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Trends and Perspectives

Review of QFD and Related Deployment Techniques

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Abstract

The paper reviews some historical developments in the quality function deployment (QFD) and extended house of quality (EHOQ) concepts that are popular for conveniently organizing product, process, and production planning information and for processing customer requirements. Since the inception of QFD in Japan in the early 1970s, it has met with varying degrees of success. This paper first reviews the literature and describes the EHOQ, which is a mature arrangement of QFD. Other related deployment techniques are examined, and a new concept called concurrent function deployment (CFD) is described. CFD is based on parallel deployment of several lifecycle "value plans" in addition to the "quality plan" used in QFD. CFD thus gives rise to integrated templates, called house of values (HOV), which are compared to EHOQ templates. The differences and similarities between QFD and CFD are discussed.

Keywords: *Quality Function Deployment (QFD), House of Quality, Process Planning, Production Planning, Deployment Techniques, Concurrent Function Deployment (CFD)*

Introduction

Quality, from an historical standpoint, has gone through four phases of development—inspection, process control, quality assurance, and strategic quality management.[39] [Note: Reference citation numbers correspond to the alphabetical reference list at the end of the paper.] While manufacturing philosophies have changed drastically during the 1980s, transition pace from concept to practice has been very slow. Despite restructuring, reorganization, and even process reengineering efforts, both the European and American automotive industries have failed to attain parity in product cost, productivity, or throughput compared to Japanese automobile producers and transplant operations.[15,46] Earlier published works[23] showed assurances that the competitive gaps could be closed using *quality function deployment* (QFD) or similar programs, causing a change in organizational effectiveness and culture. This culture motivated abandonment of many traditional functional values in favor of employee empowerment and autonomous multifunctional working teams.[12] Many combinations have been tried with QFD, along with product development teams (PDT)[33] integrating with voice of the customer (VOC)[1,18,30] and with total quality management (TQM).[45] In new product development areas,[25] QFD combinations have been tried with Pugh's concept[35] for product alternative selection[10] and for new product introduction.[25] In conjunction with Taguchi methods, QFD has been combined with the Taguchi formulation,[43,42] Taguchi with design of experiments,[36] and Taguchi with TRIZ methods (Russian Theory of Inventive Problem Solving).[44] In conjunction with optimization formulation, quality function deployment has also been combined with multiattribute design optimization,[26] with nonlinear programming techniques,[32] and for decisions using fuzzy sets.[28] QFD has also been tried with concurrent engineering techniques,[37,33] for integrated product development,[34] with design structure matrix,[20] and with design function deployment[17] to obtain concurrent design.

Though each QFD combined implementation provided new opportunities and stronger contributions toward cost and productivity improvements, many such programs have encountered difficulties in making a parent company globally competitive.[39] The implementation of QFD in industrial projects is sending conflicting messages of success in terms of (a) dealing with large applications/systems[13,21,27] within industries and (b) benefits to industrial projects.[31,20] Furthermore, the gains that would seem obvious and feasible through the exploitation of QFD and its combination (in quantifiable competitive sense) have not always been fully realized.[34] Most QFD implementations consider phased deployment of WHATs (also called "quality plans," such as product plan, process plan, and production plan) serially in arriving at the set of HOWs (known as making a quality-based design).[16] The paper reviews some of the recent developments in QFD and examines some of the newer deployment techniques that are emerging for concurrent product development.

History of Quality Function Deployment (QFD)

QFD is an innovation that is more than two decades old.[22] Historically, the concept of QFD was introduced by the Japanese[3,29] in 1967. It did not emerge as a viable methodology until 1972 when it was applied at the Kobe shipyards of Mitsubishi Heavy Industries in Japan.[2,19,43] The American Supplier Institute (ASI) and GOAL/QPC (Growth Opportunity Alliance of Lawrence, Massachusetts/Quality Productivity Center)[1,23] have done a great job in publicizing QFD in the United States. The first recorded case studies in QFD were in 1986.[23] Kelsey Hayes used QFD to develop a coolant sensor, which fulfilled critical customer requirements like "easy-to-add coolant, easy-to-identify unit" and "provide cap removal instructions." A number of companies now use QFD, including Ford, General Motors, Chrysler, AT&T, Procter and Gamble, Hewlett-Packard, Digital Equipment, ITT, and Baxter Healthcare. However, it has not yet found popularity as a design technique, though its use is appropriate for organizations of any size. Many companies have experimented with QFD ideas and have realized significant benefits.

In the span of the first seven years, between 1977 and 1984, the Toyota Auto body plant employed QFD and claimed that with its use:

1. Manufacturing startup and pre-production costs were reduced by 60%.
2. The product development cycle (that is, time to market) was reduced by 33% with a corresponding improvement in quality because of the reduction in the number of engineering changes.[46]

There are several definitions for quality function deployment.[23,45] The definition of Akao[1] states that QFD is the converting of customer demands (WHATs) into quality characteristics (QCs) (HOWs) and developing a quality plan for the finished product by systematically deploying the relationships between customer demands and the QCs, starting with the quality elements in the product plan. Later, QFD deploys this WHATs and HOWs relationship with each identified quality element of the process plan and production plan.[29,40] The overall quality of the product is formed through this network of relationships.

QFD was designed originally to take the voice of the customer (VOC) (called customer demands/objectives) and translate it into a set of design parameters that can be deployed vertically top-down through a four-phase process.[40] The four phases—known as an American Supplier Institute (ASI) four-phase or four-chart process—are as follows: Product Planning, Parts Deployment, Process Planning, and Production Planning. The main activity in most current implementations of QFD is the generation of charts corresponding to these four phases.[12,29] As outlined by Sullivan,[41] the HOWs in the product planning phase (first chart) become the WHATs for the second chart, and the HOWs in the second chart become the WHATs for the third chart, and the HOWs for the third chart become the WHATs for the fourth chart. This cascade-of-charts concept in the QFD system is meant to provide a "constancy of purpose" among the four phases. Sullivan[41] states that "the overall QFD system based on these charts traces a continuous flow of information from customer requirements to plant operating instructions, thus providing a common purpose of priorities and focus of attention." Hauser and Clausing[22] describe the first chart in detail and call this chart the *house of quality*. This cascade process, however, links the four charts (phases) so that one phase cannot start before the other phase ends.

Today's overall objective of QFD, which was quality plans deployment when introduced in 1967, is still the product's quality. Emphasis on quality plans was also the reason why the process was named quality function deployment by the Japanese.[11,14,42] Recently, Don Clausing and others have introduced some structural changes in the way QFD quality plans are arranged.[22] The new arrangement is commonly called the *extended house of quality*[19] (see *Figure 1*); however, the original emphasis aimed at providing for quality plans and quality designs has not changed.[39] The philosophy of establishing the WHATs and HOWs at different phases of product development is principal to the implementation of QFD, where WHATs are recorded as rows and HOWs are recorded as columns in a matrix structure. Use of quality function deployment as a set of planning and communication routines by cross-functional teams[15] is currently the most effective way known to cut through barriers to good design.[9,10] Many companies are now applying these routines in diverse cross-functional team environments for existing product improvements[6,31] and new product developments.[25] For existing products, the design concepts are generally known[12] and hence the conceptual status is static. Clausing and Pugh[10] argue that, during an implementation of an enhanced QFD, the product concept can be static or dynamic at the total system, subsystem, or parts level depending on the complexity of the products. QFD focuses and coordinates workgroup skills within an organization, first to design and then to manufacture and market goods that customers want to buy. QFD is intended to meet customer requirements in a better way, increase organizational capabilities, and at the same time maximize company goals.

