QUALITY FUNCTION DEPLOYMENT AS A TOOL FOR IMPLEMENTING COST AS AN INDEPENDENT VARIABLE

David R. Wollover

The essence of cost as an independent variable (CAIV) is using reliable tools to balance cost with mission needs for new program development. This article addresses concerns about implementing CAIV for Department of Defense (DoD) acquisition programs that vary by scope, budget, and dimension. Perhaps no single CAIV implementation tool is robust enough to apply to all cases. However, we are interested in tools to implement CAIV for a maximum number of programs to collect lessons learned and related beneficial aspects of the CAIV learning curve.

This article describes and illustrates Quality Function Deployment (QFD) as a tool with good potential to help implement CAIV for a variety of DoD acquisition programs. An example of a generic acquisition system (a weapon system in this writing) not attributed to any specific program is used. The example is actually elementary compared to some advanced QFD applications. However, it is still manifold enough to illustrate a fairly detailed QFD application. While this paper focuses on a weapon system, the same process may be applied to automated information system (AIS) programs, with appropriate modifications.

QFD consists of six general steps: (a) identifying and analyzing customer needs and requirements, (b) identifying technical performance measures (TPMs), (c) benchmarking TPMs, (d) assigning priority to customer requirements, (e) establishing TPMs to identify specific design characteristics, and (f) evolving technical performance measures into the follow-up design phase's requirements. This elementary example will illustrate QFD, providing a framework to transform vague customer requirement statements into TPMs that are deployed throughout system design and development.

DoD has adopted a strategy to use aggressive, realistic cost objectives to acquire systems, and managing risks to obtain objectives. These objectives must balance mission needs with projected out-year resources, accounting for existing technology as well as high-confidence maturation of new technologies.

This concept is called cost as an independent variable (CAIV), meaning that once a system's performance and objective costs are decided on the basis of cost-performance tradeoffs, the acquisition process establishes cost as a constraint, rather than as a dependent variable, while still getting the needed military capability (ODUSD [AR]), 1996). Tradeoffs are made among cost, schedule, and performance based on CAIV analysis (Office of the Secretary of Defense, 1996).

In a Dec. 4, 1995, memorandum on life cycle cost reduction, Dr. Paul Kaminski requested: (a) cost performance trades; (b) aggressive program management, making cost a major independent driver, while preserving warfighter requirements; (c) expanding use of existing techniques to meet program goals; and (d) reducing unnecessary program and product complexity (Kaminski, 1995).

Guidance attached to Kaminski's memorandum calls for CAIV to include: (a) adopting aggressive realistic cost goals for operations and support, as well as production, with well-defined steps leading to objectives; (b) using existing practices proven to have managed meeting customer requirements; and (c) formalizing the cost-performance tradeoff process through performance specifications used to state requirements in a manner that clearly directs the CAIV process to evaluate all pertinent design parameters that serve as key metrics and observables, while assuring preserving needed military capability (Longuemare, 1995).

CAIV METRIC AND OBSERVABLES

The CAIV Working Group Paper Summary, an attachment to Kaminski (1995), describes the instrumental role of key metrics and observables. This attachment describes the importance of setting early cost objectives. The ability to set cost objectives depends on results of early cost-performance tradeoff analyses. Metrics and observables are needed to assess CAIV implementation progress.

Metrics and observables identify observable steps for meeting aggressive production and operations and support cost objectives, and then managing for their achievement. Conrow (1995, p. 209) indicates that a significant influence on creating DoD program development cost, and technical and schedule risk is incorrectly

David R. Wollover is currently a candidate for the Master of Engineering Administration degree from Virginia Polytechnic and State University. Previously, he completed separate master's degrees in Resource Economics and Regional Planning. In 1985, he became an operations research analyst with the U.S. Navy , and then worked with the Air Force Center for Studies and Analyses from 1987 to 1989. In 1989, he joined Applied Research, Inc., and has provided direct cost analysis support to the Ballistic Missile Defense Organization for over five years, focusing on preparing LCC estimates for major systems facing acquisition milestone review. Currently a contract member of the Senior Staff for the United Missile Defense Company (UMDC), he performs LCC analysis and Cost as an Independent Variable (CAIV) in a systems engineering environment. He is a member of the Society of Cost Estimating and Analysis, has served as a referee for the *Journal of Cost Analysis,* and presented various cost analysis papers for SCEA, ISPA, and REVIC Users Group. The Certified Cost Estimator/Analyst (CCE/A) professional designation was attained in 1989.

specified technical possibilities. Both government and contractors "routinely underestimate the risk present in military programs." Risk reduction steps for technology development and application, manufacturing, and operations can be guided by unbiased metrics and observables tailored to specific programs.

SIGNIFICANCE OF TECHNICAL PERFORMANCE MEASURES

Examining the DoD description of "key metrics and observables" (Kaminski, 1995) reveals they are similar to what system engineers call technical performance measures (TPMs) (Verma, Chilakapati, & Blanchard, 1996, p. 39). Titles are less important than insights to correlations among key performance parameters (KPPs), critical technical parameters (CTPs), or other TPM candidates described in the literature, for example, by Higgins (1997, pp. 45–46) and Jones (1996, p. 151).

Risks to meeting performance requirements with aggressive cost goals must be managed through iterated cost, performance, and schedule tradeoffs, identifying performance, manufacturing, or operations uncertainties, and demonstrating solutions prior to final design. We seek to efficiently manage weapon system complexity, defined here as an evolving large number of interfaces, parts, and final testing requirements among maturing system configuration elements (Gindele, 1996, p. 66). In this context we seek proven means to systematically organize all independent variables and their interrelationships.

Commitments to technology, system configuration, performance, and life cycle cost are strong even in early system design. Many system characteristics interact; consequences of these static and dynamic interactions are rarely well evaluated or understood. There are ample opportunities to reduce costs while life cycle decisions continue to be made. Progress may be created by techniques that enable earlier use of integrated design information (Fabrycky, 1994, pp. 134–136).

The best time to reduce life cycle costs is early in the acquisition process, when cost-performance tradeoff analyses are conducted to decide an acquisition approach. However, because factors both internal and external to the program change, tradeoffs must occur throughout the acquisition process, and key TPMs may also significantly change throughout program evolution.

Still, it is critical to CAIV that the process of setting TPMs reflecting cost and performance objectives begin as early as possible. The ability to achieve cost objectives greatly depends on early executed cost-performance tradeoffs, including using TPMs to measure and thus better manage risk mitigation. Specifically, for example, as in the case of the F–22 program, TPM changes may be observed in direct response to risk reduction efforts (Justice, 1996, p. 70).

"Titles are less important than insights to correlations among key performance parameters (KPPs), critical technical parameters (CTPs), or other TPM candidates described in the literature..."

Consequently, applying CAIV TPMs to DoD programs entails: (a) setting cost and performance objectives as early as possible; (b) quantifying these objectives as

TPM threshold values, tailored to specific assets and activities; (c) setting pathways supporting observable transitions between objective-oriented actions; (d) adhering to a cost-performance tradeoff process that has structured all relationships among TPMs; and (e) empowering program managers to flexibly respond to changes in the set(s) of TPMs and their values.

