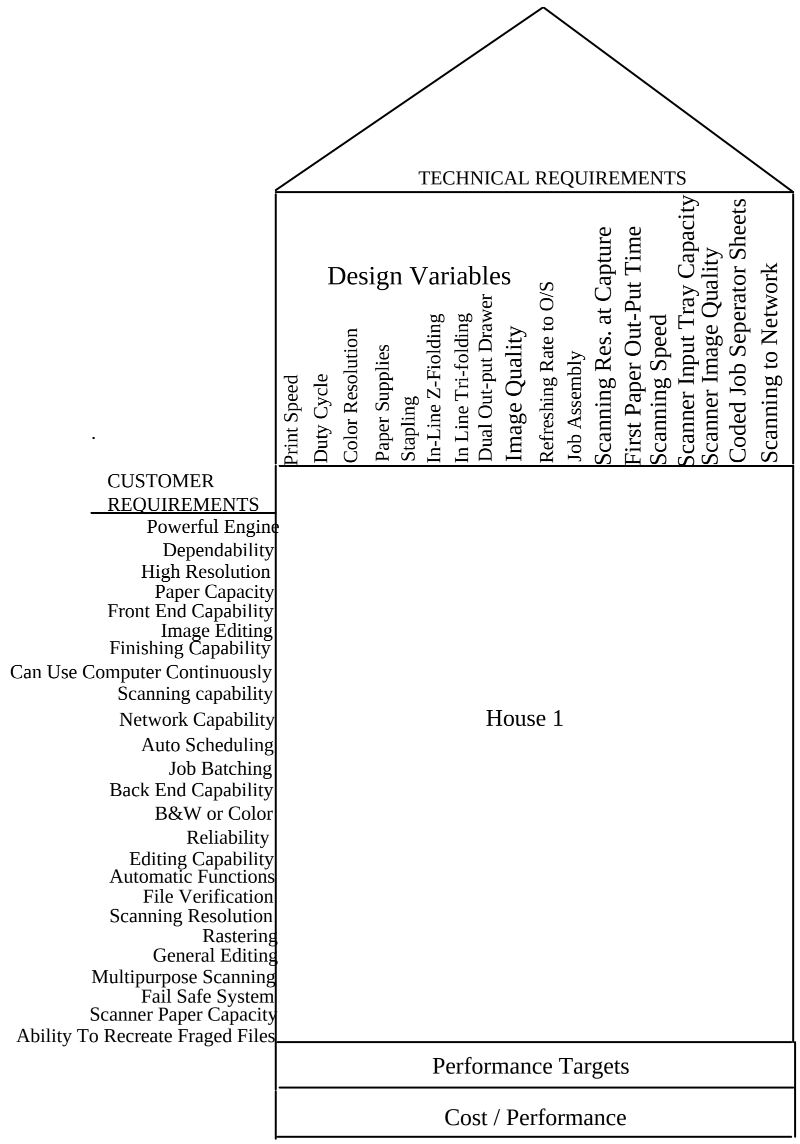

Figure 5. House One for the case study.

Overall Methodology

We used principal component analysis to reduce the dimensions of the original space (25 customer requirements space of House One). The principal components axes were rotated orthogonally to improve the practical interpretability of the solution. Finally, we calculated the factor scores (product positions) for strategic decision-making ($Z = XV$).

House zero statistical analysis and house construction

We calculated the correlation matrix *R* from the standardized product characteristics matrix *X* (ratings of customer requirements, Figure 5). Then the eigenvectors and eigenvalues were extracted. The results are in Table 1. Since the first three factors explained 74.7% of the variation of the standardized product characteristic matrix *X*, we decided to use these three factors for the axes in perceptual space.

Table 1. Principal Component Analysis results.

Extracted Factors	Eigenvalues	% of Variance	Cum. %
F1	15.37	61.5%	61.5%
F2	1.84	7.4%	68.8%
F3	1.46	5.8%	74.7
F4	1.22	4.9%	79.5%

Next, we used the varimax method (24) to improve interpretability of the factors (see Table 2).