Components of Extended House of Quality

The extended house of quality (EHOQ) consists of eight fundamental areas, all of which are not essential. *Figure 1* identifies each area, and an off-highway dump truck example[27] gives a glimpse of EHOQ's full potential. *Figure 2* is a schematic view of an EHOQ template. This template has eight rooms, four of which form the basic perimeters of the house. These four are two row-rooms (WHATs and HOW-MUCHes) and two column-rooms (HOWs and WHYs). EHOQ also encompasses relationships among these four list vectors, resulting in four relational matrices, as follows:

- HOWs versus HOWs
- WHATs versus HOWs
- HOWs versus HOW-MUCHes
- WHATs versus WHYs

The following section examines each EHOQ room's essential features.

EHOQ List Vectors

Figure 2 identifies all rooms in the EHOQ by their list vectors and matrices. The four list vectors—WHATs, HOWs, HOW-MUCHes, and WHYs—are briefly described in the following:

WHATs: Customer Requirements (CRs)

Customers define the WHATs in a QFD/EHOQ. In simple terms, WHATs are a list of customer wants or customer requirements (CRs). In most consumer goods manufacturing companies, the voice of the customer (VOC) is considered the market requirement.

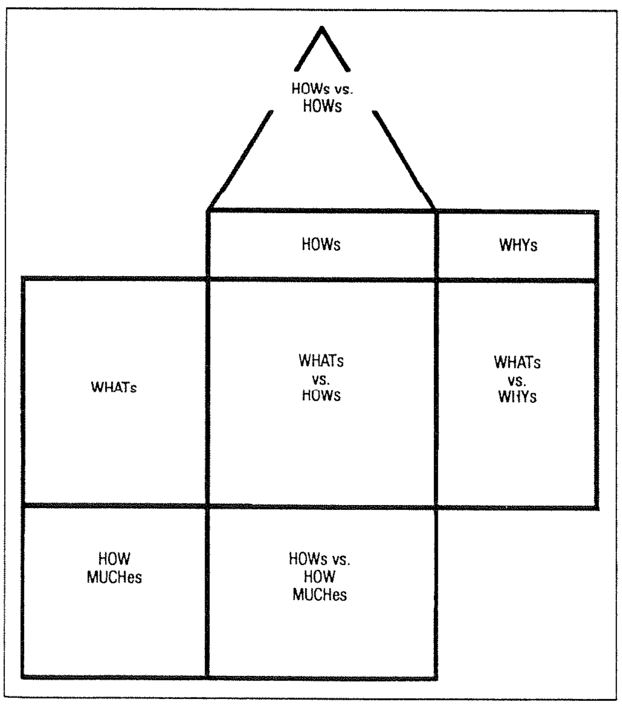

Figure 1
Extended House of Quality (EHOQ)

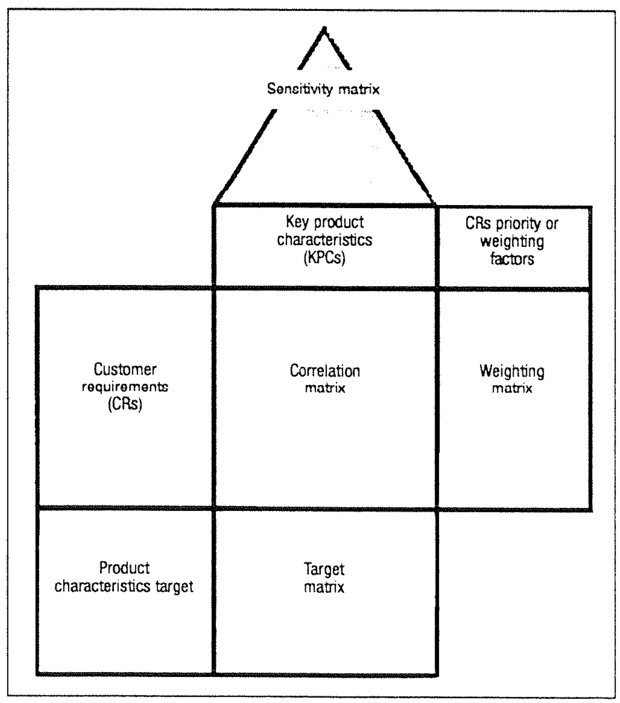

Figure 2
QFD Extended House of Quality – List Vectors and Matrixes

Customers are initially listened to, and a list of customer needs and expectations is created. Some typical WHATs might be: "pleasing to the eyes," "looks well built," "provides good visibility," or "opens and closes easily." The Kano model of quality or features defines three types of WHATs: basic, performance, and excitement. The Kano model relates customer satisfaction for each WHAT to its degree of achievement. The corresponding WHATs can further be categorized into primary (must have), secondary (may be), and tertiary (like-to-have) categories.[21] The primary needs set the strategic direction for the product and are called "strategic needs"; secondary needs are called "tactical needs"; and tertiary needs are called "operational needs."[21]

HOWs: Quality Characteristics (QCs)

Manufacturers define the HOWs in a QFD/EHOQ, as represented by the list vector in *Figure 3*. Basically, HOWs are a set of quality characteristics (QCs) through which a set of WHATs can be realized. Manufacturers do not know the magnitude of each of these HOWs (when considered as a unit) that will be needed to realize as many WHATs as possible. Using this HOW list, a company can measure and control quality to ensure that WHATs are satisfied. Typical entries on the HOWs vector list are parameters for which measurements or a target value can be established. For example, a customer need for a "good ride" (a WHAT) is achieved through "dampening," "shock isolation," "anti-roll," or "stability requirements" (four HOWs). HOWs determine the set of alternate quality features to satisfy the customer's stated needs and expectations (WHATs). Therefore, HOWs are called quality characteristics. For every WHAT in the requirements and constraints (RCs) list, there is one or more HOWs to describe possible means of achieving customer satisfaction.

HOW-MUCHes: Bounds on Quality Characteristics

HOW-MUCHes comprise a vector list that normally identifies the bounds on the feasibility of HOWs. HOW-MUCHes capture the extremes—the permissible target values for each quality characteristic (see *Figure 3*). In other words, for each HOW

