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A concurrent function deployment technique for a workgroup-based engineering design process

BIREN PRASAD†

In this paper, an alternate framework to quality function deployment (QFD) called concurrent function deployment (CFD), suitable for a workgroup-based engineering design process, is described. The methodology exploits the independence of units that manifest itself in a company strategic business unit, total quality management, and enterprise knowledge management concepts. It considers parallel deployments of a number of 'values' in addition to 'quality', as opposed to a serial four-phased deployment of quality. Consider, for example, the popular American Supplier Institute's (ASI's) four-phased QFD concept (Sullivan 1988). ASI's QFD is based on using a single measurement, 'quality', and the four phases called 'quality plans' are deployed serially. CFD employs a concurrent deployment process of its 'value sets'—'quality' happens to be one of its important values. Six concurrent value-sets, namely functionality (quality), performance (X-ability), tools and technology (innovation), cost, responsiveness, and infrastructure (delivery) are considered in CFD, running in parallel rather than serially. In the present setting, Don Clausing's QFD process emerges as a special case of this CFD (Prasad 1998). CFD is more suited early on during a product design and development process—to deal with trade-offs among the crucial factors of artifact values. A set of three-dimensional value characteristics matrices is employed in CFD to ensure that such trade-off goals are adequately addressed.

1. Introduction

While manufacturing philosophies have changed drastically during the 1980s from mass to global manufacturing, the pace of such transitions from 'value management' perspectives has been very slow. Despite painful restructuring, reorganization, and even process re-engineering efforts, both the European and American automotive industries have at times failed to attain parity in product cost, productivity, or throughput with Japanese producers and transplant operations (Wilson and Greaves 1990, Womack *et al.* 1990, Dika and Begley 1991, Liker *et al.* 1995). Earlier published work (King 1989) showed assurances that the competitive gaps could be closed using quality-based deployment techniques (such as quality function deployment (QFD) (Clausing 1994), Taguchi's robust design (Taguchi and Clausing 1990), total quality management (TQM) (Hoffherr *et al.* 1994), etc.). This has motivated abandonment of many traditional functional values at first in favour of quality deployment. Many such combinations have been tried with QFD, along with product development teams (Prasad 1996), integrating with voice of the customer (Akao 1990; Griffin and Hauser 1991; Mizuno and Akao 1994), and with TQM

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(Ungvari 1991). Some important variations of Akao's approach are described by King (1989) in the US as the Growth Opportunity Alliance of Lawrence, Massachusetts/Quality Productivity Centre (GOAL/QPC) approach and by the American Supplier Institute (ASI) as a four-phased approach (Sullivan 1988).

In new product development areas (Liner 1992), QFD combinations have been tried with Pugh's concept (Pugh 1991) for product alternative selection (Clausing and Pugh 1991) and for new product introduction (Liner 1992). In conjunction with Taguchi methods, QFD has been combined with the Taguchi formulation (Taguchi 1987, Taguchi and Clausing 1990), Taguchi with design of experiments (Ross 1988), and Taguchi with TRIZ methods (Russian Theory of Inventive Problem Solving) (Terninko 1997). In conjunction with optimization formulation, QFD has also been combined with multiattribute design optimization (Locascio and Thurston, 1993), with non-linear programming techniques (Prasad 1993), and for decisions using fuzzy sets (Masud and Dean 1993). QFD has also been tried with concurrent engineering techniques (Scheurell 1992, Prasad 1996), for integrated product development (Prasad 1997), with design structure matrix (Harr *et al.* 1993), and with design function deployment (Evbuomwan *et al.* 1994) to obtain better products. Although each QFD-based implementation provided new opportunities and stronger contributions towards product quality improvements, many such QFD-based programmes often dealt with a subset of the total problem that makes a company globally competitive (Sivaloganathan and Evbuomwan 1997). The implementations of QFD in industrial projects are sending conflicting messages as to its success in terms of (a) dealing with large applications/systems (Dean 1992, Hauser 1993, Maduri 1993) within industries and (b) benefits to industrial projects (Pandey 1992, Harr *et al.* 1993). Furthermore, the cost and productivity 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 (Prasad 1997). Most QFD-based 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 the 'Quality-based design') (Evbuomwan and Sivaloganathan 1994).

The application of QFD is a fairly old (over two decades) idea (Hauser and Clausing 1988). Historically, the concept of QFD was introduced by the Japanese (refer, for instance, to Mizuno and Akao 1978, Aswad 1989) in 1967 as a tool for subjectively quantifying the 'quality characteristics' by deploying the voice of customers. It did not emerge as a viable methodology until 1972 when it was applied at the Kobe shipyards of Mitsubishi Heavy Industries (see, for instance, Hales *et al.* 1990, Taguchi 1987, American Society for Quality Control 1992) in Japan. The ASI and GOAL/QPC (see, for instance, Akao 1990, King 1989) have done an excellent job in publicizing this in the US. QFD was designed originally to take the voice of the customer (called customer objectives) and translate them into a set of design parameters (called 'quality characteristics') (Clausing 1994). These can be deployed vertically top-down through a serial four-phase QFD process (Sullivan 1988). The four phases, known as ASI's four-phase QFD process, are: product planning, parts deployment, process planning, and production planning. The overall objective of QFD, which was 'quality plans' deployment when introduced in 1967, today is still the product's quality. Emphasis on quality plans was also the reason why it was named quality function deployment by the Japanese (Crosby 1979, Deming 1986, Taguchi and Clausing 1990). Recently, Don Clausing and other workers have

