Quality Engineering, 11(4), 593–611 (1999)

QFD: VALIDATING ROBUSTNESS

Kinnar K. Ghiya
Intel Corporation
5000 W. Chandler Blvd., CH7-306
Chandler, Arizona 85226

A. Terry Bahill
Systems and Industrial Engineering Department
University of Arizona
Tucson, Arizona 85721-0020

William L. Chapman
Raytheon Systems Company
Tucson, Arizona 85734

Key Words

Quality function deployment (QFD); Concurrent engineering; Sensitivity analysis; Total quality management (TQM).

Introduction

Quality function deployment (QFD) started in Japan in the late 1960s and is now used by half of Japan's major companies. It was introduced in American automobile manufacturing companies in the early 1980s and is being used by numerous American corporations (1,2). QFD is a handy tool for interdisciplinary teams. A typical QFD team will have members from marketing, sales, manufacturing, design, quality control, purchasing, and so on. "QFD enhances communication levels within the core team" (3).

Quality function deployment strives to get the customer's view of quality introduced in the early phases of the design cycle and considered throughout the product's entire life cycle. "QFD therefore represents a change from manufacturing-process quality control to product development quality control" (1). In most implementations, QFD uses many matrixlike charts to discover interrelationships among customer demands, product characteristics, and manufacturing processes, as shown in Figure 1. For example, the first QFD chart compares the customer's demands to quality characteristics. The second chart then investigates the relationship between these quality characteristics and characteristics of the product. The third chart subsequently examines the relationships between these product characteristics and manufacturing processes. Finally, these manufacturing processes are compared to the quality controls that will be monitored during manufacturing.

ToothBrite Inc.: A Heuristic Case Study

In order to analyze QFD as a tool, we need an example to study; therefore, we will now present ToothBrite (4). Assume that you are the Chief Executive Officer of