INTRODUCTION TO QUALITY FUNCTION DEPLOYMENT

Quality function deployment (QFD) is a well-established procedure that essentially uses a series of interdependent matrices. The matrices are used to organize and translate customer requirements, in an integrated fashion, to the successive steps that ultimately meet these requirements. QFD has been used in a wide variety of industries to use TPMs to translate and literally map customer needs into objective product outcomes. QFD is a historically proven means to guide process development using TPMs to systematically organize all independent variables (cost, etc.), and their interrelationships. QFD is cited as the most widespread implementation of total quality management (TQM) (Sage, 1992, p. 222), and as a key facilitating tool in concurrent engineering environments (Menon et al., 1994, p. 91).

"Quality function deployment (QFD) is a well-established procedure that essentially uses a series of interdependent matrices."

QFD is a process tool that helps strengthen management of key elements of the system engineering process for DoD advanced technology development programs. QFD is structured to accommodate vaguely stated customer specifications, and through a series of interdependent matrices, allocate and map requirements into specific design strategies, development processes, product characteristics, and program operations controls. For each intended result of the design and production process, engineers identify TPMs, and then specify corresponding threshold values to be met in order to achieve the required features of the overall system. These assignments set the minimum levels of achievement required to satisfy customer requirements.

ORIGINS OF QUALITY FUNCTION DEPLOYMENT

QFD was developed in the late 1960s by Shigeru Mizano of the Tokyo Institute of Technology (Menon et al. 1994, p. 94). Mitsubishi Heavy Industries also began to use it then on supertanker projects at Kobe Shipyard. Mitsubishi tried to build 300-yard-long supertankers having sophisticated propulsion, maneuvering, and balance control, challenging design and manufacturing logistical requirements, and having essentially no production line (Guinta and Praizler, 1993, p. 1).

Toyota adopted the Kobe shipyard QFD methodology in the mid-1970s. Toyota set performance benchmarks combined with customer focus groups. They experienced 40 percent reductions in new model development costs, and a 50 percent reduction in development time (Menon et al. 1994, p. 94; Prasad, 1996, p. 82). Panasonic Consumer Electronics pushed QFD to greater limits in the mid-1970s. They used it to predict what consumers would want in the future, ergo their slogan "Just slightly ahead of our time" (Guinta and Praizler, 1993, p. 4).

A 1986 survey of Japanese Union of Scientists and Engineers reported that 54% used QFD, most of them in high technology and transportation industries. The Japanese exploited QFD to structure production and supporting operations to become less sensitive to variations caused by operators, equipment, and materials (Guinta and Praizler, 1993, p. 7). A most interesting historical note is that QFD was applied principally in companies and products primary to Japan's export business, particularly to the United States (Sanchez et al., 1993, p. 239).

THE UNITED STATES EXPERIENCE WITH QFD

Ford Automotive applied QFD in the early 1980s, using it to reorganize sequential functions to concurrent interaction of design, engineering, and manufacturing. Ford used more than 50 applications of QFD to (a) establish quality goals; (b) identify customers and others affected; (c) discover customer needs, such as increased reliability; (d) develop longer maintenance-free operation; (e) clarify the impact of manufacturing process plans on design; and (f) establish process controls coordination among functions (Hauser and Clausing, 1988, p. 63).

Ernst and Young innovated QFD applied to the paper products industry during 1990, where they included importance weighting, measured correlation among customer requirements, and completed competitive evaluations (a.k.a. "benchmarking" (Juran and Gryna, 1993, p. 255). Thiokol Strategic Operations used QFD specifically to better measure and certify its parts suppliers, and consequently reduce development time to build strategic and tactical weapon system solid rocket motors (Guinta and Praizler, 1993, p. 13).

> **"Other companies using QFD include Aerojet Ordnance, ITT, IBM, Digital Equipment, Texas Instruments, Chrysler, General Motors, Procter and Gamble, Deere & Company, Polaroid, Rockwell International, Hughes Aircraft, and Hewlett Packard."**

Other companies using QFD include Aerojet Ordnance, ITT, IBM, Digital Equipment, Texas Instruments, Chrysler, General Motors, Procter and Gamble, Deere & Company, Polaroid, Rockwell International, Hughes Aircraft, and Hewlett Packard (Sanchez et al., 1993, p. 239). Research by Guinta and Praizler (1993, p. 8) revealed that various domestic service and manufacturing companies using QFD experienced 50 percent cost reductions, and 33 percent project time reductions.

The DoD Joint Strike Fighter Program (JSFP) has an activity referred to as the Strategy-to-Task Technology QFD II Analysis, which has been awarded the American Supplier Institute (ASI) "Best Application" Award, recognizing exemplary use of QFD. This award was granted at the 1995 ASI Product Development Symposium. ASI cited this QFD II analysis as “the most robust aggressive use of QFD to analyze weapon system requirements seen to date.” The award was presented by Dr. Genichi Taguchi, a four-time Deming Prize winner (JSFP, 1996a).

QFD has been successfully used in a wide variety of industries: aircraft, aerospace, automobiles, computer software, construction equipment, copiers, consumer goods, electronics, paper products, shipbuilding, and textiles (Menon et al., 1994). The literature review, taken together, reliably indicates that QFD is deeply integrated into our commercial industry culture.

“QFD has been successfully used in a wide variety of industries: aircraft, aerospace, automobiles, computer software, construction equipment, copiers, consumer goods, electronics, paper products, shipbuilding, and textiles.”

United States military cost-constrained effectiveness is influenced by our quality of organizing and deploying technology according to specific functions. Other nations that compete militarily with the United States are evidencing their understanding of this (Brauchli, 1997, p. A14; Chen, 1997, p. A15; Fisher, 1996, p. A18). The lessons learned from the competitive strategies practiced under Secretary of Defense Casper Weinberger during the Reagan administration are not lost in this era characterized by aggressive nations actively seeking technologies providing greater military leverage.

Research by Pisano and Wheelwright demonstrates that outstanding high-tech companies such as Intel and Hewlett-Packard have integrated their product development skills with new focus on process development, and built unique sustainable competitive positions without expending more resources (1995, p. 105). The type of plan chosen does make a difference!

HOW WELL-SUITED IS QUALITY FUNCTION DEPLOYMENT TO DOD CAIV?

The applicability of QFD to CAIV is enhanced through the instrumental role of integrated product and process development (IPPD). IPPD is a philosophy of integrating all acquisition activities throughout the program life cycle. Integrated product teams (IPTs) are at the core of IPPD; IPTs are most instrumental to CAIV development and implementation.

A standardized structure for cost IPT operations is desirable for common implementation of CAIV initiatives across all DoD programs. System-level cost objectives, in turn decomposed to the sub-system level, are key technical performance measures shared by the program manager and corresponding IPTs. Cost/Performance IPTs (CPIPTs) are empowered to recommend engineering and design changes to the program manager.