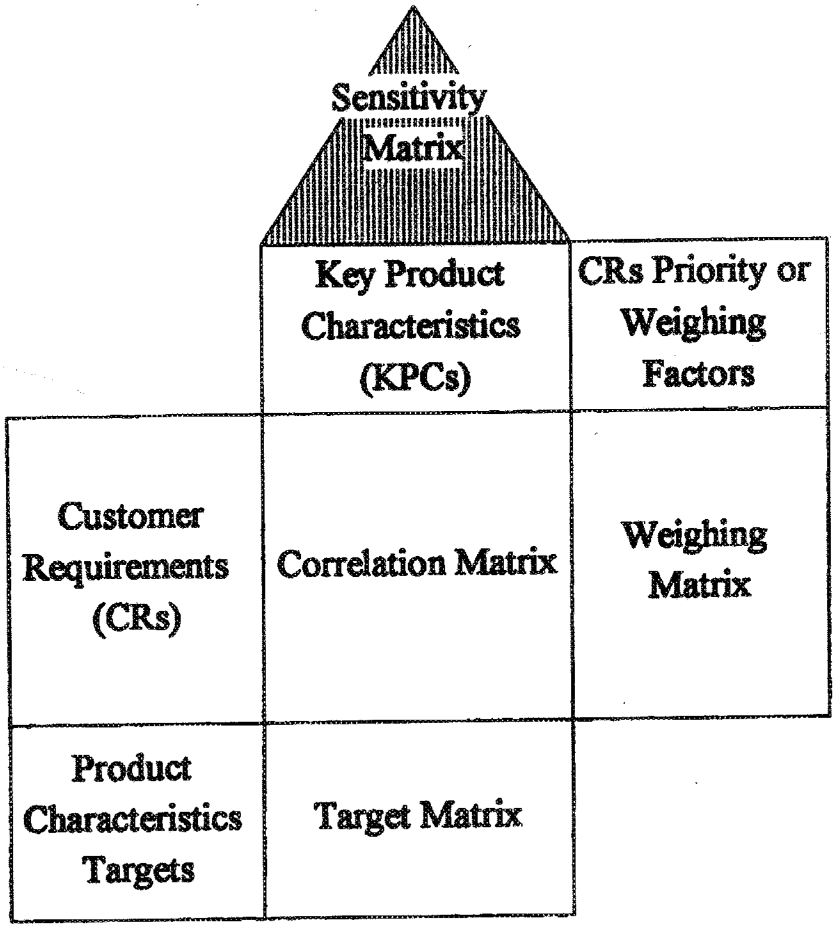

Figure 1. QFD extended house of quality: list vectors and matrices.

introduced some structural changes in the way a QFD template or a set of QFD matrices were initially arranged. The new arrangement is commonly called the extended house of quality (Hales *et al.* 1990, Taguchi and Clausing 1990). Today, QFD use has extended beyond quality such as a design tool; however, the original focus on 'quality characteristics' and its traditional orientation as four-phased deployment has not changed very much (Sivaloganathan and Evbuomwan 1997). This paper advances a newer deployment technique, called concurrent function deployment (CFD), utilizing a concept similar to an extended QFD technique. This CFD technique is most appropriate for 'values' other than 'quality' and its use in concurrent product development (Prasad 1998).

2. Components of an extended QFD

An extended house of quality (HOQ) consists of eight fundamental areas, all of which are not essential (see figure 1). Prasad (1996, figure 2.23) identifies the names of each area, and the door example (Prasad 1996, figure 2.24) gives a glimpse of its full potential. In the following section, we examine its limitation in deploying to a workgroup-based product design process.

3. Limitations in deploying an extended QFD in a workgroup-based design process

In the early 1990s, when the Japanese became successful in bringing cars to market in record time, many automotive world leaders mistakenly assumed that their success was solely because of quality and quality-based tools. This explains the initial flurry of activities with quality (like QFD, TQM, Taguchi, Pugh, Kaizen, etc.) that American industries went through during 1980s. As many American automotive industries failed to be at par with the Japanese on productivity and competitiveness fronts, manufacturers began to unearth the cause of their failures. It did not take very long to realize their apparent pitfalls. They discovered that many of the barriers to global competitiveness were rooted in their quality-centred assumptions. American Manufacturers were basing their product design, development and delivery (PD^3) decisions primary on 'quality characteristics', while ignoring other product design aspects such as costs, design for x-ability, tools and technology, infrastructure (Prasad 1997) and their concurrent use during life-cycle management.

In the early 1980s, when manufacturers based their PD^3 decisions on 'quality plans' while ignoring other important aspects, they did so because it was the right thing to do then (Sullivan 1988). Today, manufacturers consider other aspects such as costs (Hauser 1993), design for x-ability, tools and technology (Bascaran 1991, Carey 1992), environmental factors (Berglund 1993), infrastructure (Ungvari 1991), in addition to quality plans (Mizuno and Akao 1994). Today, quality is given or considered a minimum set of requirements to entry into the commercial marketplace (Sivaloganathan and Evbuomwan 1997). The full set of 'value characteristics', not simply the 'quality plans', has relevance to the overall design output and is required to be deployed with 'quality characteristics' simultaneously.

QFD does not specifically address the cost, tools and technology (Carey 1992), responsiveness (time-to-market) and organizational aspects (Evbuomwan *et al.* 1994) directly—meaning in the same vein as it does to the 'quality' function deployment (FD) aspect (see figure 1) originally. While some may consider the product design process as being independent from technology, design-for X-ability, cost and responsiveness, the reality is that these functions are tied together by a common set of product and process requirements. Design process only provides a product design from a perspective of performance (i.e. quality plans) (Evbuomwan and Sivaloganathan 1994). The product design performance requirements drive the product selection (including system, subsystems, components, parts and material selection) and influence the selection of the fabrication (process and production) method. Other workers have argued that while performing quality FD, designers could choose to include requirements, which belongs to considerations other than quality in the original customers' list of HOQ (Dika and Begley 1991, Carey 1992, Pandey 1992). Satisfying multiple characteristics through a serial deployment process like QFD is not easy (Pandey 1992). Working on the multiple lists of requirements as part of a single function deployment (say under a serial four-phased quality plan) is a complex undertaking (Dean 1992).

- First, if we use a conventional QFD process and if all relational matrices are combined into a single deployment, the size of each of the combined relational matrices would be very large. This is similar to making the QFD procedure 'all embracing' and bringing everyone together at the same time. Ultimately, the information content will rapidly exceed human capacity to absorb it.

- Second, deploying the value characteristics (VCs) serially via a QFD process would obviously be a long drawn-out process.
- Third, cascading the requirements and constraints (RCs), all together, as we did in the case of 'quality function deployment' (through a serial four-phased process) would be very cumbersome, if not impossible. With the size of each relational matrices as large as indicated in the first bullet, it would be difficult to handle the sheer complexity of such four-phased serial deployment.
- Fourth, there is no way of insuring that the design obtained by repeating this 'quality FD' process combinatorially for each VC one at a time (serially) would not result in a sub-optimized design. This means a product may appear to be optimized for a set of all possible value considerations globally but truly may just be optimal with respect to characteristics related to quality only.

What is required in optimizing an artifact is designing a product with respect to all-important functional considerations that characterize a 'world-class product' today. Normally, in actual practice, information for these measurements is independently specified, and tasks in a PD^3 process often proceed in parallel. Paralleling allows the combinatorial problems to be addressed in sizable chunks of tasks, which in turn can be handled by a number of specialized work-groups comfortably (Scheurell 1992). Parallel deployment of values would also allow concurrent teams to work independently on each concurrent task, thus reducing the PD^3 cycle time.

Extended HOQ deployment alone cannot account for the increasing complexities of our product and the conflicting requirements that need to be addressed. As a result, the best efforts of the concurrent workgroups simply do not result in products that optimally meet all types of customer requirements. This is not because the workgroups are not able to work closely, but because the deployment vehicle via QFD is not robust enough to accommodate multiple function deployment simultaneously. Large-scale deployment of QFD—while implementing simultaneously various conflicting value characteristics such as cost, responsiveness, quality, etc. (Pandey 1992) through a standard QFD process—takes a long time. In the absence of any better deployment vehicle, the workgroup may repeat the QFD process for each value (X-ability, etc.) one at a time (Pandey 1992, Evbuomwan *et al.* 1994). This elongates the PD^3 cycle time into a multi-year ordeal. This paper presents a methodology for concurrently deploying a series of value objectives and a value-based plan for successive product refinements, leading to 'world-class manufacturing' (see figures 2–4).