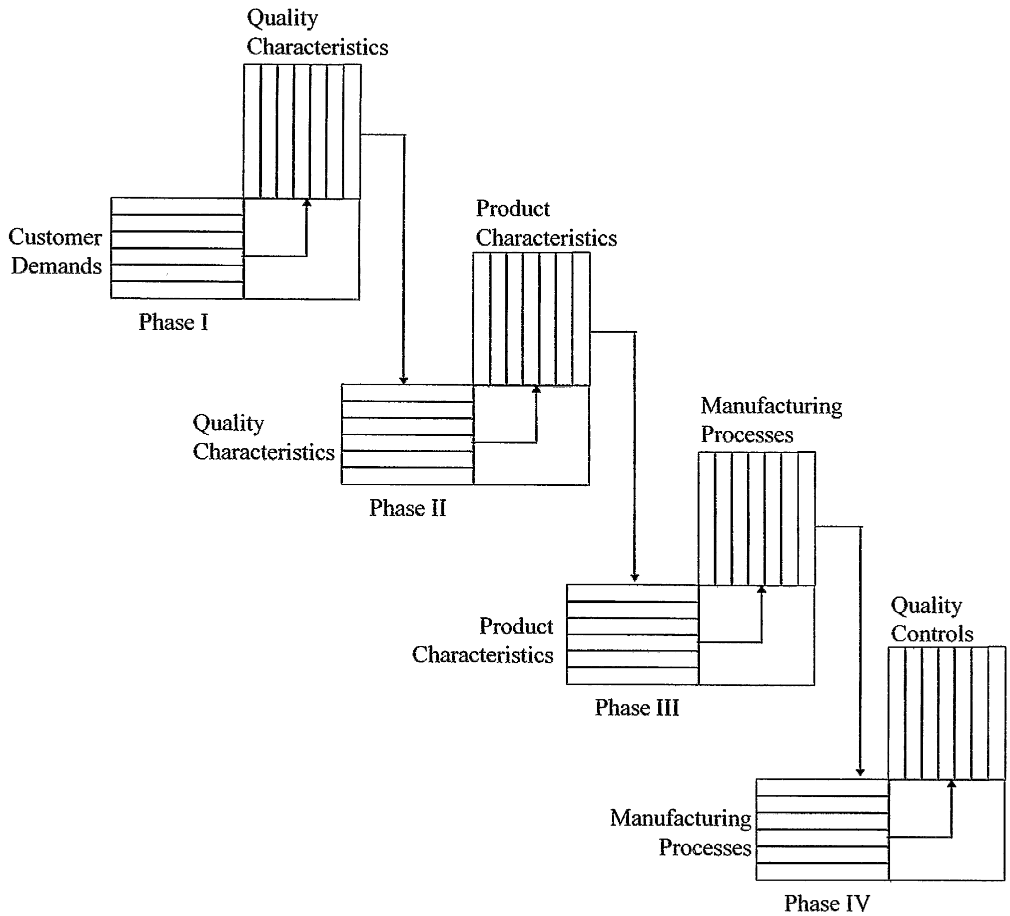

Figure 1. Relationship of the four QFD charts.

ToothBrite Inc., a major toothpaste manufacturer, and your market share has suddenly dropped. You suspect that this is a result of your competitor's new innovation. Crest® has developed a new toothpaste container called the Neat Squeeze dispenser and has endowed it with a substantial advertising budget. (To understand this example better, you might cut open a Crest® Neat Squeeze dispenser or a Colgate® Neat and Easy Stand Up dispenser and see how it is produced and what is inside.) To recapture your market share, you decide to redesign your product; therefore, you decide to use QFD as your analysis tool. We had our marketing department interview all people we thought could provide inputs for the system design. In the QFD literature, the aspects deemed important by the customer are called customer demands. Our marketing department derived the following customer demands:

Neatness
- Tidy tip: The tip stays neat and clean.
- Retains shape: the container retains its original shape.
- Stays put: The container will not roll off the counter.

Hygienic: Toothpaste cannot touch the brush and then be drawn back into the container.

Squeezable: People want to squeeze the container, not pump.

Easy open: The cap opens and closes easily.

No waste: Almost all the toothpaste comes out.

Small footprint: Container takes little counter space.

Reasonable cost: It should cost about the same as present containers.

Attractive container: The sales department says that it must look good.

After listing the demands, the customer assigns a weight indicating the relative importance of each demand. Usually, the weights are between 1 and 10, with 10 being most important. Figure 2a shows the customer demands on the left side and the associated weights in the right column.

Original ToothBrite Phase I

	Amount of Mess	Amount of Pullback	Amount of Pressure	Amount of Effort	Amount of Waste	Counter Space	Amount of Deformation	Pleasing Appearance	Cost to Produce	Selling Price	Importance (1 to 10)
Neatness											
Tidy Tip	9	3			1			5	9		10
Retains Shape			1		1	3	9	1	1		4
Stays Put						3	3				6
Hygienic	1	9							9		4
Squeezable			9		1		3		1		8
Easy Open	1			9					3		4
No Waste	3	1	3		9		1				6
Small Footprint						9	1				5
Reasonable Cost								1	3	9	9
Attractive Container	3					1	3	9	1	9	7
Score	137	72	94	36	76	82	110	126	184	144	
Rank	3	9	6	10	8	7	5	4	1	2	

(a)

Modified ToothBrite Phase I

	Suction Device	Dashpot & Air Chamber	Elastic Walls	Rigid Walls & Pump	Plastic Walls	Paste Viscosity Requirement	Fixed Amount Dispensed	New Cap Design	Flat Top & Bottom	Squeezable Top & Bottom	Inexpensive Materials	Simple Manufacturing Processes	Graphic Designer	Tamper Proof Package	Importance (1 to 10)
Neatness															
Tidy Tip		9	9			3	3	3							10
Retains Shape		9	9	9	1		1			3			3		4
Stays Put				1					9	1			3		6
Hygienic		9	9			1	3	1				3		9	4
Squeezable		9	9		9	1				3					8
Easy Open				3				9			3	1			4
No Waste		3	9		9	9	9	1		9					6
Small Footprint				1					9	1			3		5
Reasonable Cost			3		9			1			9	9	1	3	9
Attractive Container								1	3	1	1	1	9	1	7
Score		252	315	59	211	96	100	92	120	108	100	104	117	70	
Rank		2	1	13	3	10	8	11	4	6	8	7	5	12	

(b)

Figure 2. The original (a) and the modified (b) ToothBrite Phase I charts.