IPPD facilitates IPTs for synthesizing acquisition activities throughout the program life cycle. As such, IPTs offer DoD an unprecedented opportunity to implement QFD as an interfunctional planning and communications tool. This is especially true for currently planned advanced military technology implementation programs that require demonstrating a clear path toward reducing costs as well as meeting operational requirements (Wollover and Koontz, 1996, pp. 1–7).

ILLUSTRATION OF APPLYING QFD: GENERIC WEAPON SYSTEM DESIGN

Now we'll illustrate the application of QFD to the process of developing a generic weapon system. A notional weapon system example was selected to provide adequate design complexity, to permit a fairly detailed QFD application example. This example system need not be platform-specific; it is most broadly considered deployable to strike any target (e.g., underwater, surface, or airborne) from any platform (e.g., human, vehicle, aircraft, ship, spacecraft).

The QFD process consists of the following steps: (a) identifying and analyzing customer needs and requirements, (b) identifying TPMs, (c) benchmarking TPMs, (d) assigning priority to customer requirements, (e) establishing TPMs to identify specific design characteristics, and (f) evolving TPMs into the follow-up design phase's requirements. Actual steps do vary in the literature (Guinta and Praizler, 1993; Sanchez et al., 1993; Menon et al., 1994; Verma et al., 1996). The above steps suit our example.

IDENTIFY AND ANALYZE CUSTOMER NEEDS AND REQUIREMENTS

Customer need is defined in the context of a single on-target engagement. Initially, customer language is qualitative and subjective, imparting vagueness and imprecision to the early weapon system design. For example, needs such as maximizing mission effectiveness, maximizing affordability, maximizing supportability, minimizing risk, and optimizing personnel use are all too general for design engineers to immediately respond to. Hence these fuzzy statements are analyzed and translated into more specific requirements to better understand and respond to the perceived deficiency.

The first two columns of Table 1 illustrate these translations. For example, "maximize mission effectiveness" is translated into more concrete goals, such as "locate, track, reach, and destroy target." Developing a common dictionary for the overall QFD model aids in understanding user requirements in light of later tradeoff decisions (Bregard and Chasteen, 1996, p. 172). Once identified, similar customer requirements are grouped with like functional items. Referring again to Table 1, note how the five general customer requirements are the basis of the grouping of subsequent more concrete requirement statements.

IDENTIFY TECHNICAL PERFORMANCE MEASURES

TPMs are the keys to estimating progress for the weapon system's design and development. As "design-dependent parameters," TPMs offer various functionalities. They provide visibility into the status of actual versus required system performance, define corresponding future design goals, provide guideposts to evaluating design concepts and configurations, provide early detection of perfor-

Table 1. Notional Generic Weapon System Objectives Table

CUSTOMER REQUIREMENTS [a]	TPM		QUANTITATIVE REQUIREMENT
Maximize mission effectiveness	Locate target	Motor burnout velocity	(km/sec)
	Track target	Range	(km)
	Reach target	Maneuverability	(Gl/ms)
	Destroy target	Data processing speed	Mhz
		Data reception speed	Kb/Sec
		Length * diameter	M ^ 2
		Mass	kg
		Sensor accuracy	S / N
Maximize affordabilty	Minimize R&D cost	R&D	Constant year $M
	Minimize production cost	Production	Constant year $M
	Minimize support cost	O&S	Constant year $M
	Minimize operations cost		
Maximize supportability	Maximize reliability	MTBF	Months
		Failure rate	Failures / mission Engagement
		MTBM	Months
	Maximize maintainability	Mean prevent maint. time -BITE (MPMT-B)	Minutes
		Mean prevent maint. time -ExTE (MPMT-E)	Minutes
		Mean corr. maint. time (MCMT) - org. level	Minutes
Minimize risk	Maximize producibility	Amount of major modifications (Reintegrating subsystems)	Percent
		Amount of minor modifications (Repackaging subsystems)	Percent
	Minimize design complexity	Hardware complexity	No. of interfaces/No. subsystems
		Software complexity	No. of interfaces/No. subsystems
		Subsystems integration complexity	No. of interfaces/No. subsystems
Optimize personnel use	Maximize operator effectiveness	Operator response times	Seconds
		Errors per mission engagement	No. errors
	Minimize Support Errors	Errors per testing event series	No. errors
		Errors per maintenance action	No. errors
	Optimize anthropometric factors	Size of maintenance access panel areas	In. x in. x in.
		Time to open each maintenance access panel	Seconds
	Optimize sensory factors	Each maintenance access panel lighted	Lumens
		Color coded panels	Indicate tool needs

a Ranking Order determined on basis of customer perceived relative degree of shortfall toward existing benchmark

b Because Mission Engagements are not continuous, it is readily assumed that the relationship between Reliability and Operating Time / MTBF is not exponential. Hence MTBF and Failure Rate may be somewhat more independently specified as design goals.

mance problems requiring management attention, assess technical impact of proposed changes, and contrast implications of design alternatives. Consequently, TPMs are integral to the program's risk management.

At this early stage of design, TPMs are key parameters that are under the control

Table 2. Notional Generic Weapon System Objectives Table Benchmarking of Technical Performance Measures Pre-Rank-Ordering

Technical Performance Measure	Quantitative Requirement	Current Benchmark (Competing systems)	Relative Importance
Motor burnout velocity (km/sec)	2N	N	8
Range (km)	1.5N	N	6
Maneuverability (Gl/ms)	2N	N	8
Data processing speed	5N Mhz	N Mhz	3
Data reception speed	10N Kb/sec	N Kb/sec	3
Length * diameter	N Meter ^ 2	N Meter ^ 2	1
Mass	.8N Kg	N Kg	1
Sensor accuracy	2N:N Signal/noise	N:N Signal/noise	8
R&D (constant year $M)	.9N Dollars	N Dollars	4
Production (constant year $M)	.8N Dollars	N Dollars	6
O&S (constant year $M)	.7N Dollars	N Dollars	7
MTBF	.5N Months	N Months	2
Failure (F) rate	.5N F / mission engagement	N F / Mission engagement	2
MTBM	.5N Months	N Months	1
Mean prevent. maint. time -BITE (MPMT-B)	.8N Minutes	N Minutes	1
Mean prevent. maint. time -ExTE (MPMT-E)	.8N Minutes	N Minutes	1
Mean corr. maint. time (MCMT) -Org Level	.8N Minutes	N Minutes	1
Amount of major modifications	.5N %	N %	7
Amount of minor modifications	.5N %	N %	3
Hardware complexity	Sustain	No. of Interfaces	4
Software complexity	Sustain	No. of Interfaces	4
Subsystems integration complexity	Sustain	No. of Interfaces	5
Operator response times	N Sec	N Sec	3
Errors per mission engagement	.5*(0.N) Errors	0.N Errors	5
Errors per testing event series	.5*(0.N) Errors	0.N Errors	1
Errors per maintenance action	.5*(0.N) Errors	0.N Errors	1
Size of maintenance access panel areas	Sustain	n in. x n in. x n in.	1
Time to open each maintenance panel	.8N Seconds	N Seconds	1
Each maintenance access panel lighted	1.5N Lumens	N Lumens	1
Color coded panels	Reflect tool needs	Using B&W symbols only	1

of the design team. They are manipulated either directly or indirectly to meet customer requirements. TPMs are tangible and describe any relevant system attribute in measurable terms.