4. Concurrent product development

The first step in creating a great product is an understanding of what exactly makes a product great and how to integrate its process into it. Kim Clark defines a great product as one that meets all pertinent characteristics, which are required to ensure its (product) overall integrity (Clark and Fujimoto 1991). Generally, development of a new artifact does include considerations for several life-cycle values that are pertinent to meeting the customers' requirements. Many of these values are independently specified, meaning there could be very little or no interactions between them. Through a prior course of investigations and study (Prasad 1997), the author has found that the deployment of many non-quality artifact functions or values can proceed in parallel with 'quality' FD as shown in figure 2.

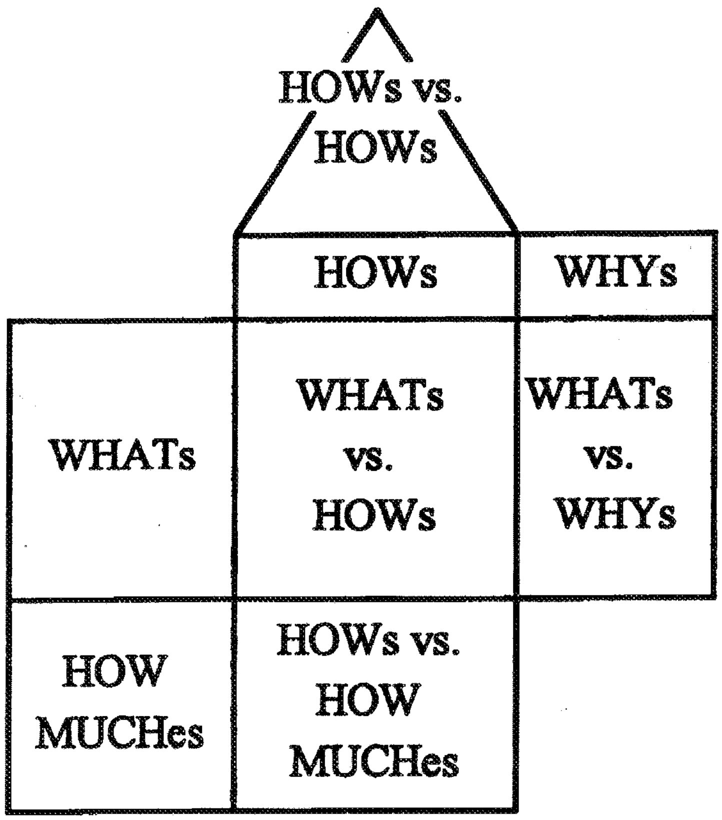

Figure 2. Typical house of values template for each X_i, $I = 1, 6$.

Examples are: x-ability (performance) (Shillito 1994) FD, tools and technology FD (Carey 1992), cost FD (Kroll 1992), responsiveness FD and infrastructure FD. Generally, these functions or values are independently specified or estimated (Kroll 1992) by work-groups in a concurrent engineering organization. The results of experience can be used to specify the requirements and expectations for each of the 'values' in parallel without having to wait until a deployment of 'quality FD' is complete.

5. Concurrent function deployment

To eliminate the phased (serial) nature of deployments in QFD, Prasad expanded the original definition of extended quality FD to include parallel deployments of multiple functions and features (Prasad 1998). The author has called this approach concurrent function deployment (CFD) since it entails parallel deployments of competing product values. CFD provides a method to deploy competing values simultaneously and assign concurrent work-groups to accomplish the jobs in an orderly non-serial fashion.

5.1. CFD architecture

CFD uses a three-axis approach for orderly deployment of its value functions or features (see figure 3). It spans three dimensions: horizontal (x axis), axial (y axis), and vertical (z axis) (Prasad 1997). Artifact values (AVs) are deployed along the x axis, VCs, associated with each class of artifact values, are deployed along the y axis and RCs are deployed along the z axis (see figure 3). The components of axial

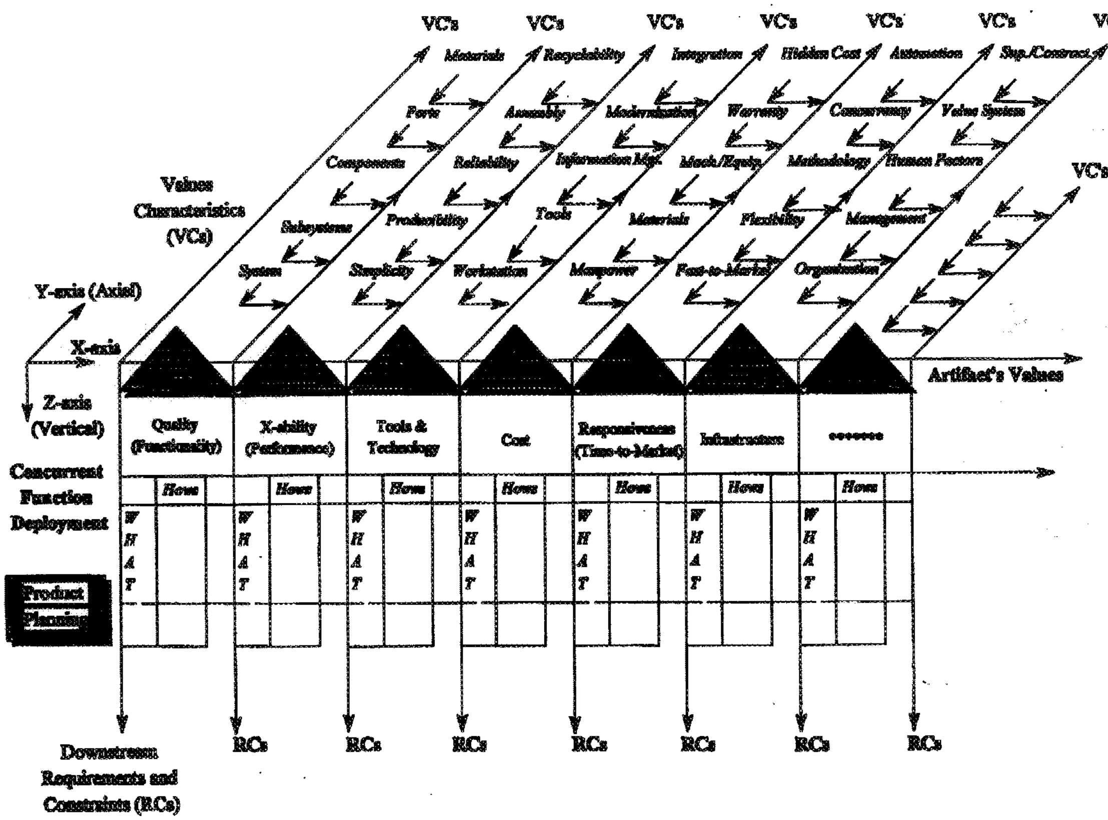

Figure 3. Concurrent function deployment: three-dimensional deployment schema. (a) Artifact values along the x axis; (b) value characteristics along the y axis; and (c) requirements and constraints along the z axis.

and horizontal dimensions are arranged in a matrix and deployed concurrently, while vertical dimension is staggered in tier form. The VC vector for each value class is identified so that specifications developed, using this methodology, will yield an optimum product configuration for the first time and every time the CFD is used. The methodology is considered independent of the types of manufacturing processes and products to be designed.