In this example, our customer is the person who brushes his or her teeth with the toothpaste. However, "the customer" should also include all people who should provide inputs for the system design. This includes buyers, store managers, mothers, the manufacturer's sales force, the design team, and the production facility. See Chapter 5 of Ref. 5 for a fuller exposition of this matter.

Next, we asked our Systems Engineering Department to derive measures to assure that these customer demands are being satisfied. In the QFD literature, these measures are called figures of merit, quality characteristics, or, sometimes, measures of effectiveness. Quality characteristics should be quantitative and measurable. The following are the quality characteristics we used for the ToothBrite project.

Mess: amount of toothpaste scraped off the tip when half empty
Pull-back: amount of toothpaste pulled back when done dispensing
Pressure: amount of pressure needed to squeeze out the toothpaste
Effort: number of turns, or time, or effort needed to remove cap
Waste: amount of toothpaste left in the container at end of life cycle
Counter space: amount of counter space occupied by container
Deformation: amount of change in shape of container when half empty
Cost of materials: cost of raw materials used to make the container
Pleasing appearance: based on results of customer survey

In general, QFD charts have a desire that needs to be satisfied listed along the side, and measures or approaches for satisfying the desires across the top, as shown in Figure 2a. The items listed on the left are called Whats and items listed along the top are called Hows. To help determine the Hows we ask, "This is What the customer wants, now How can we measure it?" We will often associate optimal or target values with these measures. These measures become the desires on the next chart.

The next step in QFD analysis is determining the strength of the relationships (or the degree of correlation) between the Whats and the Hows. This is done by filling in the center matrix on a column-by-column basis as shown in Figure 2a. Each What is compared to each How. Four classifications are given: If they are strongly related, a value of 9, or a black disk with a white dot inside, is recorded in the appropriate cell. Moderate relationships are given a 3, or a circle; weak relationships are given a 1, or a triangle; and no relationship is given a 0, or the cell is left blank. Depending on the customers, symbols and number can be mixed.

The next step is multiplying each cell's value by the weight of the customer demand and totaling the column for each quality characteristic. This is shown in the row across the bottom labeled Score in Figure 2a. The total score for each column is an indication of the importance of that characteristic in measuring the customer's satisfaction. Typically, measures with low scores receive little consideration. However, this does not necessarily mean that these measures will not be used in the product design: They still may be necessary for contractual or other reasons. To satisfy the customer, we must pay strict attention to the measures with the highest scores. Focusing attention on the customer is the main purpose of the QFD chart. The chart and its results are not as important as the process of concentrating on the "Voice of the Customer" rather than the "Voice of the Manufacturer." For the ToothBrite project, the Cost to Produce (with a score of 184) and Selling Price (with a score of 144) were the most important measures.

Subsequent QFD Charts

To continue our QFD analysis, we will relate the quality characteristics of Figure 2a to characteristics of the product. One of the purposes of a QFD analysis is to investigate many alternative designs. However, as the analysis progresses, we must limit the number of alternatives under consideration. The characteristics of the product will be different for each alternative design. Thus, if we wish to continue investigating alternative designs, then we might have to create a second QFD chart for each alternative. The following product characteristics, provided by the Design Engineering Department, seem to imply a suction type of container:

Double lead threads on cap and tip—allowing cap removal with a half-turn
Size of dispensing hole in tip
Thickness of side walls
Type of material for side walls
Size of dashpot (the portion of the tube containing air)
Viscosity of dashpot
Total weight of the container
Size of the container
Printing on label—must be colorful and easy to read

These product characteristics now become Hows in our second QFD chart shown in Figure 3a. The score of each

Original ToothBrite Phase II	Double Lead Thread	Size of Hole in Tip	Material Thickness	Material Type	Size of Dashpot	Viscosity of Dashpot	Weight of Container	Size of Container	Printing on Label	Shape of Container	Weights
Amount of Mess		1	1	3	3	3					137
Amount of Pull-back		3	3	9	3	9					72
Amount of Pressure		3	3	9		9					94
Amount of Effort	9	1		1							36
Amount of Waste		3	1	3		1		3		1	76
Counter Space							3	9	1	9	82
Amount of Deformation		1	1	3				1		1	110
Pleasing Appearance				1				3	9	3	126
Cost to Produce			1	9	1	3	1	3	3	9	184
Selling Price			1	3	1	1		1			144
Score	324	1009	1149	4713	955	2677	430	2150	1768	2958	
Rank	10	7	6	1	8	3	9	4	5	2	