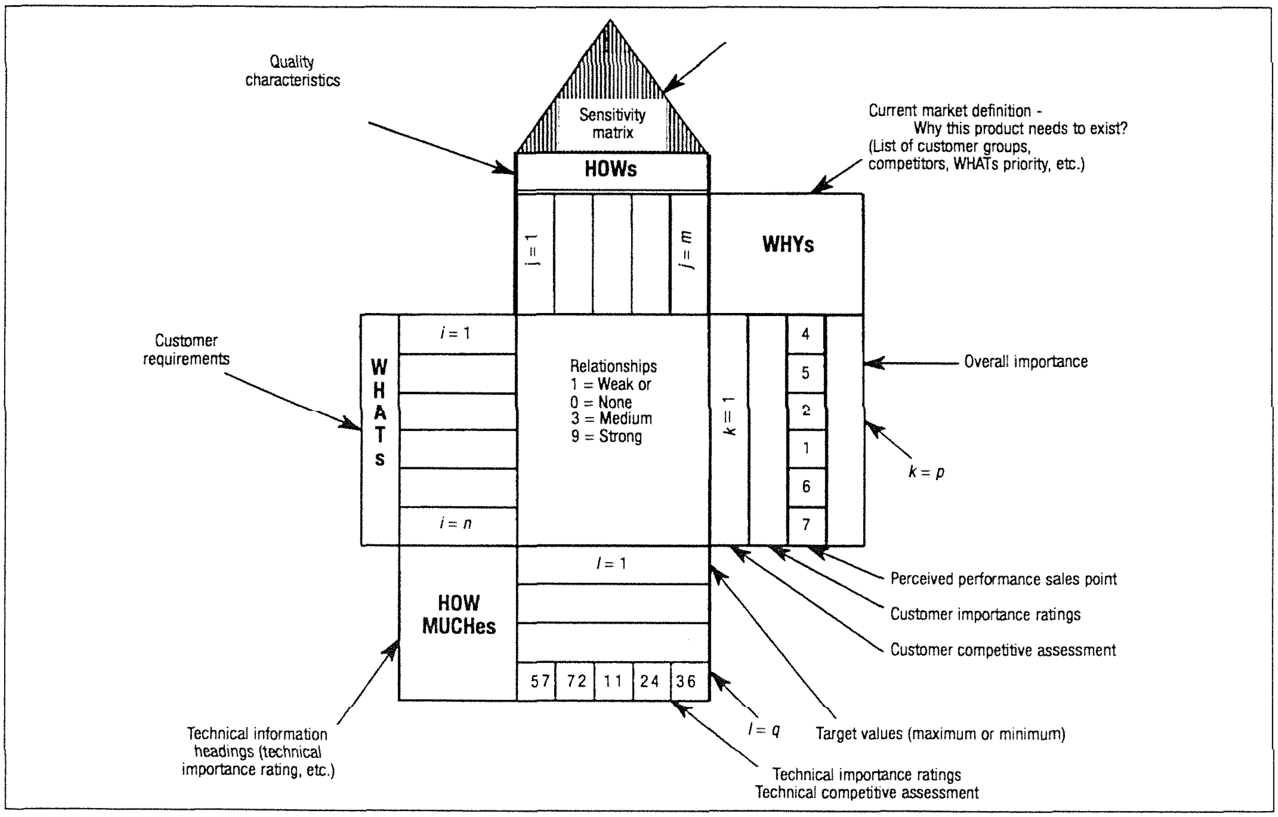

Figure 3
Expanded House of Quality – Terminology and Conventions

(quality characteristic) on the list vector, there is a corresponding value for a HOW-MUCH entry. The idea is to quantify the solution parameters into achievable ranges or specification tables, thereby creating a criterion for assessing success. This information is often obtained through market evaluation and research. A typical HOW-MUCH measures "the importance of HOWs," a "performance of Product X," or a set of "target values." In an optimization formulation discussed in Prasad,[32] a row of HOW-MUCHes is used to collect upper and lower bounds for the attributes in the HOWs vector list.

WHYs: Weighting Factors on WHATs

Similar to WHATs and HOWs, a set of WHYs is also a vector list that describes the relative importance of current competitive products, referred to as "world-class" or "best-of-class" products. Best-of-class products contain HOWs that satisfy a set of WHATs in some prioritized manner (see *Figure 3*). WHYs are names of competitors, competitive products, market segments, or other items that describe current market conditions. WHYs are also factors for "weighting" the decisions that must be taken into account for a future product. Once these weighting factors are multiplied with the corresponding set of WHATs and then summed over, they provide a single pseudo measurement index for "overall customer satisfaction." A typical WHY might be a vector list of "overall importance," a vector list of "importance to the world purchaser," or a set of "world-class achievable performance of product X."

EHOQ Relational Matrices

The four EHOQ relational matrices employ either numbers or symbols, depending on the purpose of the QFD and the context in which it is being used (see *Figure 3*). Two possible rationales are traditionally proposed depending on whether a relational matrix is used for calculations or for visual aid.

- ***Quantitative Reasoning:*** Numbers are used for specifying magnitudes of EHOQ matrices. This facilitates comparing magnitudes of computed vector lists by mathematical means.
- ***Qualitative Reasoning:*** Symbols are used to represent list vectors or matrices. This provides a better visual communication. Three symbols are often used to indicate the relationship between WHAT and HOW entries. A solid circle (●) implies a strong relationship, an open circle (○) a medium relationship, and a triangle (△) a weak or small relationship.

This process of evaluating expressions in QFD gives concurrent engineering teams a basic method of comparing the strengths, weaknesses, and importance of column vectors (WHATs, WHYs) or row vectors (HOWs, HOW-MUCHes) and measuring interactions between them. *Table 1* shows a convention that is typically followed in defining QFD relational matrices. According to Akao,[1] there is no established theory in attaching these numbers to mark the priorities. Literature shows ratings on 1 to 5 or 1 to 9 scales, with the larger number indicating

Table 1
Standard Relationship Conventions (Weight and Symbols)

Matrix		Quantitative	Qualitative
WHATs versus HOWs	**Grade**	**Weight**	**Symbols**
	Strong relationship	9	Double or Solid Circle and/or •
	Moderate relationship	3	Circle (o)
	Weak relationship	1	Triangle (Δ)
	None	0	Blank
HOWs versus HOWs	**Grade**	**Weight**	**Symbols**
	Strong Positive relationship	9	Double or Solid Circle and/or •
	Medium Positive relationship	3	Solid Triangle (Δ)
	Positive relationship	1	+
	None	0	Blank
	Negative relationship	–1	–
	Medium Negative relationship	–3	Open Triangle (Δ)
	Strong Negative relationship	–9	Open Circle (o)

the higher priority.[22] A close analysis reveals that the scale 1 to 5 represents an arithmetic progression, while the 1 to 9 scale represents a geometric progression.[39] This means that the 1 to 9 scale discriminates the weak relationships heavily against the strong relationships, while the 1 to 5 scale discriminates evenly.

WHATs vs. HOWs

To get a relationship between market requirements and quality characteristics, a correlation matrix is created by placing the HOWs list along the column of a matrix and the WHATs list along its rows (see *Figure 3*). The rectangular area between the rows and the columns depicts the relationships between the WHATs and HOWs. Relationships within this matrix are usually defined using a four-level procedure: strong, moderate, weak, or none (*Table 1*). An example is shown in *Figure 3*. This matrix may be densely populated (more than one row or column affected); this results from the fact that some of the quality solutions may affect more than one market requirement. For example, what a customer wants in "good ride" and "good handling" (WHATs) are both affected by quality characteristics like "dampening," "anti-roll," or "stability requirements" (HOWs). A diagonal correlation matrix means there is no or very little interaction between the rows and columns.

WHATs vs. WHYs

This is a matrix of influence coefficients that prioritizes the WHATs based on criteria for competitiveness. Usually, a list vector in the matrix (say, a column) consists of one or more of the following (see *Figure 3*):

(a) Marketing information ratings, which identify the relative importance of each of the WHATs.
(b) Ratings showing how important the different customer groups perceive each of the WHATs. These are often referred to as customer importance ratings (CIRs).
(c) Ratings showing how well a competitor's product is perceived as meeting each of the WHATs.
(d) Ratings showing where the product ranks or is perceived relative to the competition (better or worse).
(e) Factors that a company would like to consider in its (a product) specification set to be a "world-class quality producer."

The above criteria provide a set of possible options for identifying the stated importance ratings and factoring—in how a product is perceived relative to competitors. Most importantly, the above criteria can be used to determine a weighted average of WHATs as a single performance index.

HOWs vs. HOW-MUCHes

This is a feasibility matrix that lets a team decide how much each HOW can be varied to meet customer requirements. Typically, the data in this matrix (say, a row) consists of one or more of the following (see *Figure 3*). In this case, a row of matrix "HOW-MUCHes of HOWs" may contain:

(a) What an organization perceives its product ranks relative to its competitors (technical competitive assessment).
(b) Ratings that identify the relative importance of each HOW.
(c) How a competitive product performs relative to each chosen HOW (benchmark data).
(d) Estimate of realistic upper limits for a chosen HOW.
(e) Estimate of realistic lower limit for a chosen HOW.
(f) Estimate of service repair cost data, direction of improvements, legal, safety, and other control items.
(g) Computed values of the technical importance rating (TIR). This is a weighted sum of quality characteristics (QCs) computed with respect to customer importance ratings (CIRs).