Let us denote, the following: X_i represents an ith track of an AV for horizontal deployment, Y_{ij} represents a jth level VC for axial deployment, and Z_{ijk} represents a kth tier RC for vertical deployment. The following is the process used for concurrent function deployment.

5.1.1. Step 1: horizontal deployment. The CFD process starts with a horizontal deployment of an artifact value, X_i. The workgroup chooses a set of artifact values (along the x axis) that need to be deployed. Deployment is concurrent, meaning deployment for each VC can proceed in parallel. X_i represents an ith track of an artifact value. The following artifact values are commonly found relevant during product development.

A typical X_i for a six-value set ($i = 1, 6$) may look like:

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

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

$$X_3 = \text{tools and technology} \tag{3}$$

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

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

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

Similar to QFD, 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 or list vectors. The basic matrix of CFD is *the* 'house of values', so named to keep resemblance with 'house of quality' that forms one of the many objectives of CFD (Prasad 1998). The relational matrix in CFD translates the corresponding RCs into VCs.

Figure 2 is a schematic view of a multi-dimensional 'house of values (HOV)' template that results from such deployment. If the quality is the only consideration in design, this template degenerates to an extended house of quality template (Prasad 1998). Similar to an extended house of quality template, this HOV template has eight rooms. Four of the rooms are along the basic perimeters of the house. There are two row-rooms, WHATs and HOW-MUCHes, and two column-rooms, HOWs and WHYs. Concurrent HOV also encompasses relationships among these four list vectors, resulting in four sets of 'relational matrices':

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

5.1.2. Step 2: axial deployment. The second step is to identify a set of axial (y axis) VCs, Y_{ij}, for axial deployment corresponding to each X_i. This process is concurrent, meaning the VC functions corresponding to an artifact value that can be deployed simultaneously.

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

where Y_{ij} is a matrix. j takes a value from 1 to J and J is the maximum number of VC levels selected for an ith value track. A typical Y_{ij} for a matrix of size ($I = 6$ and $J = 5$) is shown in table 1 for illustration.

5.1.3. Step 3: vertical deployment. The third step is the vertical deployment of Y_{ij} in relation to RCs for each kth tier. X_i and Y_{ij} are the artifact value and VC functions that were identified in steps 1 and 2, respectively. There are three tiers to CFD deployment, tier $k = 1$ through tier $k = 3$. A tier structure means a line of vertical (z axis) deployment series proceeds before the next tier of vertical deployment series begins. This means there is an overlap between tiers. Tier deployment does not require reaching the end of one tier before starting another (not phased-in as in QFD). From these definitions:

$$Z_{ijk} \quad \text{for} \quad 1 \le i \le I, 1 \le j \le J \quad \text{and} \quad 1 \le k \le K \tag{8}$$

Where Z_{ijk} represents a kth tier for vertical deployment. k takes number 1, 2, 3 corresponding to tiers 1, 2 and 3, respectively.

Y_{ij}, $i = 1, 6$ and $j = 1, 5$	X_1 = quality (functionality)	X_2 = X-ability (performance)	X_3 = tools and technology	X_4 = cost	X_5 = responsiveness (time to market)	X_6 = infrastructure
Y_1	Systems	Simplicity	Workstation	Manpower	Fast to market	Organization
Y_2	Subsystems	Producability	Tools	Materials	Flexibility	Management
Y_3	Components	Reliability	Information management	Machines/ equipment	Methodology	Human factors
Y_4	Parts	Assembly	Modernization	Warranty	Concurrency	Value system
Y_5	Materials	Recyclability	Integration	Hidden cost	Automation	Supplier/ contractor

Table 1. A typical *Yij* matrix (when $I = 6$ and $J = 5$)

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

$$Z_{ij}1 \equiv \text{product planning (tier 1)} \tag{9}$$

$$Z_{ij}2 \equiv \text{process planning (tier 2)} \tag{10}$$

$$Z_{ij}3 \equiv \text{production planning (tier 3)} \tag{11}$$

Deployment through a particular tier (say 1, 2 or 3) completes a CFD pass. The presented set of three steps, described earlier, form a trio (horizontal–axial–vertical) deployment. CFD is complete if a series of trio (horizontal–axial–vertical) deployment is carried out for all passes and for all value tracks, X_i.

5.2. *Trio deployment technique*

As already discussed, the three-step CFD architecture utilizes a trio (horizontal–axial–vertical, . . .) deployment technique (see figure 3) to arrive at the end of the first pass. This results in a product design validated with a manufacturing process concept. During 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 repeated for tiers 2 and 3.

$$\text{First pass} \equiv \text{(horizontal–axial–vertical) for tier 1} \tag{12}$$

$$\text{Second pass} \equiv \text{(horizontal–axial–vertical) for tier 2} \tag{13}$$

$$\text{Third pass} \equiv \text{(horizontal–axial–vertical) for tier 3} \tag{14}$$

At each tier level, differences between proposed RCs and the computed outputs provide a measure of the differences that exist among alternate trial designs. If a specification chart is being developed for the product, the taxonomy for RCs must reflect all value considerations. RCs thus include customer requirements (CRs), voices of customers and all types of WHATs that a global company may encounter to be a 'world-class' producer. Dealing with 'value characteristics' at each tier level is also straightforward, since problem definitions (number of RCs, inputs, and the transformation matrix) are small and manageable at that scale. Satisfaction of RCs during these early tier levels (say during first, second or third pass) is easier when problem definition is more explicit in form than when the product is somewhat mature, say after the product has crossed several decision boundaries.