TPM ratios may be used. An example is effectiveness-to-cost ratios, for which a very wide variety of options may be specified (Wollover, 1991, pp. 149–153). While discrete changes in design measures leading to distinct effectiveness changes may be discerned, effectiveness-to-cost ratios may be normalized so equivalent comparisons of TPMs may be made for purposes such as the six functions mentioned at the beginning of this section. Ratio examples are: system effectiveness to life cycle cost, or reliability to development cost. Ratios such as these may be specified in the form of [gkD] customer benefit -/[gkD]cost, to facilitate comparison of relative changes among alternative TPM values.

In Table 1, the TPMs in the third column evolve from the more concretely defined customer requirements shown in the second column. The fourth column displays specific quantitative requirements associated with each TPM.

BENCHMARK TECHNICAL PERFORMANCE MEASURES

Table 2 lists the TPMs and the quantitative requirement (the latter being the same measure found in the fourth column of Table 1). The third column in Table 2, "Current Benchmark," holds the corresponding quantified TPMs found either in the predecessor weapon system or in either domestic or foreign competing weapon systems. Consequently, the system developers would like to surpass these benchmarks.

PRIORITIZE CUSTOMER REQUIREMENTS

Various system requirements will likely conflict. For example, adding weapon speed and range conflicts with minimizing development and production costs. Consequently, assuming a limited budget, tradeoffs are inevitable. The issue here is on what basis should the various interdependent tradeoffs be made. To help resolve if not overcome these conflicts, the requirements are assigned relative weights that reflect the customer's priorities. For this step, there is little substitute for direct customer survey techniques (Salomone, 1995, p. 108), although appropriate weapon system operations simulations are invaluable for enhancing customer decision processes.

Here we have used an arbitrary and systematic process to assign relative weights, as follows. The last column of Table 2, "Relative Importance," is reserved for assigning customer weights to TPMs. The first pass through the entire TPM series assigned a weight, equal to one, to all TPMs. The second pass entailed assigning a relative weighting equal to two for more important TPMs. The third pass assigned weights of three to those progressively more important TPMs, and so on, until the sum of the relative importance measures equaled 100. Finally, this list of TPMs was sorted based on these relative importance measures; Table 3 lists these sorted TPMs.

The above ranking procedure is suitable for our illustration; more rigorous prioritizing procedures are available. For example, variations of the commonly referenced analytical hierarchy process (AHP) are cited in the literature (Armacost et al. 1994, p. 72; Wasserman, 1993, p. 59; Lyman, 1990, p. 307). These proce-

Table 3. Notional Generic Weapon System Objectives Table
Prioritization of Technical Performance Measures
Rank-Ordered According to Priority

Technical Performance Measure	Quantitative Requirement	Current Benchmark (Competing Systems)	Relative Importance
Motor burnout velocity (km/sec)	2N	N	8
Maneuverability (Gl/ms)	2N	N	8
Sensor accuracy	2N:N Signal/noise	N:N Signal/noise	8
O&S (constant year $M)	.7N Dollars	N Dollars	7
Amount of major modifications	.5N %	N %	7
Range (km)	1.5N	N	6
Production (constant year $M)	.8N Dollars	N Dollars	6
Subsystems integration complexity	Sustain	No. of Interfaces	5
Errors per mission engagement	.5*(0.N) Errors	0.N Errors	5
R&D (constant year $M)	.9N Dollars	N Dollars	4
Hardware complexity	Sustain	No. of Interfaces	4
Software complexity	Sustain	No. of Interfaces	4
Data processing speed	5N Mhz	N Mhz	3
Data reception speed	10N Kb/Sec	N Kb/Sec	3
Amount of minor modifications	.5N %	N %	3
Operator response times	N Sec.	N Sec	3
MTBF	.5N Months	N Months	2
Failure (F) rate	.5N F / Mission engagement	N F / Mission engagement	2
Length * diameter	N Meter ^ 2	N Meter ^ 2	1
Mass	.8N Kg	N Kg	1
MTBM	.5N Months	N Months	1
Mean prevent. maint. time -BITE (MPMT-B)	.8N Minutes	N Minutes	1
Mean prevent. maint. time -ExTE (MPMT-E)	.8N Minutes	N Minutes	1
Mean corr. maint. time (MCMT) -org. level	.8N Minutes	N Minutes	1
Errors per testing event series	.5*(0.N) Errors	0.N Errors	1
Errors per maintenance action	.5*(0.N) Errors	0.N Errors	1
Size of maintenance access panel areas	Sustain	N in. x N in. x N in.	1
Time to open each maintenance access panel	.8N Seconds	N Seconds	1
Each maintenance access panel lighted	1.5N Lumens	N Lumens	1
Color coded panels	Reflect tool needs	Using B&W symbols only	1

dures essentially are driven by using sophisticated customer query techniques to develop and assign explicit weighting variables that represent customer priorities. These techniques, while "methodologically intense," should result in fairly unambiguous communication of which customer inputs most greatly influence QFD.

Table 4. First-Order Quality Function Deployment Correlation Matrix

		TECHNICAL/ENGINEERING CHARACTERISTICS																												
		Mission Effectiveness								Cost			Supportability						Risk			Personnel Use								
CUSTOMER DESIRED ATTRIBUTES		Motor burnout velocity (km/sec)	Range (,km)	Maneuverability (Gl/ms)	Data processing speed (mhz)	Data reception speed (kb/sec)	Length * diameter	Mass (kg)	Sensor accuracy (S/N)	R&D expenditure (constant year $M)	Production expenditure (constant year $M)	O&S expenditure (constant year $M)	MTBF (months)	Failure rate (failures/mission engagements)	MTBM (Months)	Mean prevent. maint. time - BITE (MPMT-B)(min)	Mean prevent. maint. time - ExTE (MPMT-E)(min)	Mean corr. maint. time (MCMT-B) - org. level (min)	Amount of major modification (%)	Amount of minor modificaiton (%)	Hardware, software, integ. complexity (No. interfaces)	Operator response times (sec)	Errors per mission engagement (No. errors)	Errors per testing event series (No. errors)	Errors per maintenance action (No. errors)	Size of maintenance access panel areas (in. x in.)	Time to open each maintenance access panel (sec.)	Each maintenance access panel lighted (lumens)	Color coded panels)	RELATIVE IMPORTANCE
MAXIMIZE MISSION EFFECTIVENESS	Locate target				3	3			3				1	1								2	1							5
	Track target			2	3	3		1	3				1	1								3	1							5
	Reach target		3	3			1	1	1				1	1								1	1							8
	Destroy target	3	3	3			2	3	1				1	1								1	1							8
								Example 1							Example 2															
MAXIMIZE AFFORDABILITY	Minimize R&D cost	(1)	(1)	(2)	(1)	(1)	(1)			(3)									3	2	2									4
	Minimize production cost	(1)	(1)	(2)			(2)				(3)								3	3	2									6
	Minimize support cost			(1)			(1)					(3)							1	1	1									7
	Minimize operations cost						(1)					3									1									7
																							Example 3							
MAXIMIZE SUPPORTABILITY	Maximize reliability	(1)		(1)						(2)	(1)		3	3	3															5
	Maximize maintainability	(1)		(1)			(1)			(2)	(1)					3	3	3			3				2	3	3	3	3	5
MINIMIZE RISK	Maximize producibility	(1)		(1)				(1)		1	(1)	(1)							3	3										5
	Minimize design complexity	(1)		(1)				(1)		1	(1)	(1)			1	1	1	1	2	2	3									5
OPTIMIZE PERSONNEL USE	Maximize operator effectiveness	(1)		(2)	1	1				1	1	(3)										3	3	2	2	1	1	1	1	4
	Minimize support errors	(1)		(1)						1	1	(3)										1	1	3	3	2	2	1	1	4
	Optimize anthropometric factors									1	1	(3)										1	1	1	1	3	3	2	2	4
	Optimize sensory factors									1	1	(3)										1	1	1	1	2	2	3	3	4
TECHNICAL DIFFICULTY (10 = Most Difficult)		8	8	8	7	7	5	5	7	6	6	6	5	5	5	4	4	4	8	6	8	4	3	4	3	3	3	2	2	
IMPUTED IMPORTANCE (10 = Most Important)		8	6	8	3	3	1	1	8	4	6	7	2	2	1	1	1	1	7	3	4	3	5	1	1	1	1	1	1	