Based upon these results, we named the perceptual axes. We called the first axis (factor) *basic performance* as it contained *scan speed, reliability, print speed, copy out-time, stapling* and *resolution at capture* customer needs. The second axis was called *front end functionality,* and contained *scheduling & batch, accounting & billing, saddle stitch, verification, scanning hopper capacity, inserts,* and *dual draws* customer needs. The third factor included *Z-folding, job assembly, scanning,* and *scanning to network* customer needs, which we called *back end functionality* (Table 2). These three new factors were entered into the new House Zero along with the customer requirements (Figure 6).

After the factors were identified and named and the new loading matrix was derived from our orthogonal rotation via the varimax algorithm, we calculated the average product positions of Kodak and Xerox in our reduced customer perceptual space. In the second part of the questionnaire, the customers rated the performance level of Kodak and the perceived performance level (brand perception) of Xerox.

Table 2. Results of orthogonal rotation of factors and naming of the three factors.

	Basic Performance	Front End Functionality Factor	Back End Fuctionality Factor
Scan Speed	0.81789	0.0	0.0
Reliability	0.81132	0.0	0.0
Print Speed	0.78409	0.0	0.0
Out-Time	0.75265	0.0	0.0
Stapling	0.74762	0.0	0.0
Res.at Capture	0.61235	0.0	0.0
Sched.&Batch	0.0*	0.75414	0.0
Acct.&Billing	0.0	0.75351	0.0
Saddle Stich	0.0	0.73430	0.0
Verification	0.0	0.73267	0.0
Scanning Hopper	0.0	0.69569	0.0
Inserts	0.0	0.65236	0.0
Dual Draws	0.0	0.61112	0.0
Trifolding	0.0	0.0	0.86579
Z-Folding	0.0	0.0	0.86554
Job Assembly	0.0	0.0	0.64998
Scanning	0.0	0.0	0.61120
Scan to Network	0.0	0.0	0.60000
Image Quality	0.0	0.0	0.55642
Color	0.0	0.0	0.49366

* Actual values < 0.50

The customers placed brackets to draw the upper and lower bounds of performance for each dimension that they expect any network computer manufacturer to fall within. We used data from the second part of the questionnaire to calculate the product positions in customer perceptual space by using the equation $Z = X V$ where

- Z is the average product position matrix of factor scores based on the weighted sum of 25 customer evaluations of Kodak, Xerox, and the upper and lower parameter level of product performance on the 25 customer requirements (Figure 7);

- X is the new product performance rating matrix where the columns of the X matrix are the product characteristics, and the rows are Kodak, Xerox, and a upper and a lower parameter level of product performance; and

- V is the new factor matrix (Figure 7).

Areas of new product opportunities can be explored by searching for new product positions. We can calculate product position using the equation $Z = XV$ and then map backward to customer requirements space using the equation $X = ZV^{T}$.