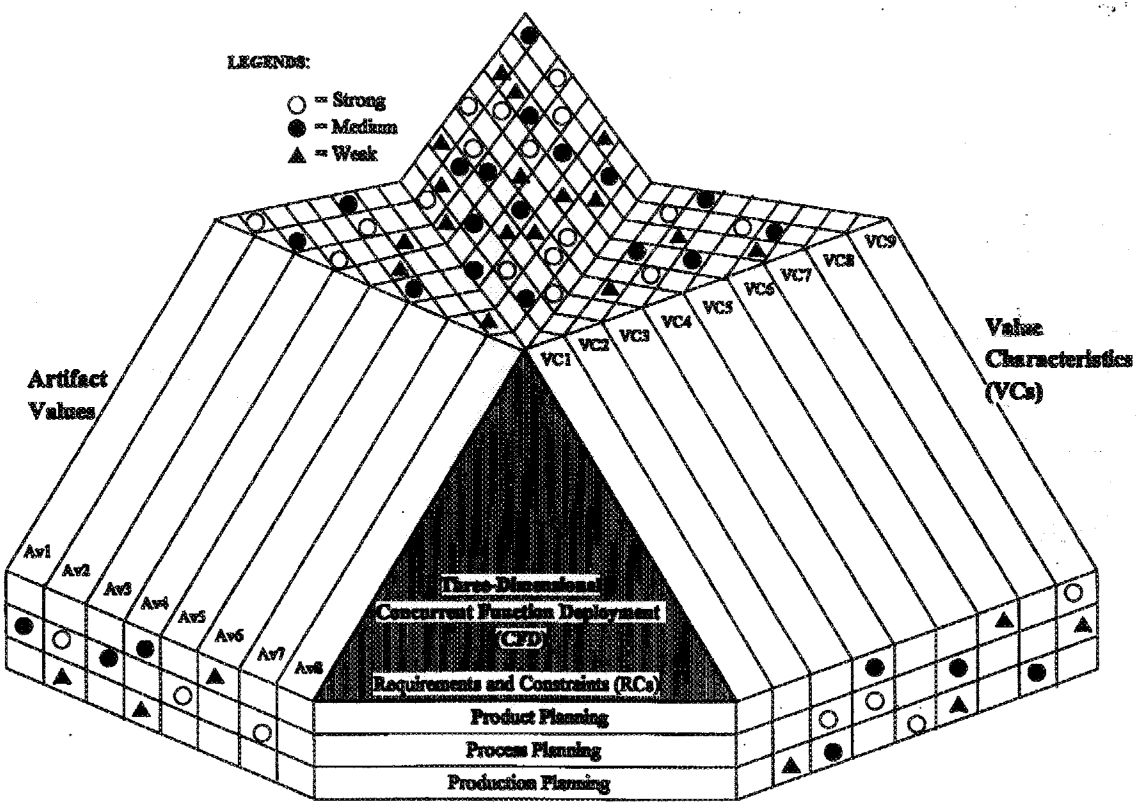

Figure 4. Relationship between CFD components.

6. CFD methodology

CFD is a methodology that allows designers and manufacturing engineers to communicate early and work in parallel during various stages of a PD^3 process. One critical new tool to facilitate this early communication is 'house of values', which is a concept similar to the extended 'house of quality' introduced in Akao's QFD. However, the term 'values' is not used here to mean only 'quality'. It ranges from quality characteristics, as it was in the conventional deployment, to other value characteristics imposed by attributes, such as X-ability, tools and technology, cost, responsiveness, infrastructure and other similar type of functions. The CFD 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, etc. House of quality thus becomes a degenerate or a special case of this CFD series—'House of Values'—template.

6.1. Three-dimensional house of values

The relationships between CFD components are shown in figure 4. The three-dimensional matrix takes the form of three roofs and three relational matrices as shown in figure 4. It has three list vectors: artifact values, value characteristics, and requirements and constraints. Eight elements of AVs, nine elements of VCs and three major elements of RCs vectors are shown in figure 4 for illustration purposes. These lists may contain any number of values as necessary. The line vectors are:

- RCs is deployed along the z axis (vertical dimension)
- AVs are deployed along the x axis (horizontal dimension)
- VCs are deployed along the y axis (axial dimension).

The three relational matrices are:

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

These relational matrices are also shown in figure 4. This completes the CFD's concurrent deployment of values along the three independent axes. This process of trio deployment is very much concurrent. There are overlaps between vertical (z axis), axial (y axis) and horizontal (x axis) passage from start and end-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 workgroups, etc.). It is a concept of three-dimensional (concurrent trio structure) deployment. This trio process 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 typical CFD pass of deployment) (see figure 3). Other WHATs and HOWs are further addressed in greater detail in subsequent passes. The process leads to a selection of the best design and process (HOWs) for the overall product specifications (WHATs). CFD's WHYs and HOW-MUCHes metrics support this selection with sound analytical rationale and targets for quality (functionality), cost (profitability), X-ability (performance), tools and technology (innovation), responsiveness (time-to-market, flexibility, etc.) and infrastructure goals performed almost simultaneously. The CFD methodology drastically reduces dependence on trial and error methods such as 'prototype fabrication' or testing.

6.2. *A degenerate case of CFD*

The next section illustrates a degenerate case of CFD, that is deploying a quality FD through a CFD trio process. This concept is virtually equivalent to a conventional deployment (similar to QFD for instance) where the 'quality' is the primary 'value function' for deployment.

6.3. *Quality FD—an example*

Products are often divided into logical hierarchical blocks depending upon their complexity levels. Different parallel workgroups can work in these different hierarchical groups. Work-groups at each level can work concurrently. Some dependencies can exist between the levels. Establishing common quality standards for communications and definitions of VCs can allow parallel work-groups to work concurrently. The most commonly employed quality characteristics, Y_{ij}, are (Prasad 1993):

(1.1) Assembly
(1.2) Sub-assemblies
(1.3) Components
(1.4) Parts
(1.5) Materials, etc.

where Y_{ij} for $i = 1$ (quality FD) and $j = 1, 5$.

Figure 3 also shows this set of 'quality characteristics' spanned along the axial (y axis) dimension for a CFD setting. In figure 5, the 'quality' value for CFD tier 1 is further spanned axially (along the y axis) into its characteristic (VCs). This axial