(a)

Modified ToothBrite Phase II	Double Lead Threads	Size of Hole in the Tip	(Tube) Material Thickness	(Tube) Material Type	Size of the Dashpot	Viscosity of the Dashpot	Weight of the Container	Size of the Container	Printing on Label	Shape of the Container	Weights
Suction Device											
Dashpot & Air Chamber		3		3	9	9		3			252
Elastic Walls		3	3	9							315
Rigid Walls & Pump			3	9			3			1	59
Plastic Walls			3	9					1		211
Paste Viscosity Requirement		3	1	1	3	9				1	96
Fixed Amount Dispensed		3			1		1	1		1	100
New Cap Design	9	1		3						1	92
Flat Top & Bottom										9	120
Squeezable Top & Bottom			3	3						1	108
Inexpensive Materials			9	9		3		1	3	3	100
Simple Manufacturing Processes	1	1	3	3	1	9	1	1	3	9	104
Graphic Designer								9	9	9	117
Tamper-Proof Package	1		3	3					1	3	70
Score	1002	2485	3597	8139	2760	4368	381	2113	1946	4034	
Rank	9	6	4	1	5	2	10	7	8	3	

(b)

Figure 3. The original (a) and the modified (b) ToothBrite Phase II charts.

quality characteristic as determined in the first chart is used as the weight in the second chart. The quality characteristics become the new Whats and the product characteristics become the new Hows. The question becomes, "This is what I am going to measure, now How will I build the product to make it optimum?" We fill out this chart using the same process used for the first chart. Fill out each cell based on how strongly each product characteristic is related to each quality characteristic. Multiply the weights by the numerical values for the relationships and sum the columns to give the scores at the bottom of the chart. The column scores now indicate how strongly each product characteristic is related to the customer's demands. For the ToothBrite project, these scores indicate that the type of material used for the sides of the container is the most important product characteristic. This is an important finding that was not obvious at the outset.

The third QFD chart, shown in Figure 4a, compares the product characteristics to manufacturing processes provided by the Manufacturing Department. The manufacturing processes are as follows:

- Molding process (cap, body, and bottom)—assume a blow molding process
  - Create mold
  - Blow material—assume polycarbonate material will be used
  - Remove container
- Insert and bond liner—the bag that holds the toothpaste
- Insert toothpaste
- Screw on cap
- Weld bottom—assume use of ultrasonic welding to attach sides and bottom
- Paste or print label

These manufacturing processes are listed in the approximate temporal order that we envision. From the scores and ranks at the bottom of this chart, we can see that blowing the material into the mold is the most important process.

Finally, our fourth QFD chart, shown in Figure 5a, compares the manufacturing processes to the quality controls provided by the Quality Control Department. These are the quality control items that will be monitored and controlled during the manufacturing process:

- Mold dimensions
- Material controls (when material is being injected into the mold)
  - Temperature
  - Pressure
  - Time
- Liner attachment inspection
- Toothpaste flow rate
- Cap attachment torque
- Welding controls (when attaching bottom to the sides)
  - Intensity
  - Duration
  - Pressure
- Labeling pressure
- Cleanliness and hygiene controls

As we progressed through this ToothBrite project, the QFD charts became more and more specific. The fourth QFD chart is very specific to particular alternative materials and manufacturing process chosen.

This chart tells us that in order to satisfy the customer, during manufacturing we should pay very special attention to the material temperature and the mold dimensions. This may not have been obvious to the manufacturing engineers before this QFD analysis.