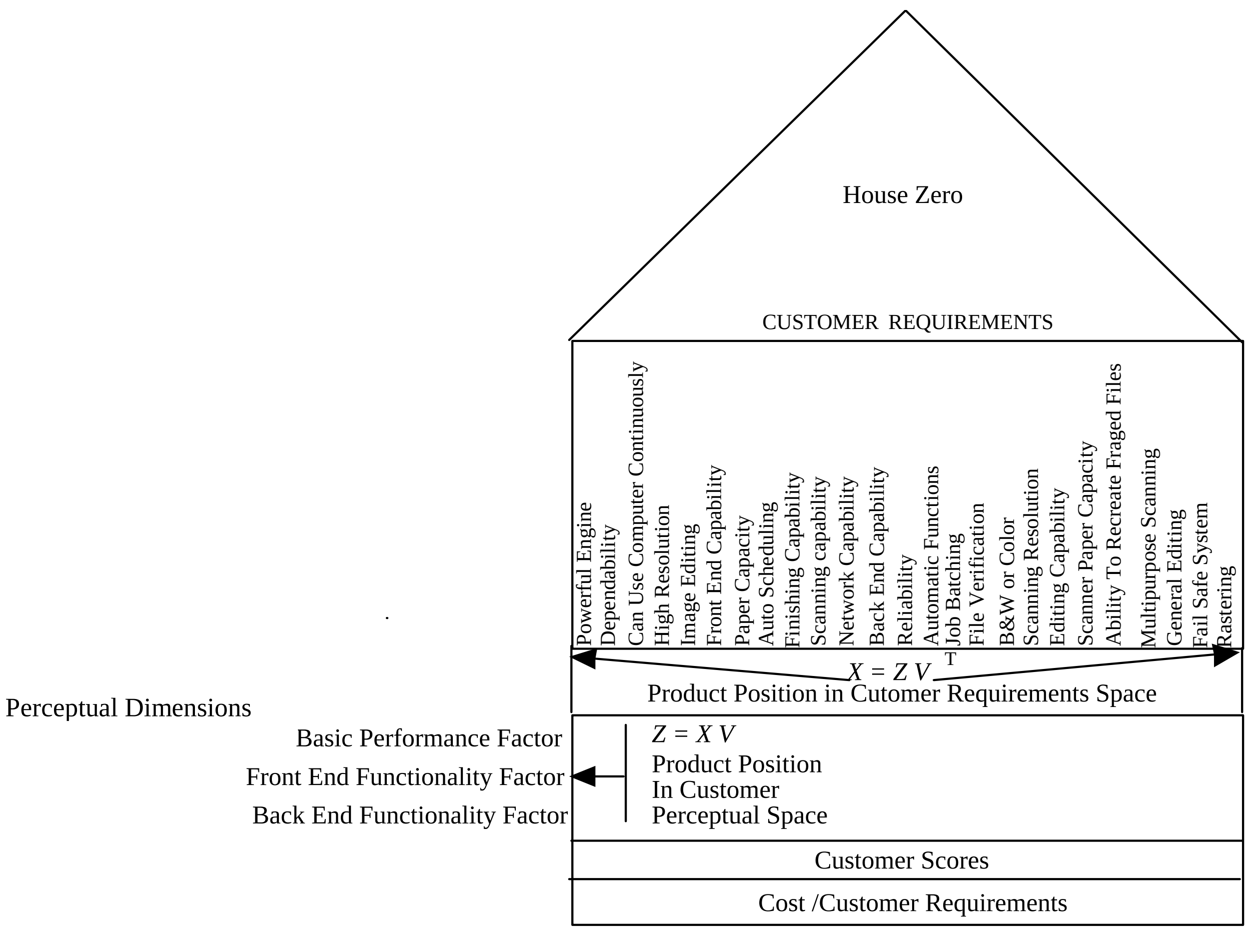

Figure 6. New House Zero.

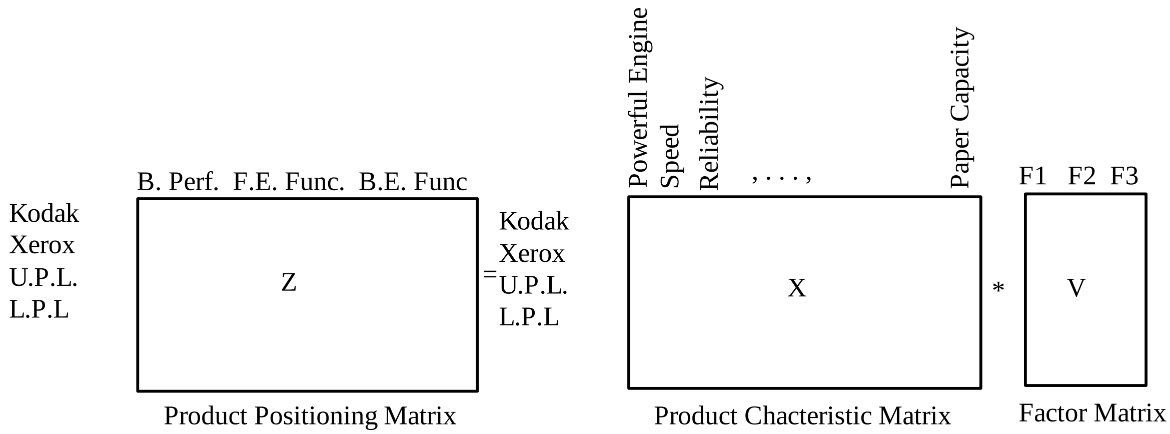

Figure 7. Calculating the average product positions in customer perceptual space**.**

Market share

Market share was calculated via equations (3) and (4) with the results being a predicted 39% (3.03 / 4.70 + 3.03) of market share for Kodak (Figure 9). Hsu and Wilcox discussed how to calculate confidence intervals for market share estimates in this way. This market share is a disappointing result for Kodak. Thus, it was necessary to examine new product positions and recalculate market share.