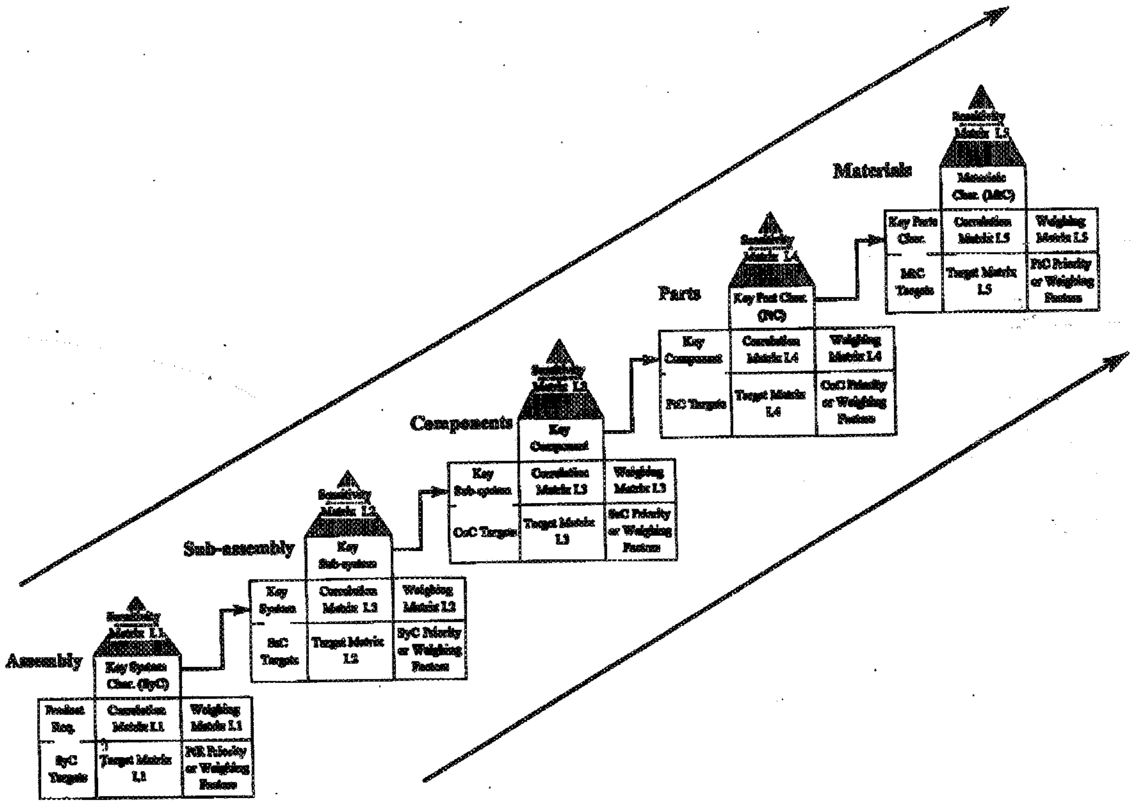

Figure 5. Linked CFD house of values for quality: axial deployment (y axis).

expansion corresponds to the five VCs for quality that were listed in figure 3. The axial expansion of the product planning tier ($Y_{ij}, j = 1, 5$; levels $I.1$ through level $I.5$) uses a set of key product characteristics—PtCs, defined in tier 1 to evaluate alternatives and filter a design that meets most of the customers' demands. At the end of tier 1 (level $I.5$), a set of key product characteristics, PtCs, is identified that represents best of the class (see figure 5). Process planning (tier 2) deals with the selection of process concept and identification of critical operation parameters, here called key process characteristics (PsCs), which can cause the product characteristics, PtCs, identified in tier 1 to be satisfied. Production planning (tier 3) identifies key production characteristics, PnCs, (control requirements, maintenance requirements, mistake proofing, education and training issues, etc.) in line with the key process (PsCs) characteristics identified in tier 2.

Figure 6 illustrates the CFD concept of deploying quality RCs vertically (along the z axis), often embedded in the voice of the customer. The three-tier deployment structure is shown in figure 6 for the quality FD. Tier 1 is for a product planning path, tier 2 for a process planning path, and Tier 3 is for a production planning path. The same three-dimensional trio process is repeated for each tier. For example, during product planning, CRs or WHATs are related to key quality-characteristics, for which a list of WHYs and a list of HOW-MUCHes are then identified. HOWs define the desired key product characteristics (PtCs) of a product to counter the WHATs. WHYs are the overall evaluation criteria used within the organization to define acceptability of the product. Targets for the PtCs (HOW-MUCHes) are established based upon competitive benchmarks and the customer's competitive assessment. Such deployment methodology is followed for tier 2 and the tier 3 trio sequences.

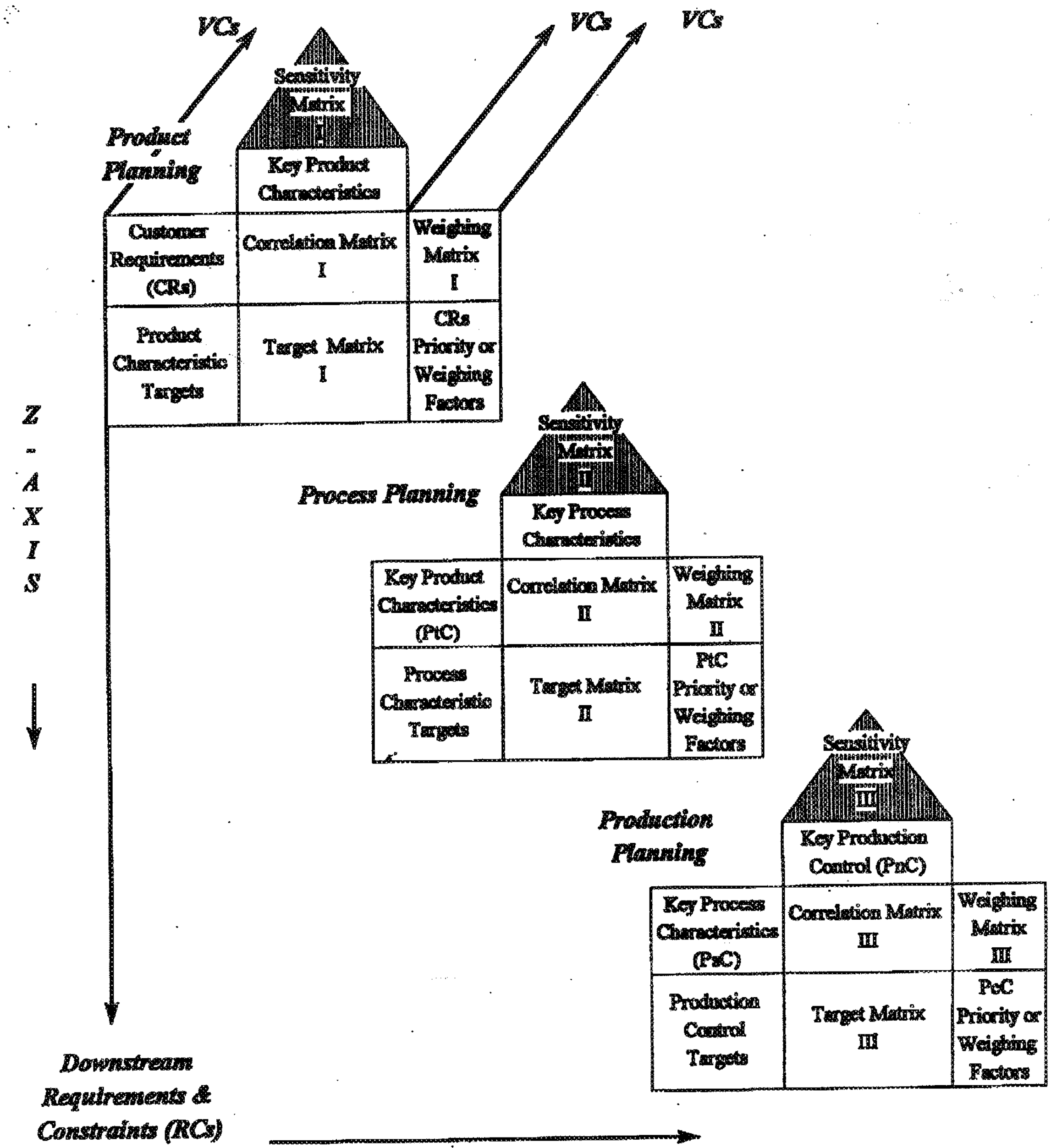

Figure 6. Linked CFD house of values for quality: vertical deployment (z axis).

7. Analysis of benefits

Table 2 compares a conventional deployment technique (such as ASI's QFD approach) and CFD approaches in great depth. ASI's QFD is actually a subset of CFD template.