ESTABLISHING TPMs TO IDENTIFY SPECIFIC DESIGN CHARACTERISTICS

All TPMs are considered on an integrated basis using the QFD correlation matrices. This is the first opportunity to integrate all requirements, including effectiveness, cost, operations, and logistics support into the mainstream design and development process.

Configure the QFD matrix. Customer requirements from the first two columns of Table 1 are set as the “customer desired attributes” (Table 4, the first-order QFD matrix, left-hand section). These are the “whats” to be satisfied. In response to these requirements, TPMs from Tables 1 through 3 are positioned along the top of the matrix. These TPMs are the “hows,” to the extent that they support customer requirements.

Correlate customer requirements With TPMs. This is the key step of the QFD process. It involves populating the correlation matrix to reflect program-directed or otherwise inherent cause and effect relationships. Each TPM is analyzed in terms of the extent of its influence on customer requirements.

Varying relative levels of this correlation are notionally depicted in the example correlation matrix (Table 4), ranging from a value of +3, the maximum positive correlation, depicted in the matrix as 3, to –3, the maximum negative correlation, depicted in the matrix as (3). We especially note that these values do not simply correlate, but rather indicate the degree to which the TPMs support the customer requirements. Three examples follow; their occurrences in the first-order QFD matrix shown in Table 4 are highlighted using bold borders surrounding the relevant correlation cells.

Example 1: Note the negative correlations between the TPM mass and the customer requirements for minimizing R&D and production cost. Here, the matrix is not negatively correlating mass with cost, but with the customer requirement of minimizing cost.

Example 2: An interesting example occurs where all six Supportability TPMs are negatively correlated with R&D and production costs, but are more positively correlated with operations and support costs. This reflects the normative view purported by CAIV proponents that greater up-front investment in supportability is warranted for ultimately reducing overall life cycle costs through disproportionately greater savings in the operations and support phase of the program. This example particularly helps to emphasize QFD’s utility in identifying clusters of interaction elements.

Example 3: The last example occurs to illustrate the relatively minor yet real contribution that increasing personnel performance (e.g., greater human response time, fewer errors, reduced maintenance durations) contributes to overall system performance reliability. This example is intended to call attention to the high value-added human machine interface (HMI) avenues to cost reduction such as anthropometric factors, as described generally by Blanchard and Fabrycky (1990, pp. 436–440), and as directly applied to advanced aerospace design as described by Reed (1994, pp. 54–59).

General evaluation of the correlation matrix. Empty matrix rows represent unaddressed customer requirements. Where this is so, the set of TPMs is reevaluated, and additional TPMs are specified where needed. By contrast, empty columns in the matrix indicate design or other development actions that are not traced to any customer requirement; they may indicate either under-leveraged, redundant, or unnecessary system-level design requirements (Verma et al., 1995, pp. 38). Other matrix evaluation strategies not covered by the above example could involve the following five avenues:

- Contrast complimentary technical solutions versus each other, to assess the degree they conflict (Hartzell and Schmitz, 1996, p. 36). Correlations among design inputs may be shown using a triangular table at the top of the matrix. However, care is needed to validate the true interactions between design inputs, as many of these interactions may strengthen or weaken as the design evolves (Maisel,1996, p. 16).

- Evaluate the functional (cause-effect) relationships among concurrent activities to determine not only how flexible the overall development process is, but where additional flexibility is most needed to maintain process responsiveness to customer requirements volatility (Jordan and Graves, 1995, pp. 577–583).

- Cooper and Chew argue that it is insufficient to focus on customers; competitors are a parallel concern (1996, p. 95). Expand the matrix to focus on competitors as well as customers, using key mission or other customer satisfaction TPMs. Use existing competitor TPMs in a bench-marking fashion, as illustrated earlier.

- Thurston and Locascio (1993, p. 208–213) use multiattribute utility theory to interpret QFD matrices as a general formulation of a design optimization problem. Customer requirements are expressed as constraint functions, and tradeoffs among design attributes are formally specified as sets of variables whose optimal values are solved using selected mathematical optimization models (p. 211).

- Sanchez et al. (1993, pp. 244–249) display perhaps the most creative and productive QFD application. They show matrix appendages containing trend line analyses of data populating the matrix, and separately illustrate iterating successive matrices to the extent of serving inputs to statistical process control. Both of these enhancements help take QFD beyond the realm of a cognitive tool to that of hard empirical data generator.

Other value-added assessments from checking the correlation matrix are likely. Well-populated QFD matrices permit synergistic insights particular to a program's chief concerns.

EVOLVE TPMS INTO THE NEXT DESIGN PHASE'S REQUIREMENTS

Table 5 illustrates the transition of the "hows" in the first-order matrix to the "whats" in the second-order matrix. This series of steps, where the TPM outputs of a *n*th-ordered matrix become input to the successive *n*th +1-ordered matrix, as the design resolution is enhanced, until system design detail has ideally progressed to the point where: (a) all significant design tradeoffs are defined and resolved,

Table 5. Second-Order Quality Function Deployment Correlation Matrix

TECHNICAL ENGINEERING CHARACTERISTICS		Motor thrust (Newtons)	Total missile Available fuel mass (kg)	Missile divert thruster thrust acceleration (m/s2)	COTS processor generation upgrad (200 Mhz)	Missile uplink-receive antenna gain (watts)	Miniaturization techniques	Selection of lighter materials	Peak transmitted power (watts)	RELATIVE IMPORTANCE
MAXIMIZE MISSION EFFECTIVENESS	Motor burnout velocity (km/sec)	3	2				2	2		8
	Range (km)	3	3			1	2	2		6
	Maneuverability (Gl/ms)	1	2	3	2	1	1	1	1	8
	Data processing speed (MHz)				3		1			3
	Data reception speed (Kb/sec)				2	3	1		2	3
	Length * diameter (m * m)	1	2				3	2		1
	Mass (kg)	1	3				2	3		1
	Sensor accuracy (S/N)					1	1	1	3	8
TECHNICAL DIFFICULTY (10 = Most Difficult)		8	8	8	7	7	5	5	7	
IMPUTED IMPORTANCE (10 = Most Important)		8	6	8	3	3	1	1	8	

(b) specific subsystem or component packaging is determined and tested, so that (c) overall program risk is reduced to acceptable levels.