Commonly, a PDT team, through a row of a feasibility matrix, establishes a set of realistic target values (upper and lower bounds) for each HOW. Product values or target values identify engineering tolerances and specification limits on quality characteristics.

HOWs vs. HOWs

This relationship is described by means of a sensitivity matrix that forms the roof of the house of quality (see *Figure 3*). The purpose of the roof is to identify the qualitative correlation between the characteristic items (HOWs). This is a very important feature of the house of quality because, at times, the possible solutions could be redundant and may not add much value to customer wants. If two HOWs help each other meet the target values (HOW-MUCHes), they are rated as positive or strong positive. If meeting one HOW target value makes it harder or impossible to meet another target value, those two HOWs are rated as negative or strongly negative (see *Table 1*). In actuality, correlation between quality characteristics (solution parameters) could be positive or negative in varying degrees: strong, medium, or none. For example, "fuel economy" and "gross weight" are considered as having a positive correlation because reducing gross weight will increase fuel economy, keeping all other remaining parameters constant.

After the EHOQ relationship matrices are developed, the constructs are reviewed. Blank rows or columns call for closer scrutiny. A blank row implies a potential unsatisfied customer and emphasizes the need to develop one or more HOWs for that particular market requirement (WHAT). A blank column implies that the corresponding quality characteristic item does not directly relate to or affect any of the market requirements.

Limitations in Deploying QFD

In the 1980s, most manufacturers based their product development, design, and delivery (PD^3) decisions on quality plans while ignoring other important aspects because it was the right thing to do.[41] Today, manufacturers consider other aspects, such as costs,[21] design for X-ability,[12] tools and technology,[4,7] environmental factors,[5] and infrastructure,[45] in addition to quality plans.[29] Today, quality is a given or considered a minimum requirement to enter the marketplace.[39]

Quality function deployment does not specifically address the cost, tools and technology,[7] responsiveness (time-to-market), and organizational aspects[17] in the same vein as it addresses the quality aspect (see *Figure 1*). While some consider the product design process independent from technology, design for X-ability, cost, and responsiveness, the reality is that these are tied together by a common set of product and process requirements. The design process only provides a product design from the perspectives of performance (that is, quality plans).[16] The product design performance requirements drive the product selection (including system, subsystems, components, parts, and material selection) process and influence the selection of the fabrication (process and production) method.[12] Others have argued that, while performing QFD, designers could choose to include requirements that belong to considerations other than quality in the original customers' list of HOQ.[15,7,31] Accomplishing this through a conventional deployment process, as in QFD, is not simple.[12,31] Working on multiple lists of requirements as part of a single function deployment (say, under quality plans) through QFD is a much tougher problem.[13]

- First, it would be a complex undertaking considering just the size of the resulting relational matrices in QFD.
- Second, deploying them serially would be a long-drawn process.
- Third, cascading the requirements all together as was done in the case of quality functions would be large and cumbersome to handle.[13]
- Fourth, there is no way of ensuring that the design obtained through this combinatorial QFD process would not result in a suboptimized design, that is, a product particularly designed for characteristics related to quality.

What is required in optimizing an artifact is designing with respect to all-important functions that characterize a "world-class product" today. Normally in actual practice, information for these measurements is independently obtained, and design often proceeds in parallel. Paralleling allows the combinatorial problems to be addressed in sizable chunks, which in turn can be handled by specialized workgroups comfortably.[37] Parallel deployment of values would allow concurrent teams to work independently, thus reducing the PD^3 cycle time.

Major pitfalls of Akao's QFD approach are as follows:

- ***Conventional function deployment is mainly quality focused:*** One pitfall of conventional deployment (like QFD) is that it is based on a single measurement, mostly quality plans.[40] Today, manufacturing sectors are more fiercely competitive and global than ever.[44] Consumers are more demanding, competition is more global, fierce, and ruthless, and technology is advancing (and changing) rapidly. The quality-based philosophy inherent in Akao's *quality* function deployment style introduced during the early 1970s does not account for the time factor inherent in today's complex PD[3] process.[12] Competitors are always finding better and faster ways of doing things. Catching up in quality is not enough—it only makes a company at par with its competitors in terms of inheriting some product quality characteristics but, relatively speaking, getting there a few years later. What is required is a total control of the process—identifying and satisfying the needs and expectations of consumers better than the competition and doing so profitably faster than any competitor.[9]

Conventional function deployment is a phased process: The conventional deployment process in QFD prescribes a set of structured cross-functional planning and communication matrices for building quality as specified by customers into a product. Such a methodology is described by Sullivan[41] and is based on the most popular four-phased deployment[40] due to Macabe, a Japanese reliability engineer, in 1970.[3] This is often represented in a cascade time-bound process where characteristics of a prior phase feed as requirements for a subsequent phase.[22] The serial nature of deployment tends to make the QFD process sequential.[3] If each phase of deployment is a "multipart" process, the elapsed time can be significantly large. This elongates the total time this QFD would take for an artifact realization process. It is not essential that each phase be a hands-off process with no overlap between the consecutive phases.[33]

Conventional function deployment is one-dimensional: The roles of the organization and engineers are changing today, as are the methods of doing business.[16] Competition has driven organizations to consider concepts such as time compression (fast-to-market), concurrent engineering,[37] design for X-ability, and tools and technology (TQM,[45] Taguchi and TRIZ,[44] and value engineering and technological forecasting methods[38]) while designing and developing an artifact. Quality function deployment addresses major aspects of quality plans with reference to the functions a product has to perform, but this is one of the many functions that need to be deployed. With conventional QFD, it is difficult to address all aspects of total values management (TVM),[31] such as X-ability, cost, tools and technology,[7] responsiveness, and organization issues.[34] It is not enough to deploy quality into the product and expect the outcome to be world-class. TVM efforts are vital in maintaining a competitive edge in today's world marketplace. The question is how to deploy all the aspects of TVM.

Conventional function deployment cannot account for the increasing complexities of a product and the conflicting requirements that need to be addressed. As a result, the best efforts of the concurrent teams simply do not result in products that optimally meet customer requirements. This is not because the teams are not able to work closely enough, but because the quality function deployment vehicle is not robust enough to accommodate multiple-function deployment. The conventional QFD process lacks the vigor while implementing simultaneously various conflicting value characteristics such as cost, responsiveness, quality, and so on.[31] In the absence of any better deployment vehicle, the team repeats the conventional QFD process for each value one at a time.[17,31] This elongates the PD[3] cycle time into a multiyear ordeal.

Concurrent Product Development

The first step in creating a great product is an understanding of what exactly makes up a product and its process.[12] Clark defines a great product as one that meets all pertinent characteristics that are required to ensure product integrity.[8] Generally, development of a new artifact does include several lifecycle value considerations that are pertinent to meeting the customers' requirements. Many of these values are independent; that is, there is very little or no interaction between them. Through the course of investigations and study, the author has found that the deployment of many artifact functions (values) can proceed in parallel with what is known today as "quality FD." Examples are: X-ability (performance),[38] tools and technology,[7] cost,[24] responsiveness, and infrastructure. Generally, these functions or values are independently specified or estimated.[24] The results of experience can be used to specify the requirements for each of the values in parallel without having to wait until a "deployment of quality FD" is complete.

Concurrent Function Deployment

To eliminate the phased nature of deployments in QFD, Prasad expanded the original definition of QFD to include parallel deployments.[34] The author called this approach concurrent function deployment (CFD) because it allowed deployments of competing values simultaneously.