In most traditional deployment processes (also true with QFD), quality is generally associated with manufacturing, for which several quality measurement tools are typically employed. For instance, activities such as performance measurements, dimensional control, and others, are often used to check 'quality characteristics' compliance during manufacturing. In reality, such measurements need not be limited to only quality. Quality is a necessary requirement but not sufficient to make a company self-reliant and competitive in the marketplace. Considerations of values

Conventional deployment (e.g. QFD)	Concurrent function deployment
Conventional deployment is a phased (or serial process	CFD is a concurrent process
Conventional deployment is inside-out focused	CFD is outside-in holistically focused
Conventional deployment works with the pieces of objects (car door, roof, hinges, etc.)	CFD works with the whole product rather than its pieces
Conventional deployment is mainly successful in solving pockets of problems	CFD is used in conjunction with company mission deployment principles
Conventional deployment is a problem-solving process (e.g. a rusty car door, a leaking seal, etc.) or sometimes a re-design process	Asystematic approach to handling all life-cycle values relevant to the product
Conventional deployment focuses on technical parameters that are not necessarily looped back to the whole product	Customer requirements are considered separately from QCs values
Conventional deployment provides a technical importance rating for quality characteristics (QCs)	CFD provides a value index—cummulative effectiveness rating
Conventional deployment deals with pieces of product or pieces of requirements	CFD optimizes the system with consistency of purpose as target goals
Because of its serial nature of processing, conventional deployment is perceived to take a long time	Because of its concurrent processing, CFD is conceived to be faster than conventional deployment

Table 2. Comparison of CFD with a conventional deployment.

and functions in addition to quality are essential for weighing the decisions that are made during an entire product life cycle.

CFD methodology promotes a concurrent deployment process and, as such, quality in CFD begins with the quality of the introduced AVs, VCs and RCs. AVs, VCs and RCs, in this context, are not only those sets specified by the customers, but also include those sets introduced directly by the cooperating concurrent engineering teams (Prasad *et al.* 1993). The burden of poor outcome of a design in a conventional deployment process has been shifted from the work-groups expertise in product manufacturing to the teams' choice (or selection) of AVs, VCs and RCs at each CFD transformation pass. If appropriate methods can be employed in systematically classifying, deploying, and solving the transformed problems, the assurance of VCs' considerations during CFD becomes merely a scheduling and distribution job. Quality considerations are ensured by the proper selection of matrices (AVs, VCs, and RCs) and methods for solving the constrained problems. Satisfaction of RCs and VCs at each trio pass (transformation state) is what constitutes an 'artifact's values (AVs) deployment'. By following this trio methodology, it is expected that the taxonomy of transformation (Prasad 1996) would lead to a great 'world-class product', whose 'value characteristics (VCs)' are appropriately distributed across various levels of transformation. The intent of CFD is to incorporate 'voice of the customers' into all nine phases of the product development cycle through mission definition, concept definition, engineering and analysis, product design, prototyping, production engineering and planning, production operations and control, manufacturing and, finally, into continuous improvement, support and delivery (see Prasad 1996, figure 4.2). In other words, CFD is customer-driven PD^3 methodology. The RCs and VCs identified for an artifact can be plotted as shown in figure 3. Such taxonomy will ensure that all-important aspects for product and process designs have been identified and included. The focus of CFD is on systematically capturing product and process information, such as market competitive analysis and customer satisfaction rating, analyzing these ratings to improve product functionality (say an X-ability value) and then adding an array of values that are important to both—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'. The 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 VCs for artifacts such as quality, X-ability, tools and technology, costs, responsiveness, infrastructure, etc. The artifact value deployment is through all its life-cycle phases. CFD, deploys the value plans (AVs, VCs and RCs) concurrently, as opposed to serial (in-turn) deployment of quality plans during concurrent product development. CFD, thus, breaks the multi-year QFD ordeal by allowing work-groups to work concurrently on a number of conflicting values and compare their results at common checkpoints (in this case pass 1 through pass 3).

8. Concluding remarks

In the example described herein, only a three-tier trio (horizontal–axial–vertical) structure for CFD is shown. This is the most common (Prasad 1997). However, such a CFD structure can have as many tiers as needed. In the proposed development, the filtering process is shown through a solid pipeline connecting the 'characteristics' (HOWs) room to the WHATs room (see figure 5). It ensures that VCs (namely PtCs, PsCs and PnCs) which are critical to meeting the product, process, and production objectives are given proper and early attentions (during y-axis deployment). It also ensures that HOWs are further deployed into their root or key characteristic factors during the subsequent vertical tiers (z axis deployment). In order to make this practical, however, some computer tools and aids need to be developed to capture this methodology. The manuscript, due to the limitations in releasing proprietary information, could not include results of some benchmarking studies. Adequate technical benchmarking, implementation examples, case studies or mathematical development of CFD methodology are future topics of research yet to be pursued. In summary, more research work needs to be done, but not necessarily by this author alone. Also, effective introduction requires total buy-in at all levels in the organization and is likely to be derailed by any 'non-believer'.

References

AKAO, Y. A., 1990, *Quality Function Deployment—Integrating Customer Requirements into Product Design* (Cambridge, MA: Productivity Press Inc.). Also in AKAO, Y., ed., 1990, *Quality Deployment*, translated by Glen Mazur, Methuen, MA: Japanese Standards Association and GOAL/QPC.

AMERICAN SOCIETY FOR QUALITY CONTROL, 1992, *Transactions from the Fourth Symposium on Quality Function Deployment (QFD)*, 15–16 June (Novi, MI: Automotive Division, American Supplier Institute (ASI), GOAL/QPC).

ASWAD, A., 1989, Quality function deployment: a tool or a philosophy. SAE Paper No. 890163, Society of Automotive Engineers, International Congress and Exposition, 27 February–3 March.

BASCARAN, E., 1991, Design through selection: the use of QFD in the attribute generation process. *Design Theory and Methodology Conference, Vol. DE-31* (New York, NY: ASME Press).

BERGLUND, R. L., 1993, QFD—a critical tool for environmental decision-making. 47th Annual Quality Congress of the ASQC, 24–26 May (Boston, MA).

CAREY, W. R., 1992, Tools for today's engineer—strategy for achieving engineering excellence: Section 1: quality function deployment, SP-913, SAE Paper # 920040. Proceedings of the SAE International Congress and Exposition, 24–28 February (Detroit, MI).

CLARK, K. B. and FUJIMOTO, T., 1991, *Product Development Performance* (Boston, MA: Harvard Business School Press).

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

CLAUSING, D. P. and PUGH, S., 1991, Enhanced quality function deployment. Design and Productivity International Conference, 6–8 February (Honolulu, HA). Also in Enhanced QFD workshop. Seminar Conducted at General Physics Corp., 17–18 April (Troy, MI).

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

DEAN, B. E., 1992, Quality function deployment for large systems. Proceedings of the International Engineering Management Conference, Management in a Global Environment (Eatontown, NJ: Sheraton Hotel and Conference Center).

DEMING, W. E., 1986, *Out of Crisis*, 2nd edition (Cambridge MA: MIT Center for Advanced Engineering Study).