Third-, fourth-, fifth-, etc.-order QFD matrices are preferred for translating customer requirements into highly detailed subsystem attributes, or even detailed control of operations (Menon et al. 1994, p. 94). For diverse examples of progressive QFD translation matrix series used to translate the "voice of the customer" into the more evolved "voice of the engineer," see Guinta and Praizler (1993), Hauser and Clausing (1988), Sanchez et al. (1993), and Sage (1992). The number of translation matrices is influenced by the complexity and diversity of the program, in combination with the degree of required design detail. While translation matrices content may vary widely, they all do have a similar structure.

Using QFD to Benefit Implementing CAIV

QFD's multi-attribute structure can systematically capture data and interrelate it in a variety of tailored arrangements. This enables higher quality integrated program analysis and evaluation (including cost and effectiveness analysis) earlier in the weapon system life cycle. With QFD's collective knowledge, program managers can less ambiguously evaluate what technologies or other initiatives will fit in and advance the program.

QFD facilitates comprehensively displaying relationship nodes among cost and noncost variables. This encourages structured analyses to yield improved rank orderings into which cost reduction opportunities due to earlier discovery and resolution of conflicts are most significant, before large shares of system life cycle cost become locked in during the earliest program phases.

"QFD is a procedure-oriented yet nonmechanistic enabling technology for new program development."

Also, there is perhaps no better tool to ascertain whether the degree of system definition and development is commensurate with requirements determination, or alternatively, whether requirements determination is lagging behind system specification and development.

The traditional system engineering process provides a standardized "top-down" context comprehensively to apply QFD to program management, as described, for example, by Blanchard and Fabrycky (1990, p. 22, 50). It consists of: conceptual design and advanced planning, preliminary systems design and advanced development, and detail system design and development.

Applying QFD through sound system engineering principles will allow greater exploitation of modern manufacturing processes and controls. Marshall and Van der Ha (1996, pp. 218–226) provide a pertinent beneficial example of the system engineering approach applied to designing space system ground segments to reduce operations costs.

QFD provides a consistent robust structure to arrange interactions among cross-functional team members. As organizations gain experience with QFD, the model becomes a source of historical information and "hard-wired" corporate memory. This promotes growing an integrated product team-facilitating learning curve. Thus, an expected output of implementing QFD is to advance the efficiency of the organization, especially for better controlling the flow of IPT interactions, while safeguarding against organizational de-evolution due to loss of corporate memory.

SUMMARY

QFD is a procedure-oriented yet nonmechanistic enabling technology for new program development. It provides a structured framework that uses TPMs to ensure that customer needs are deployed into all phases of design, development, production, and operations. This framework drives the process of developing a road map showing how key steps from design to manufacturing, operations, and support interact at various levels to fulfill customer requirements. This road map promotes documenting overall system logic, reflected by a series of interrelated matrices that translate customer needs into process and product characteristics. Well-documented QFD matrices provide a flexible dynamic communication vehicle of prior, present, and future actions. Thus, QFD provides a communications tool to accelerate building better relationships and promote trust among cross-functional team members earlier in the system life cycle.

QFD is a team-building, consensus-oriented, flexibly disciplined approach that structures synthesizing new ideas. It works as a cognitive map to ease communication of evolving knowledge across cost performance integrated product team elements—enhancing their work in an integrated fashion to give customers what they are asking for. QFD can apply throughout steps ranging from requirements determination through design through delivery through operations and support.

Incorporating QFD in the design helps to identify critical driving design attributes that should be addressed up front, where they most greatly benefit design evolution. QFD models integrate data from many areas: customer requirements, strategic plans, engineering expertise, cost, mission effectiveness, production capability, logistic support, hardware and software reliability, and operations and maintenance. The QFD model presents these data in a side-by-side format showing relationships, correlations, and conflicts. It can show, where needed, tradeoffs among requirements, resources, and organizations. A single-page QFD matrix can easily communicate what would require a large number of text pages.

By better connecting developer, user, and supporter, QFD facilitates making CAIV tradeoffs among performance, schedule, and cost. QFD's iterative nature of using progressively refined TPMs clarifies system design detail to where signifi-

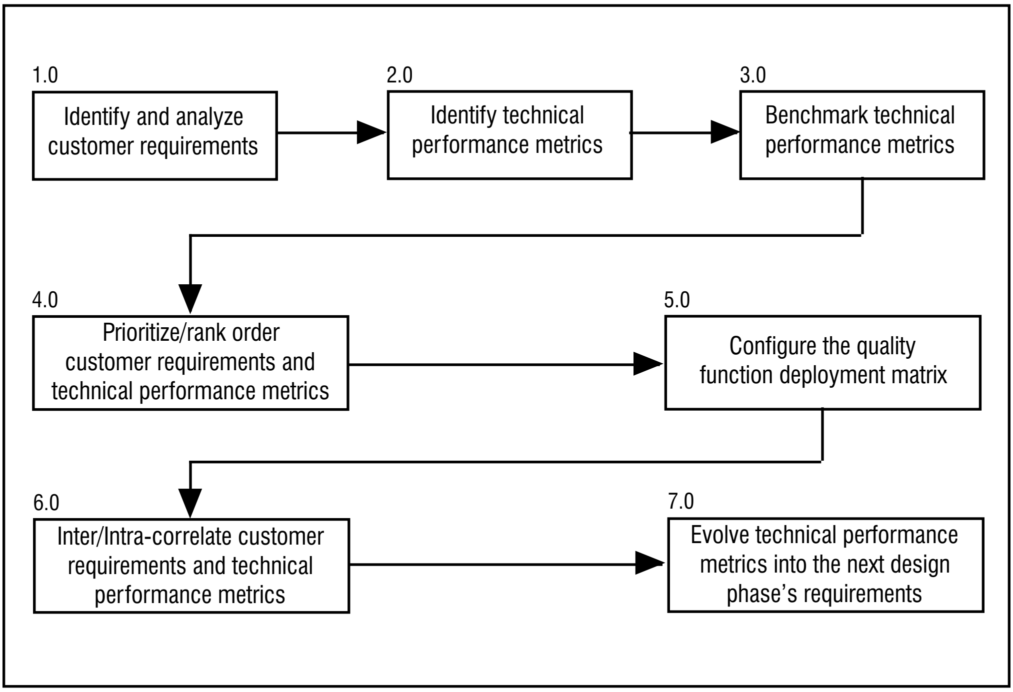

Figure 1. An Iteration of the Quality Function Deployment Process

cant design tradeoffs are defined and resolved, and subsystem function and packaging are determined and tested. This reduces program risk. Consequently, through exploiting detailed coordinated TPMs, QFD functions as a key part of program risk management. Figure 1 generalizes a single iteration of the overall QFD sequence.