CFD Architecture

Concurrent function deployment uses a three-axis approach for orderly deployment of functions or features (see *Figure 4*) spanning in three dimensions: horizontal (x-axis), axial (y-axis), and vertical (z-axis).[34] Artifact values (AVs) are deployed along the x-axis, value characteristics (VCs) associated with each class of artifact values are deployed along the y-axis, and requirements and constraints (RCs) are deployed along the z-axis (see *Figure 4*). The components of axial and horizontal dimensions are arranged in a matrix and deployed concurrently, while the vertical dimension is staggered in tiers. The VCs vector for each value class is identified so that specifications developed using this methodology will yield an optimum product configuration the first time and every time CFD is used. The methodology is independent of the types of manufacturing processes and products to be designed.

The following notations are used:

X_i represents the ith track AVs for horizontal deployment.

Y_{ij} represents the jth level VCs for axial deployment.

Z_{ijk} represents the kth tier RCs for vertical deployment.

The following is the process used for concurrent function deployment:

Step 1: Horizontal Deployment Leg

The CFD process starts with X_i, the horizontal

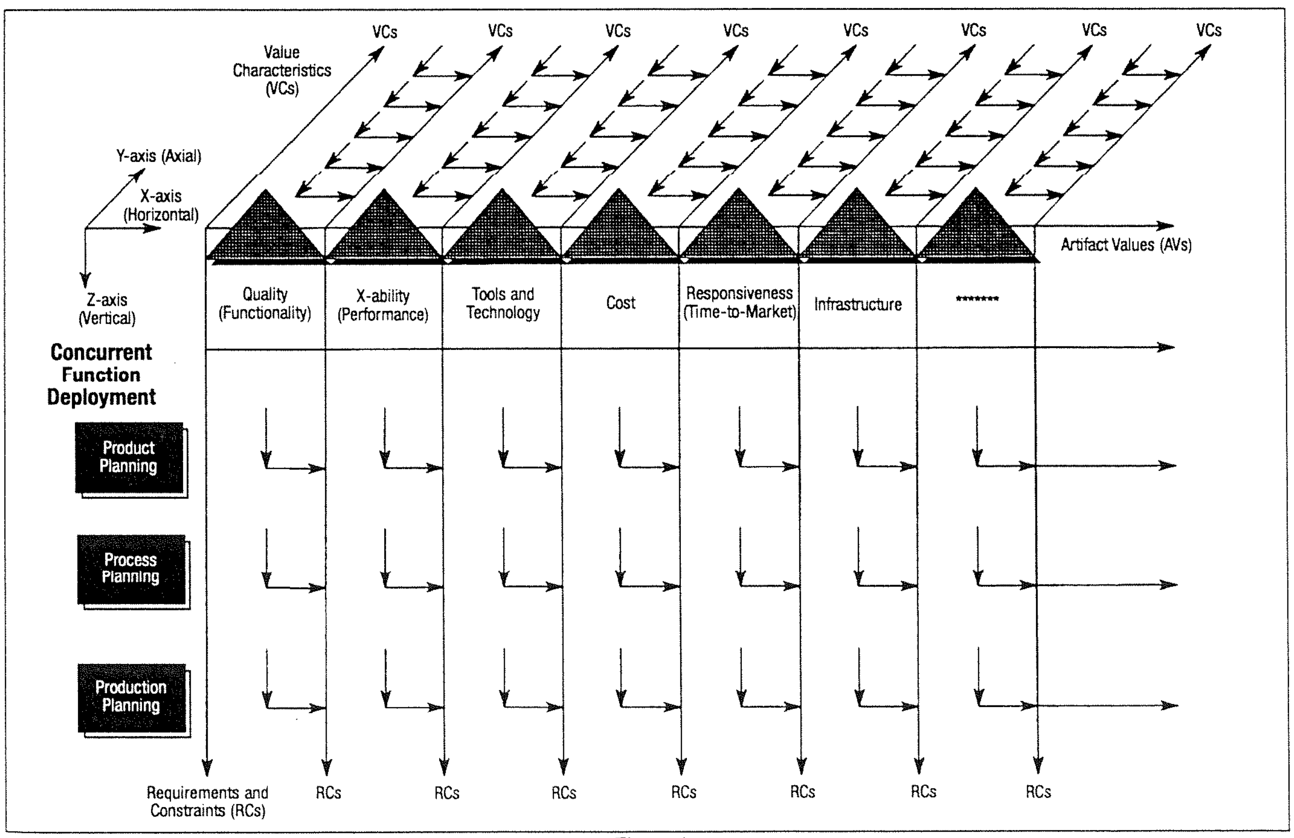

Figure 4
Concurrent Function Deployment – Three-Dimensional Deployment Schemata
(a) Artifact values along x-axis
(b) Value characteristics (VCs) along y-axis
(c) Requirements and constraints (RCs) along z-axis

deployment of an artifact value (AV). The team chooses a set of artifact values (along the x-axis) that need to be deployed. Deployment is concurrent, meaning deployment for each value characteristic (VC) can proceed in parallel. The following artifact values are commonly found relevant during product development:

A typical X_i for a class of six-value sets (i = 1, 6) may look like this:

$$X_1 = \text{Quality (functionality)} \tag{1}$$

$$X_2 = \text{X-ability (performance)} \tag{2}$$

$$X_3 = \text{Tools and Technology} \tag{3}$$

$$X_4 = \text{Cost} \tag{4}$$

$$X_5 = \text{Responsiveness (time-to-market)} \tag{5}$$

$$X_6 = \text{Infrastructure} \tag{6}$$

Step 2: Axial Deployment Leg

The second step is to identify a set of axial (y-axis) value characteristics (VCs), Y_{ij}, for axial deployment corresponding to each X_i. This process is concurrent, meaning the VC functions corresponding to an artifact value can be deployed simultaneously.

$$Y_{ij} \text{ for } 1 \leq i \leq I \text{ and } 1 \leq j < J \tag{7}$$

where Y_{ij} is a matrix, j takes the value from 1 through J, and J is the maximum number of VCs selected for an ith value track. A typical Y_{ij} for a matrix of size (I = 6 and J = 5) is shown in *Figure 5*.

Step 3: Vertical Deployment Leg

The third step is the vertical deployment of Y_{ij} in relation to RCs for a tier k. X_i and Y_{ij} are the AV and VC functions that were identified above in steps 1 and 2, respectively. There are three tiers to CFD deployment (tier k = 1 through tier k = 3). A tier structure means that each vertical (z-axis) deployment precedes the next tier of vertical deployment, and hence there is an overlap between tiers. The structure does not require finishing the end of one deployment before starting another (that is, not phased as in QFD). From the above definitions:

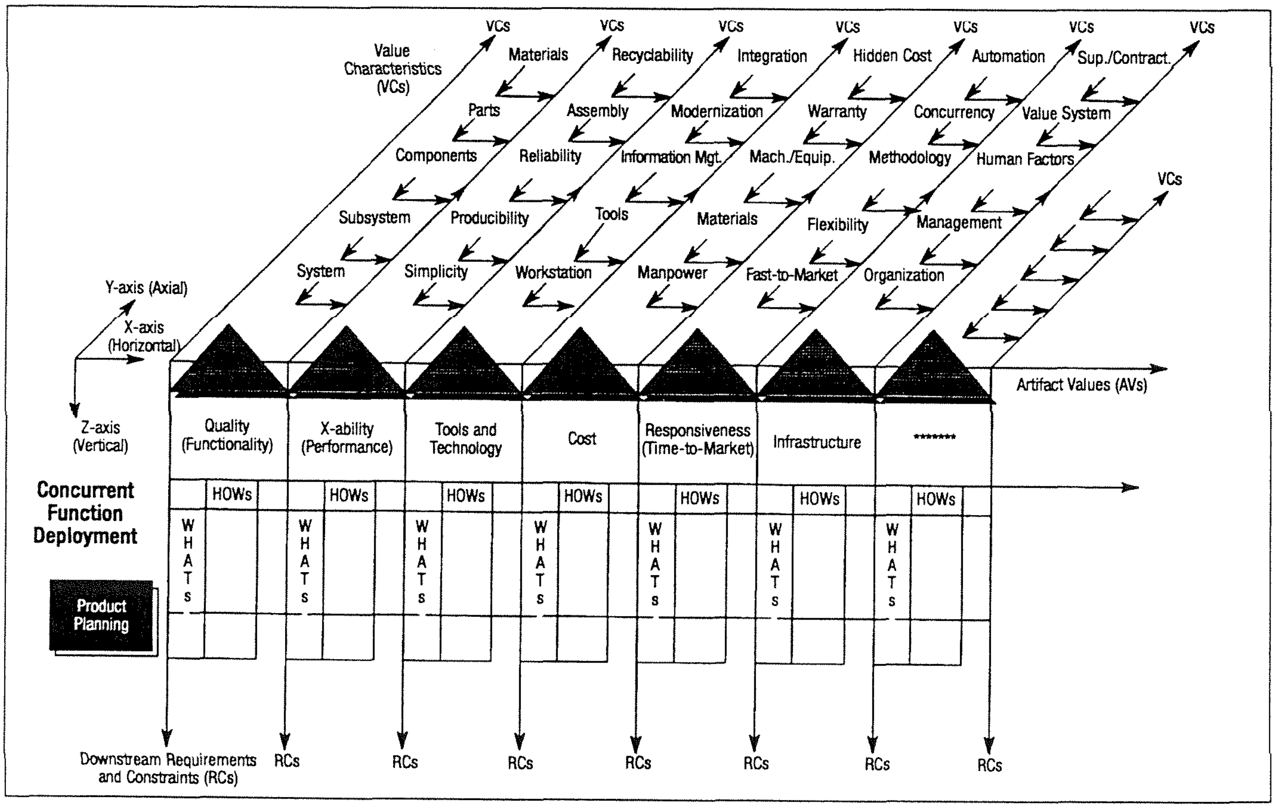

Figure 5
Concurrent Function Deployment: *X*-Axis – WHATs and HOWs

$$Z_{ijk} \text{ for } 1 \leq i \leq I,\ 1 \leq j \leq J, \text{ and } 1 \leq k \leq K \quad (8)$$

where Z_{ijk} represents a kth tier for vertical deployment; k assumes the value 1-3 corresponding to tiers 1, 2, and 3, respectively.

A typical Z_{ijk} for a three-tier RC structure (k = 1, 3) may look like this:

$$Z_{ij1} \equiv \text{Product Planning (Tier 1)} \quad (9)$$

$$Z_{ij2} \equiv \text{Process Planning (Tier 2)} \quad (10)$$

$$Z_{ij3} \equiv \text{Production Planning (Tier 3)} \quad (11)$$

Steps 1 through 3 form a trio. Deployment through a particular tier (say 1, 2, or 3) completes a CFD pass. CFD is complete if a trio of horizontal-axial-vertical deployment is carried out for all passes and for all value tracks, X_i.

Trio Deployment Technique

As discussed, the three-step CFD architecture utilizes a trio (horizontal-axial-vertical, ... , ...) deployment technique (see *Figure 4*) to arrive at the end of a pass. This results in a product design validated with a manufacturing process concept. During the above step 3, each tier completes a pass for a CFD. The first pass is horizontal-axial-vertical deployment for tier 1. The CFD trio is then repeated for tiers 2 and 3 as follows:

First Pass ≡ Trio (horizontal-axial-vertical) for Tier 1 (12)

Second Pass ≡ Trio (horizontal-axial-vertical) for Tier 2 (13)

Third Pass ≡ Trio (horizontal-axial-vertical) for Tier 3 (14)

This process of trio deployment is concurrent. There are overlaps between vertical (z-axis), axial (y-axis), and horizontal (x-axis) passages from timing perspectives. The CFD methodology interweaves the three-axis deployment with several other concurrent engineering techniques (such as TQM, goal-oriented management, integrated product development, cross-functional teams, and so on). It is a concept of three-dimensional (concurrent trio structure) deployment. This quickly allows many of the downstream steps (WHATs and HOWs) of a PD^3 process to be brought in earlier and satisfied at the first available opportunity (during a CFD pass) (see *Figure 5*). Other WHATs and HOWs are further addressed in greater detail in subsequent passes. The trio deployment process leads to selection of the best design and process (HOWs) for the overall product specifications (WHATs). During the concurrent function deployment, WHYs and HOW-MUCHes metrics support this selection, with sound analytical rationale. Targets for quality (functionality), cost (profitability), X-ability (performance), tools and technology (innovation), responsiveness (time-to-market, flexibility, etc.), and infrastructure goals are performed simultaneously. The CFD methodology is aimed at reducing dependence on trial-and-error methods such as "prototype fabrication" or testing.

Three-Dimensional House of Values (HOV)

The basic tool of CFD is the "relational matrix" concept. Matrices are schemata to generically define and directionally relate multiple lists of identifiers, often referred to as line vectors or list vectors. The basic matrix of CFD is the "house of values," so named to keep resemblance with its predecessor, "house of quality," which forms one of the many objectives of CFD. The relational matrix in CFD translates the corresponding requirements and constraints (RCs) into value characteristics (VCs).

The relationships between CFD components are shown in *Figure 6*. The three-dimensional matrix takes the form of three roofs and three relational matrices, as shown in *Figure 6*. It has three list vectors: artifact values (AVs), value characteristics (VCs), and requirements and constraints (RCs). Eight elements of AVs, nine elements of VCs, and three major elements of RCs vectors are shown in *Figure 6*. These lists may contain any number of values as necessary. The three relational matrices are:

- RCs versus VCs
- RCs versus AVs
- AVs versus VCs

This completes the concurrent deployment of artifact's values AVs along the three axes.

The intent of CFD is to incorporate the voice of the customer into all nine phases of the product development cycle: (1) mission definition, (2) concept definition, (3) engineering and analysis, (4) product design, (5) prototyping, (6) production engineering and planning, (7) production operations and control, (8) manufacturing, and (9) continuous improvement,