DIKA, R. J. and BEGLEY, R. L., 1991, Concept development through teamwork—working for quality, cost, weight and investment, SAE Paper # 910212. Proceedings of the SAE International Congress and Exposition, 25 February–1 March (Detroit, MI: SAE), pp. 1–12.

EVBUOMWAN, N. F. O. and SIVALOGANATHAN, S., 1994, The nature, classification and management of tools and resources for concurrent engineering. In: Proceedings of the Ist International Conference on Concurrent Engineering: Research & Applications, edited by A. J. Paul and M. Sobolewski, 29–31 August (Pittsburgh, PA), pp. 119–126.

EVBUOMWAN, N. F. O., SIVALOGANATHAN, S. and JEBB, A., 1994, Concurrent design with design function deployment. Proceedings of the 2nd International Conference on Concurrent Engineering and Electronic Design Automation, 7–8 April (Poole, Dorset, UK: Haven Hotel).

GRIFFIN, A. and HAUSER, J. R., 1991, The voice of the customer. Working Paper, Sloan School of Management of the Massachusetts School of Management, Cambridge, MA.

HALES, R., LYMAN, D. and NORMAN, R., 1990, Quality function deployment and the expanded house of quality. Technical Report, International TechneGroup Inc., Ohio, pp. 1–12.

HARR, S., CLAUSING, D. P. and EPPINGER, S. D., 1993, Integration of quality function deployment and the design structure matrix. Working Paper No. LMP-93-004, Laboratory for Manufacturing and Productivity, Massachusetts Institute of Technology, Cambridge, MA.

HAUSER, J. R., 1993, How Puritan–Bennet used the house of quality. *Sloan Management Review*, **34**.

HAUSER, J. R. and CLAUSING, D. P., 1988, The House of Quality. *Harvard Business Review*, **66**, 63–73.

HOFFHERR, G. D., MORAN, J. W. and NADLER, G., 1994, *Breakthrough Thinking in Total Quality Management* (Norcross, GA: Industrial Engineering and Management Press, Institute of Industrial Engineers; and Englewood Cliffs, NJ: PTR Prentice Hall).

KING, B., 1989, *Better Designs in Half the Time—Implementing QFD Quality Function Deployment in America* (Methnen, MA: GOAL/QPC).

KROLL, E., 1992, Towards using cost estimates to guide concurrent design processes, PED-Vol. 59, Concurrent Engineering, ASME. In: Proceedings of the Winter Annual Meeting of ASME, edited by Dutta, W., Chandrashekhar, B. *et al.*, 8–13 November (Anaheim, CA: ASME Press), pp. 281–293.

LIKER, J., ETTLIE, J. and CAMPBELL, J., 1995, *Engineered in Japan: Japanese Technology Management Practices* (New York: Oxford University Press).

LINER, M., 1992, First experiences using QFD in new product development, *Design for manufacture*. A. Agogino (Editor) In: Proceedings of the Winter Annual Meeting of ASME, edited by A. Agogino Anaheim, CA, 8–13 November Volume DE-51 (New York: ASME Press).

LOCASCIO, A. and THURSTON, D. L., 1993, Multiattribute design optimization using QFD. In:

Proceedings of the 2nd Industrial Engineering Research Conference, edited by D. A. Mitta *et al.* (Norcross, GA: Industrial Engineering and Management Press).

MADURI, O., 1993, Design planning of an off-highway dump truck—a QFD approach. Golden Conference on Quality through Engineering Design, edited by W. Kuo (Amsterdam: Elsevier Science Publishers BV), Volume 16.

MASUD, A. S. M. and DEAN, E. B., 1993, Using fuzzy sets in quality function deployment. In: Proceedings of the 2nd Industrial Engineering Research Conference, edited by D. A. Mitta *et al.* (Norcross, GA: Industrial Engineering and Management Press).

MIZUNO, S. and AKAO, Y., 1978, *Quality Function Deployment: Approach for Total Quality Control, JUSE* (published in Japanese) (Tokyo).

MIZUNO, S. and AKAO, Y., 1994, *QFD: The Customer-driven Approach to Quality Planning and Deployment* (Tokyo: Asian Productivity Organization).

PANDEY, A., 1992, 'Quality function deployment: a study of implementation and enhancements. M.Sc. Dissertation, Sloan School of Management, Massachusetts School of Technology, Cambridge, MA.

PRASAD, B., 1993, Product planning optimization using quality function deployment. In: *AI in Optimal Design and Manufacturing*, edited by Z. Dong, series editor M. Jamshidi (Englewood, NJ: Prentice Hall), pp. 117–152.

PRASAD, B., 1996, *Concurrent Engineering Fundamentals: Integrated Product and Process Organization, Volume 1* (Upper Saddle River, NJ: Prentice Hall).

PRASAD, B., 1997, *Concurrent Engineering Fundamentals: Integrated Product Development, Volume 2* (Upper Saddle River, NJ: Prentice Hall).

PRASAD, B., 1998, Review of QFD and related deployment techniques. *Journal of Manufacturing Systems, Society of Manufacturing Engineers (SME)*, **17**, 221–234.

PRASAD, B., MORENC, R. S. and RANGAN, R. M., 1993, Information management for concurrent engineering: research issues. *Concurrent Engineering: Research & Applications*, **I**, 1–19.

PUGH, S., 1991, *Total Design—Integrating Methods for Successful Product Engineering* (New York: Addison Wesley).

ROSS, P. J., 1988, The role of Taguchi methods and design of experiments in QFD. *Quality Program*, June, 41–47.

SCHEURELL, D. M., 1992, Concurrent engineering and the entire QFD process: one year after start-up of a new mill. Transactions of the Fifth Symposium on Quality Function Deployment (Novi, MI: QFD Institute) (Co-sponsored by ASI and GOAL/QPC).

SHILLITO, M. L., 1994, *Advanced QFD—Linking Technology to Market and Company Needs* (New York: John Wiley and Sons).

SIVALOGANATHAN, S. and EVBUOMWAN, N. F. O., 1997, Quality function deployment—the technique: state of the art and future directions. *Concurrent Engineering: Research & Applications*, **5**, 171–182.

SULLIVAN, L. P., 1988, Policy management through QFD. *Quality Progress*, **XXIII**.

TAGUCHI, G. and CLAUSING, D. P., 1990, Robust quality. *Harvard Business Review*, **68**, 65–75.

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

TERNINKO, J., 1997, *Step-by-Step QFD Customer Driven Product Design*, 2nd edition (Boca Raton, FL: CRC Press LLC (Imprint St. Lucie Press)).

UNGVARI, S., 1991, Total quality management and quality function deployment. Proceedings of the 3rd Symposium on Quality Function Deployment, Michigan, 24–25 June.

WILSON, P. M. and GREAVES, J. G., 1990, Forward engineering—a strategic link between design and profit. *Mechatronic Systems Engineering*, **I**, 53–64.

WOMACK, J. P., JONES, D. T. and ROOS, D., 1990, *The Machine That Changed the World* (New York: Macmillan Publishing).