One of the most challenging system development steps is sustaining the translation of subjective evolutionary customer requirement statements into objective engineering performance measures. Hartzell and Schmitz (1996, p. 36) point out that volatile customer requirements are a significant developmental program risk driver. Here, QFD may be used to relate different aspects of design, test, manufacturing, cost, reliability, and technology while both maintaining and archiving the changing customer's voice as the product development driving force. In this sense, QFD is usable as a DoD-equivalent of sound commercial business practices that do not lose sight of the fact that the developing voice of the customer is critical to successful implementation.

DoD has recognized QFD as a viable option in complex analyses involving integrated product teams. QFD has been acknowledged as a process enabling true understanding of user requirements and expectations, and documenting the best approach to satisfy requirements. DoD has cited QFD as a way to track the expected tradeoffs through determining requirements, (design decisions, production, and support (OUSD[A&T], 1996, pp. 2–5, 6).

No single management tool is a panacea. DoD acquisitions heavily dependent on integrated product teams will benefit from QFD. It is a strong tool for structuring IPT processes to comprehensively identify what to do, coordinate actions and their interfaces, monitor all tradeoffs among activities, and understand evolutions of program features and interrelationships. QFD imposes a self-revealing logic and structure to program development.

Implementing QFD emphasizes the requirement that IPT members take time to learn other functional areas' terminology and develop a common definition of terms, to build renaissance multidisciplinary teams. It is best to set QFD use objectives that stretch organizations, not break them.

Upper-level management may benefit from becoming familiar with QFD. This familiarity can furnish the benefit of understanding what questions to ask to evoke useful information from the QFD framework. A chief example of this is the QFD matrix revealing new relationships among cost and performance variables that indicate emerging cost reduction responsibilities associated with implementing new weapon system technologies. This information, revealed by QFD, may be then used to evolve management strategies that support organization efforts in a manner that guide development toward optimizing system cost-effectiveness.

REFERENCES

Armacost, R., et al. (1994, July). An AHP framework for prioritizing customer requirements in QFD: An industrialized housing application. *Institute of Industrial Engineers Transactions, 26* (4), 72–79.

Blanchard. B., & Fabrycky., W. (1990). *System Engineering and Analysis.* Englewood Cliffs, NJ: Prentice-Hall.

Brauchli, M. (1997, January 14). China stays a magnet for overseas money. *Wall Street Journal,* p. A13.

Bregard, R., & Chasteen, T. (1996). Implementing integrated product development: A project manager's perspective. *Acquisition Review Quarterly, 3* (2), pp. 163–182.

Chen, K. (1997, January 14). Latest big China-Russia arms deal could raise concern in Asia and U.S. *Wall Street Journal,* p. A14.

Conrow, E. (1995, Summer). Some long-term issues and impediments affecting military systems acquisition reform. *Acquisition Review Quarterly,* pp. 199–211.

Cooper, R., & Chew. W. (1996, January–February). Control tomorrow's costs today's designs. *Harvard Business Review,* pp. 88–97.

Fabrycky, W. (1994, July-September). Modeling and indirect experimentation in system design evaluation. *Journal of the National Council of Systems Engineering, 1* (1), 133–144.

Fisher, R. (1996, December 30). China's missile threat. *Wall Street Journal,* p. A16.

Gindele, M. (1996, May-June). Evaluating concurrent engineering programs. *Program Manager,* 66.

Guinta, L., & Praizler, N. (1993). *The QFD book—the team approach to solving problems and satisfying customers through quality function deployment.* New York: Amacom Books (American Management Association).

Hartzell, R., & Schmitz, D. (1996, July-August). Manufacturing questions program managers should ask. *Program Manager,* 34–38.

Hauser, J., & Clausing, D. (1988, May-June). The house of quality. *Harvard Business Review,* 63–73.

Higgins, G. (1997, January-February). CAIV—An important principle of acquisition reform. *Program Manager,* 44–47.

Jones, E. (1996). Specification, harmonization, and linkage of test parameters. *Acquisition Review Quarterly, 3* (2), 147–162.

Jordan, W., & Graves, S. (1995, April). Principles on the benefits of manufacturing process flexibility. *Management Science, 41* (4), 577–594.

Juran, J., & Gryna, F. (1993). *Quality planning and analysis—from product development through use* (pp. 253–258). New York: McGraw-Hill..

JSFP. (1996b, February 7). JAST virtual manufacturing fast track demonstrated benefits. Joint Strike Fighter Program Website: http\\www.jast.mil\.

Justice, R. (1996, July-August). Risk in the F–22: A defense science board task force analyzes F–22 concurrency and risk. *Program Manager,* 68–74.

Kaminski, P. (1995, December 4). *Reducing life cycle costs for new and fielded systems.* Memorandum for distribution. Washington, DC: Office of the Secretary of Defense.

Longuemare, R. (1995). *Reducing life cycle costs for new and fielded systems.* Memorandum for distribution—implementation guidance—systems in development. Washington, DC: Office of Principal Deputy Under Secretary of Defense, Acquisition & Technology.

Lyman, D. (1990). Deployment normalization. *Transactions from a second symposium of quality function deployment, a conference co-sponsored by the Automotive Division of the American Society for Quality Control.* Dearborn, MI: GOAL/QPC.

Maisel, L. (1996). *Activity-based cost management.* Paper presented at the 1996 Conference on Life Cycle Analysis: Refining the Trade-Off Tool for Integrated Product and Process Development (IPPD). Harrison, NY: Paramount Consulting Group.

Marshall, M., & Van der Ha, J. (1996). Reducing mission operations cost. In J. Wertz and W. Larson (Eds.), *Reducing space mission cost.* Torrance, CA: Space Technology Library Publishers.

Menon, U. et al. (1994). Quality function deployment: An overview. In C. Syan and U. Menon (Eds.), *Concurrent engineering—concepts, implementation and practice* (pp. 90–99). London: Chapman and Hall.

Office of Deputy Under Secretary of Defense (AR). (1996). Cost as an independent variable. *Defense acquisition deskbook.* Defense Acquisition Joint Program Office. http://deskbook@deskbook.osd.mil.

Office of Principal Deputy Under Secretary of Defense, Acquisition and Technology. (1995). *CAIV working group paper—executive summary.* Washington, D.C.

Office of the Secretary of Defense. (1996, March 15). *DoD directive 5000.2-R. Mandatory procedures for major defense acquisition programs (MDAP) and major automated information systems (MAIS) acquisition programs.* DoD 5000.2-R, part 3.3.3.1. Washington, D.C.

Pisano, G., & Wheelwright, S. (1995, September-October). High-tech R&D. *Harvard Business Review,* 93–105.

Prasad, B. (1996). *Concurrent engineering fundamentals: Vol. 1. Integrated product and process organization* (pp. 82-89, 154-156). Upper Saddle River, NJ: Prentice Hall.