Alternate product positions in perceptual space

Since there are only three needs dimensions, it is fairly easy to focus on one dimension or two dimensions or even all three needs dimensions without the analysis becoming too cumbersome or costly.

Suppose that Kodak chooses to improve its position in the Basic Performance dimension to exceed that of Xerox, while keeping the other aspects (Front End and Back End) at the original planned levels (Figure 8). This position corresponds to an improvement in all of the customer needs associated with the Basic Performance perceptual axis. These customer needs are *scan speed*, *reliability*, *print sp*eed, *copy out-time*, *stapling*, and *resolution at capture*.

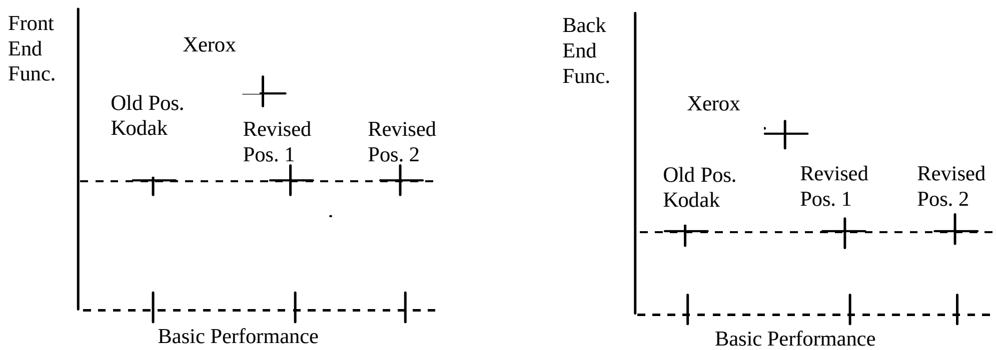

Figure 8. Original and revised product positions varying only the performance dimension.

We calculated market share using equations (3) and (4) and then plotted the market share for each of these new designs (Figure 9). The results were that in the revised position two, Kodak could increase its market share to 51%. This would entail investment in R&D that Kodak could actually accomplish.

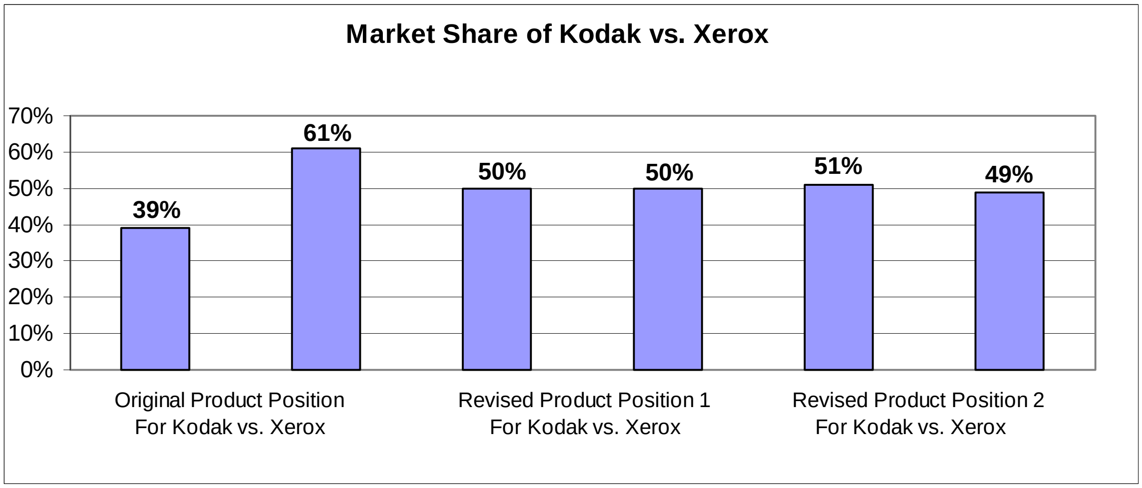

Figure 9. Market share of Kodak vs. Xerox.

The model suggests that Kodak could use R&D efforts to greatly improve Basic Performance by focusing on the customer requirements of *scan speed*, *reliability*, *print speed*, *copy out-time*, and *resolution at capture*. If it were successful, its market share would exceed that of Xerox.