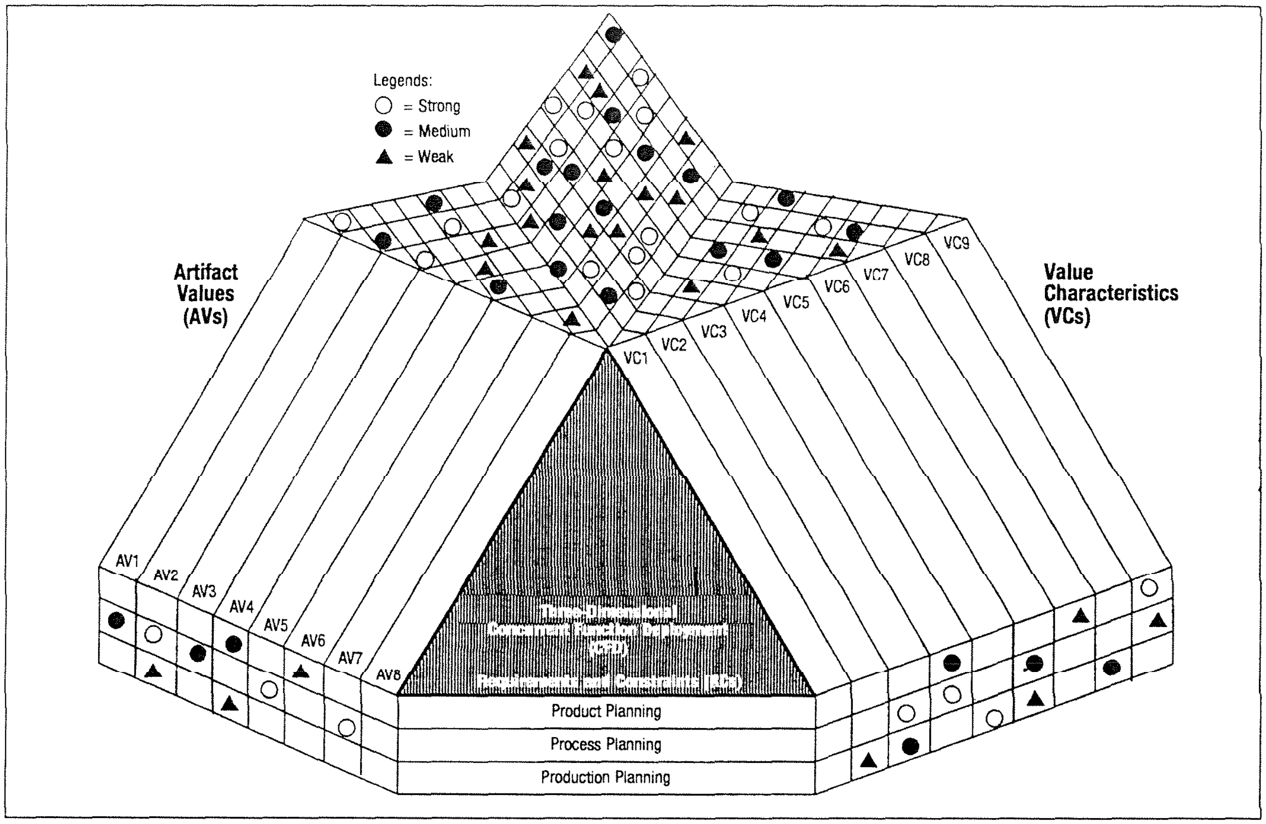

Figure 6:
Relationship between the CFD Components

support, and delivery (see Fig. 4.2 in Prasad[33]). If a specification chart is being developed for the product, the taxonomy for requirements and constraints must reflect all value considerations. RCs thus include customer requirements (CRs, VOCs, and all types of WHATs that one may specify for a product . In other words, CFD is a customer-driven PD^3 methodology. The RCs and VCs identified for an artifact can be arranged as shown in *Figure 4*. Such taxonomy will ensure that all-important aspects for product and process design have been identified and included. The focus of CFD is on systematically capturing product information, such as market competitive analysis and customer satisfaction ratings, and analyzing these ratings to improve product functionality (say, an X-ability value) and then adding an array of qualified values that are important to the customers and to the company.

CFD is a concurrent engineering methodology that enforces the notion of concurrency and deploys simultaneously a number of competing artifact values, not just the "quality plans as found in QFD." QFD's extended house of quality emerges as a degenerate case of CFD's house of values when 'quality' is one of its 'values' and a set of 'quality characteristics' is one of its 'VCs'. There are many value characteristics (VCs) for artifacts, such as quality, X-ability, tools and technology, costs, responsiveness, infrastructure, and so on. The artifact value deployment is through all its lifecycle phases. CFD deploys the value plans (AVs, VCs, and RCs) concurrently, as opposed to serial deployment of quality plans during QFD. CFD thus breaks the multiyear QFD ordeal by allowing workgroups to work concurrently on a number of conflicting values and compare their output at common checkpoints.

New Product Development and Other Perspectives

Though QFD has been used in many situations, the common usage of QFD is mostly for product improvement.[45] An example of this is the actual design engineering changes to be brought about in the next version of the product, which will incorporate a list of proposed customer desires for improvements.[12] Usage of QFD for generating entirely a new product idea has been very limited.[25] Clausing and Pugh[10] have shown, however, that if the Stuart Pugh[35] concept selection method is coupled with QFD, its usage can be extended to new product introduction.

Such coupling enables teams to evaluate various concepts using the Pugh approach[35] and later determine their technical importance ratings using QFD. Thus, coupling the two methods allows critical evaluation of a number of alternatives before a set of characteristics is finally chosen. The Pugh selection matrix becomes an input to the QFD process. Similarly, Ross[36] has shown that if the Taguchi method and design for experiments are coupled with QFD, its usage can be extended to process improvement. This enables teams to conduct a number of experiments to minimize the impact of variations in the process parameters using Taguchi methods[36] and later determine their importance rating using QFD. Berglund has shown that the concept of QFD is not limited to only quality plans; it can be applied to other lifecycle domains, such as environmental decision making.[5]

CFD is a methodology for concurrently deploying a line of value objectives for successive product refinements leading to a "world-class" category.[34] Also, since each TVM's lifecycle value addresses only a partial set of artifact specifications, the selection of the chosen TVM values will dictate the lifecycle concerns of the entire product. CFD is a simple and powerful tool that leads to long-range strategic thinking and better communication across several value functions.

Concluding Remarks

Quality function deployment (QFD) is a methodology that allows designers and manufacturing engineers to communicate their requirements early during various stages of a PD^3 process. One critical new tool to facilitate this early communication and concurrency is a house of values (HOV). HOV is a concept similar to the house of quality that was introduced by Akao in QFD formulation.[29] However, the term "values" is used here not to mean just "quality plans." It ranges from quality plans as it was in QFD to other values, such as X-ability, tools and technology, cost, responsiveness, Infrastructure, and other similar types of functions. The concept gives rise to a line of concurrent houses; namely house of quality, house of X-ability, house of tools and technology, house of cost, and so on. House of quality, thus, becomes a degenerate or a special case of this series—"house of values" templates. Both methodologies, QFD and CFD, exploit the independence of units that manifest themselves in strategic business units, TQM, and total enterprise management concepts that are now emerging.[45] However, CFD enables planners and strategic decision-makers early on to deal with trade-offs among the crucial factors of artifact values. A number of concurrent values, such as functionality (quality), performance (X-ability), tools and technology (innovation), cost, responsiveness, and infrastructure (delivery) can be deployed simultaneously rather than serially. Three-dimensional value characteristic matrices (VCM) employed in CFD ensure that both company and customer goals are optimally met and that the key artifact values are deployed in parallel tracks, making it less likely to have them ignored by omission.

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References

1. Y.A. Akao, *Quality Function Deployment—Integrating Customer Requirements into Product Design* (Cambridge, MA: Productivity Press, 1990). Also in *Quality Deployment*, a series of articles edited by Yoji Akao, Japanese Standards Assoc. and translated by Glen H. Mazur, GOAL/QPC, Methuen, MA.

2. *Trans.* of 4th Symp. on Quality Function Deployment (QFD), June 15-16, 1992, Novi, MI (American Society for Quality Control (ASQC) Automotive Div., American Supplier Institute (ASI), GOAL/QPC, 1992).

3. A. Aswad, "Quality Function Deployment: A Tool or a Philosophy," SAE paper no. 890163, *Proc.* of SAE Int'l Congress and Exposition, Feb. 27-Mar. 3, 1989, Detroit (Society of Automotive Engineers, 1989).

4. E. Bascaran, "Design Through Selection: The Use of QFD in the Attribute Generation Process," Design Theory and Methodology Conf. (Vol. DE-31) (New York: ASME Press, 1991).

5. R.L. Berglund, "QFD—A Critical Tool for Environmental Decision Making," 47th Annual Quality Congress of the ASQC, Boston, May 24-26, 1993 (American Society for Quality Control, 1993).

6. J.L. Bossert, *Quality Function Deployment: A Practitioner's Approach* (Milwaukee: ASQC Quality Press, 1991).

7. W.R. Carey, "Tools for Today's Engineer—Strategy for Achieving Engineering Excellence, Section 1: Quality Function Deployment," SAE paper no. 920040, *Proc.* of SAE Int'l Congress and Exposition, Feb. 24-28, 1992, Detroit (Society of Automotive Engineers, 1992).