Reed, F. (1994, April-May). You can look but you can't touch. *Air&Space Magazine,* 54–59.

Sage, A. (1992). *Systems engineering* (pp. 278–284). Fairfax, VA: George Mason University, School of Information Technology and Engineering.

Salomone, T. (1995). *What every engineer should know about concurrent engineering* (pp. 100–115). New York: Marcel Dekker.

Sanchez, S., et al. (1993). Quality by design. In A. Kusiak (Ed.), *Concurrent engineering—automation, tools, and techniques* (pp. 235–251). New York: John Wiley and Sons.

Thurston, D., & Locascio, A. (1993). Multiattribute design optimization and concurrent engineering. In H. Parsaei and W. Sullivan (Eds.), *Concurrent engineering—contemporary issues and modern design tools* (pp. 207–213). London: Chapman and Hall.

Under Secretary of Defense for Acquisition and Technology. (1996). DoD Guide to Integrated Product and Process Development (Version 1.0). Washington, D.C.

Under Secretary of Defense for Acquisition and Technology. (1995). *Rules of the road, a guide for leading successful integrated product teams.* Washington, D.C.

Verma, D., Chilakapati, R., & Blanchard, B. (1996). *Quality function deployment (QFD): Integration of logistics requirements into mainstream system design* (Department Paper). Blacksburg, VA: Virginia Polytechnic and State University, Department of Industrial and Systems Engineering, Systems Engineering Design Laboratory (SEDL).

Wasserman, G. (1993, May). On how to prioritize design requirements during the QFD planning process. *Institute of Industrial Engineers Transactions, 25* (3), 59–65.

Wollover, D. (1991). Accounting for residual value and the probability of war when estimating cost-to-effectiveness ratios for evaluating alternative weapon systems. In R. Kankey and J. Robbins (Eds.), *Cost analysis and estimating: Shifting U.S. priorities* (pp. 143–154). New York: Springer-Verlag.

Wollover, D., & Koontz, R. (1996). *Issues surrounding the joint common cost model of the joint strike fighter program.* Rockville, MD: Princeton Economic Research, Inc.

SUPPLEMENTAL BIBLIOGRAPHY

Akao, Y. (1990). *Quality function deployment—integrating customer requirements into product design.* Cambridge, MA: Productivity Press.

ASI. (1988). *Implementation manual for the three day QFD workshop.* Dearborn MI: American Supplier Institute.

Aswad, A. (1989). Quality function deployment: A systems approach. *Proceedings of the 1989 Institute of Industrial Engineers Integrated Systems Conference.* Atlanta, GA.

Bordley, R., & Paryani, K. (1990). *A concept for prioritizing design improvements using quality function deployment.* Dearborn MI: American Supplier Institute.

Bossert, J. (1991). *Quality function deployment—a practitioners approach.* Milwaukee, WI: ASQC Press/Marcel Dekker.

Burgar, P. (1994). Applying QFD to course design in higher education. *Proceedings, American Society of Quality Control Congress.* Las Vegas, NV.

Cavanagh, J. (1990, June). What do I put on my QFD charts? *Proceedings, Second Symposium on Quality Function Deployment.* Novi, MI.

Chang, C. (1989). Quality function deployment process in an integrated quality information system. *Computers and Industrial Engineering, 17* (1–4).

Clausing, D., & Pugh, S. (1991, February). Enhanced quality function deployment. *Proceedings, Design Productivity Conference.* Honolulu, HI.

Drucker, P. (1995). *Managing in a time of great change.* New York: Truman-Talley/Dutton.

Ernst and Young Quality Improvement Consulting Group. (1990). *Total quality.* Homewood, IL: Dow Jones-Irwin.

Eureka, W., & Ryan, N. (1988). *The customer-driven company: Managerial perspectives on QFD.* Dearborn MI: American Supplier Institute.

Funk, P. (1993). How we used quality function deployment to shorten new product introduction cycle time. *Proceedings, APICS International Conference and Exhibition.* San Antonio, TX.

Gavoor, M., & Wasserman, G. (1989). *Framing QFD as a mathematical program* (internal technical report). Detroit, MI: Wayne State University, Department of Industrial and Manufacturing Engineering.

Hales, R. et al. (1990). *Quality function deployment and the expanded house of quality* (technical report). International TechneGroup Inc.

Hales, R., et al. (1993). Quality function deployment in concurrent product/process development. *Proceedings, IEEE Symposium on Computer-Based Medical Systems.* Ann Arbor, MI.

King, B. (1987). *Better designs in half the time: Implementing QFD in America.* Methuen, MA: Goal/QPC.

Langdon, R. (1990, February-March). Quality function deployment: New weapon in the zero defects war. *Automotive Engineer.*

Locascio, A., & Thurston, D. (1993). Multiattribute design optimization with quality function deployment. *Proceedings, 2nd IE Research Conference.* Los Angeles, CA.

Maddux, G. et al. (1991, June). Organizations can apply quality function deployment as a strategic planning tool. *Industrial Engineering,* 33–37.

Mallon, J., & Mulligan, D. (1993, September). Quality function deployment—a system for meeting customer needs. *Journal of Construction Engineering and Management, 119* (3).

Mann, G., & Halbleib, L. (1992). Application of QFD to a national security issue. *Annual Quality Congress Transactions.*

Masud, A., & Dean, E. (1993). Using fuzzy sets in quality function deployment. *Proceedings, 2nd Industrial Engineering Research Conference.*

Prasad, B. (1995). A structured approach to product and process optimization for manufacturing and service industries. *International Journal of Quality and Reliability Management, 12* (9).

ReVelle, J. (1990). *The new quality technology—an introduction to QFD and Taguchi methods* (report B138). Los Angeles, CA: Hughes Aircraft Company.

Ross, P. (1988, June). The role of Taguchi methods and design of experiments in QFD. *Quality Program.*

Schubert, M. (1989). Quality function deployment—a comprehensive tool for planning and development. *Proceedings of the IEEE 1989 National Aerospace and Electronics Conference, 4.*

Slabey, W. (1990). QFD: A basic primer—excerpts from the implementation manual for the three-day QFD workshop. *Transactions, Second Symposium on QFD,* Novi, MI.

Smith, L. (1991, February 6–9). *QFD and its application in concurrent engineering.* Honolulu, HI: Design Productivity International Conference.

Sullivan, L. (1986, June). Quality function deployment. *Quality Progress.*

Wasserman, G. et al. (1989). Integrated systems quality through quality function deployment. *Proceedings from the 1989 Integrated Systems Conference, Institute of Industrial Engineers Conference.* Atlanta, GA.

Wheelwright, S., & Clark, K. (1992). *Revolutionizing product development.* New York: Free Press.

Williams, R. (1994, Summer). Small business manufacturing: An important component of the U.S. defense industrial base. *Acquisition Review Quarterly,* 250–267.

Zultner, R. (1990). Software quality function deployment—adapting QFD to software. *Transactions, Second Symposium on QFD,* Novi, MI.

Zultner, R. (1989). Software quality function deployment. *American Society of Quality Control Quality Congress Transactions.*