Assessment of the New Methodology

The researchers and Kodak were especially concerned to see whether the Virtual Design Method (VDM) supplied the information needed for joint decision-making for new product design. The criteria for evaluating the two methods were based on their ability to perform new product development tasks; that is, to

- Position products in the market in relationship to its competitors,
- Analyze customer needs (a linear combination of customer requirements),
- Increase the quality and the quantity of new product information,
- Focus on engineering modeling,

- Link design variables to customer perception,
- Develop new products according to market segment characteristics, and
- Improve communications.

The results are summarized in Table 3.

Kodak believes that the new structured product design methodology would facilitate communications and assist the design team in identifying new product positions and market segments, while focusing on the needs of the customer. Product design alternatives would generate realistic product positions because they are directly linked via mathematical models to the engineering design variables. The design variables assist the design team in assessing costs of production. All of the product features could be compared virtually to other competitors' features in the market place, and potential market share and profit could be determined early in the design process. Finally, the VDM determines if the customer is willing to pay for that additional product feature that could differentiate the product in the market place.

Table 3. VDM assessment table for performance criteria, VDM, and traditional method.

Criteria	V.D.M.	Traditional
Position products In relationship to competitors	VG, Q	NE--assumes perfect market knowledge
Analyze customer needs	VG, Q, q	NE
Increase quality and quantity of new product information	VG, Q, q	VG, Q, q, for technical req. space only
Focused engineering modeling	VG, Q, VDM uses engineering equations	NE
Link design variables to customer perception	VG, Q, q, by VDM architecture	NE
Develop new products according to market needs	VG, Q, q, new House Zero	NE
Improve communications	VG, Q, q, by VDM architecture	NE

How method rates: VG (Very Good), G (Good), P (Poor), NE (Non Existent)
Q = Quantitative, q = Qualitative

Limitations of the Study

The case study convinced us of the benefits of the virtual design method's construction and use of House Zero. We believe that the benefit of VDM will generally apply to companies whose product performance differentiates the product in the market. For these firms, the linking of product performance metrics with marketing performance metrics is extremely important. The company personnel should possess a fairly strong set of technical skills for constructing and interpreting House Zero.

For the VDM, the reduction of the factor matrix (*V* matrix) affects the invertibility of the map between perceptual space and customer requirements space. This results in a loss of distinction when we map backwards from arbitrary levels of customer needs, and a limited subspace in customer needs space when we map forward. The only way to avoid these inaccuracies is to use a complete factor matrix (*V*) with complete coefficients entries and a complete customer rating matrix (*X*) with all 25 customer requirements.

CONCLUSIONS

This research views product/process design as an activity that requires analyses in six different spaces: customer perception, customer requirements, technical requirements, product design, process design, and process control. Statistical and engineering analysis models are used to map between different aspects of the customer/product/process ensemble. These statistical models and engineering equations assist the design team in making design decisions based on predictions of performance, cost, market share, and risk; and, consequently, revenue and profit. The methodology provides a quantifiable measure of the impact of alternative decisions across domains, which is a tool for communication between members of the design/decision-making team.

The ability to position products in relationship to competitors in perceptual space gives businesses insight into the structure of the market. The product development team must reduce risk by developing a product that fulfills customer needs profitably. To do this, marketing and engineering must reduce market uncertainty by analyzing customer needs. Preferences and market share for hypothetical products can be calculated in perceptual space via mathematical models that reduce customer dimensions, improving interpretability. This increases the quantity and quality of the information early in the design process. Our preliminary experience indicates that this modeling approach has advantages over current product design methods.

The method takes advantage of engineering models to decide whether designs are feasible, to explore the performance envelope of a design without actually building a physical prototype, and to study the tradeoffs involved in varying the design variables. This structured, formalized method also facilitates communication between engineering, manufacturing, and marketing.

At present, complete implementation of the methodology is not practical for several reasons. First, not all functional maps between spaces are available. Many of these maps must be developed for each product family by technologists with expertise in statistical methods and marketing, economic, and engineering models. We believe that companies can develop their software and personnel resources to enable a formal mapping approach to product design, and that such an approach will provide product/process designs that are more in tune with customer needs, with higher profit and reduced time to market.

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