8. K.B. Clark and T. Fujimoto, *Product Development Performance* (Boston: Harvard Business School Press, 1991).

9. D.P. Clausing, *Total Quality Development: A Step-by-Step Guide to World-Class Concurrent Engineering* (New York: ASME Press, 1994).

10. D.P. Clausing and S. Pugh, "Enhanced Quality Function Deployment," Design and Productivity Int'l Conf., Honolulu, HI, Feb. 6-8, 1991. Also in Enhanced QFD Workshop, seminar conducted at General Physics Corp., Troy, MI, Apr. 17-18, 1991.

11. P.B. Crosby, *Quality is Free: The Art of Making Quality Certain* (New York: McGraw-Hill, 1979).

12. R.G. Day, "Using Quality Function Deployment in the Product Development Process," *Journal of Applied Mfg. Systems* (Fall 1993).

13. B.E. Dean, "Quality Function Deployment for Large Systems," *Proc.* of Int'l Eng. Management Conf., Management in a Global Environment, Eatontown, NJ, 1992.

14. W.E. Deming, *Out of Crisis*, 2nd ed. (Cambridge MA: MIT Center for Advanced Eng. Study, 1986).

15. R.J. Dika and R.L. Begley, "Concept Development Through Teamwork—Working for Quality, Cost, Weight and Investment, SAE paper no. 910212, *Proc.* of SAE Int'l Congress and Exposition, Feb. 25-Mar. 1, 1991, Detroit (Society of Automotive Engineers, 1991), pp1-12.

16. N.F.O. Evbuomwan and S. Sivaloganathan, "The Nature, Classification and Management of Tools and Resources for Concurrent Engineering," *Proc.* of 1st Int'l Conf. on Concurrent Eng.: Research & Applications, A.J. Paul and M. Sobolewski, eds., Pittsburgh, Aug. 29-31, 1994, pp119-126.

17. N.F.O. Evbuomwan, S. Sivaloganathan, and A. Jebb, "Concurrent Design with Design Function Deployment," *Proc.* of 2nd Int'l Conf. on Concurrent Eng. and Electronic Design Automation, Apr. 7-8, 1994, Poole, Dorset, UK.

18. A. Griffin and J.R. Hauser, "The Voice of the Customer," working paper (Cambridge, MA: Sloan School of Management, Massachusetts Institute of Technology, 1991).

19. R. Hales, D. Lyman, and R. Norman, "Quality Function Deployment and the Expanded House of Quality," technical report (International TechneGroup Inc., 1990), pp1-12.

20. S. Harr, D.P. Clausing, and S.D. Eppinger, "Integration of Quality Function Deployment and the Design Structure Matrix," working paper no. LMP-93-004 (Cambridge, MA: Laboratory for Mfg. and Productivity, Massachusetts Institute of Technology, 1993).

21. J.R. Hauser, "How Puritan-Bennet Used the House of Quality," *Sloan Management Review* (v34, n3, Spring 1993).

22. J.R. Hauser and D.P. Clausing, "The House of Quality," *Harvard Business Review* (v66, n3, May-June 1988), pp63-73.

23. B. King, *Better Designs in Half the Time—Implementing QFD Quality Function Deployment in America*, 3rd ed. (Methuen, MA: GOAL/QPC, 1989).

24. E. Kroll, "Towards Using Cost Estimates to Guide Concurrent Design Processes," *Proc.* of Winter Annual Meeting of ASME, PED v59, Concurrent Engineering (New York: ASME Press, 1992), pp281-293.

25. M. Liner, "First Experiences Using QFD in New Product Development," *Proc.* of Winter Annual Meeting of ASME, DE v51, Design for Manufacture (New York: ASME Press, 1992).

26. A. Locascio and D.L. Thurston, "Multiattribute Design Optimization Using QFD," *Proc.* of 2nd Industrial Eng. Research Conf. (Norcross, GA: Industrial Eng. and Management Press, 1993).

27. O. Maduri, "Design Planning of an Off-Highway Dump Truck—A QFD Approach," Golden Conf. on Quality Through Eng. Design, v16, W. Kuo, ed. (Elsevier Science Publishers BV, 1993).

28. A.S.M. Masud and E.B. Dean, "Using Fuzzy Sets in Quality Function Deployment," *Proc.* of 2nd Industrial Eng. Research Conf. (Norcross, GA: Industrial Eng. and Management Press, 1993).

29. S. Mizuno and Y. Akao, eds., *Quality Function Deployment: Approach for Total Quality Control* (Tokyo: 1978) (in Japanese).

30. S. Mizuno and Y. Akao, *QFD: The Customer-Driven Approach to Quality Planning and Deployment* (Tokyo: Asian Productivity Organization, 1994).

31. A. Pandey, "Quality Function Deployment: A Study of Implementation and Enhancements," M.Sc. dissertation (Cambridge, MA: Sloan School of Management, Massachusetts Institute of Technology, 1992).

32. B. Prasad, "Product Planning Optimization Using Quality Function Deployment," in *AI in Optimal Design and Manufacturing*, Z. Dong, ed. (Englewood Cliffs, NJ: Prentice-Hall, 1993), pp117-152.

33. B. Prasad, *Concurrent Engineering Fundamentals: Integrated Product and Process Organization*, v1 (Upper Saddle River, NJ: Prentice-Hall PTR, Inc., 1996).

34. B. Prasad, *Concurrent Engineering Fundamentals: Integrated Product Development*, v2 (Upper Saddle River, NJ: Prentice-Hall PTR, Inc., 1997).

35. Stuart Pugh, *Total Design—Integrating Methods for Successful Product Engineering* (Reading, MA: Addison Wesley Publishing Co. Inc., 1991).

36. P.J. Ross, "The Role of Taguchi Methods and Design of Experiments in QFD," *Quality Program* (June 1988), pp41-47.

37. D.M. Scheurell, "Concurrent Engineering and the Entire QFD Process: One Year After Start-up of a New Mill," *Trans.* of 5th Symp. on Quality Function Deployment, QFD Institute, Novi, MI (ASI and GOAL/QPC, 1992).

38. M.L. Shillito, *Advanced QFD-Linking Technology to Market and Company Needs* (New York: John Wiley & Sons, 1994).

39. S. Sivaloganathan and N.F.O. Evbuomwan, "Quality Function Deployment—The Technique: State of the Art and Future Directions," *Concurrent Engineering: Research & Applications*, Special Issue on Enterprise Integration and Management in CE II (v5, n2, June 1997), pp171-182.

40. L.P. Sullivan, "Quality Function Deployment," *Quality Progress* (Vol. XXI, No. 6, June 1986).

41. L.P. Sullivan, "Policy Management Through QFD," *Quality Progress* (Vol. XXIII, No. 6, June 1988).

42. G. Taguchi and D.P. Clausing, "Robust Quality," *Harvard Business Review* (v68, n1, Jan.-Feb. 1990), pp65-75.

43. S. Taguchi, *Taguchi Methods and QFD: HOWs and WHYs for Management* (Dearborn, MI: American Supplier Institute, ASI Press, 1987).

44. J. Terninko, *Step-by-Step QFD Customer Driven Product Design*, 2nd ed. (Boca Raton, FL: CRC Press LLC, imprint St. Lucie Press, 1997).

45. S. Ungvari, "Total Quality Management and Quality Function Deployment," *Proc.* of 3rd Symp. on Quality Function Deployment, June 24-25, 1991.

46. P.M. Wilson and J.G. Greaves, "Forward Engineering—A Strategic Link Between Design and Profit," *Mechatronic Systems Eng.* (vI, 1990), pp53-64.

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