Generalizations

This process of linking QFD charts together can continue until dozens of charts have been filled out (see Refs. 6–8), as suggested by the "Waterfall" chart of Figure 1. For examples of using many QFD charts on one Heuristic example, we recommend Refs. 5 and 7. For many examples derived from real manufacturing systems, see Ref. 8, which is arguably the most definitive work on QFD in the English language. QFD can also be applied to the top-level function, then to its subfunctions, and then to their subfunctions. Using QFD to design real systems will involve many, many QFD charts. Managing such a large database will certainly require computer assistance. Such programs are available (e.g., QFD/Capture by International TechneGroup Inc. and QFD plus by Ford Motor Co.). In this article, we have only scratched the surface in the use of QFD charts.

Alternative Approach

The QFD process can become complex and cumbersome, depending on the product complexity. Many times, the detailed four-chart analysis is not possible with available resources. Many QFD analyses in industry only use the first QFD chart. In this case, the Hows can have a different definition. Here, the Hows are listed as "how can we solve it" or "how can we meet a particular customer demand." Therefore, we will change the definition of the Hows in the first QFD chart and compare the result with the original chart.

Original ToothBrite Phase III	Molding Process (Cap, Body, Bottom)	Create Mold	Blow Material	Remove Container	Insert and Bond Liner	Inserting Toothpaste	Screwing on Top	Ultrasonic Weld Bottom	Pasting or Printing Label	Weights
Double Lead Thread		9	9	3		1	1			324
Size of Hole in Tip		9	9	3		9				1009
Material Thickness			9					3		1149
Material Type		1	9	1	3		1	9	3	4713
Size of Dashpot		3			1					955
Viscosity of Dashpot		9	9	3				3		2677
Weight of Container		3			1					430
Size of Container		9			1	3		1	3	2150
Printing on Label									9	1768
Shape of Container		9	9	3	3			3	9	2958
Score		90930	115470	25617	26548	15855	5037	64919	63123	
Rank		2	1	6	5	7	8	3	4	

(a)

Modified ToothBrite Phase III	Molding Process (Cap, Body, Bottom)	Create Mold	Blow Material	Remove Container	Insert and Bond Liner	Inserting Toothpaste	Screwing on Top	Ultrasonic Weld Bottom	Pasting or Printing Label	Weights
Double Lead Threads		9	9	3		1	1			1002
Size of Hole in the Tip		9	9	3		9				2485
(Tube) Material Thickness			9					3		3597
(Tube) Material Type		1	9	1	3		1	9	3	8139
Size of the Dashpot		3			1			3		2760
Viscosity of the Dashpot		9	9	3				3		4368
Weight of the Container		3			1					381
Size of the Container		9			1	3		1	3	2113
Printing on Label									9	1946
Shape of the Container		9	9	3	3			3	9	4034
Score		143580	212625	43806	41773	29706	9141	119641	84576	
Rank		2	1	5	6	7	8	3	4	

(b)

Figure 4. The original (a) and the modified (b) ToothBrite Phase III charts.

Original ToothBrite Phase IV	Mold Dimensions	Material Control	Temperature	Pressure	Time	Liner Attachment Inspection	Toothpaste Flowrate	Cap Attachment Torque	Welding Controls	Intensity	Duration	Pressure	Labeling Pressure	Cleanliness and Hygene Controls	Weights
Molding Process (Cap, Body, Bottom)															
Create Mold	9													1	90930
Blow Material			9	3	3										115470
Remove Container	3													1	25617
Insert and Bond Liner	1					9				1		1			26548
Inserting Toothpaste							9							9	15855
Screwing on Top								9						3	5037
Ultrasonic Weld Bottom										3	3	9		1	64919
Pasting or Printing Label													9	1	63123
Score	921769		1039230	346410	346410	238932	142695	45333		221305	194757	610819	568107	402395	
Rank	2		1	6	6	8	11	12		9	10	3	4	5	

(a)

Modified ToothBrite Phase IV	Mold Dimensions	Material Control	Temperature	Pressure	Time	Liner Attachment Inspection	Toothpaste Flowrate	Cap Attachment Torque	Welding Controls	Intensity	Duration	Pressure	Labeling Pressure	Cleanliness and Hygene Controls	Weights
Molding Process (Cap, Body, Bottom)															
Create Mold	9													1	143580
Blow Material			9	3	3										212625
Remove Container	3													1	43806
Insert and Bond Liner	1					9				1		1			41773
Inserting Toothpaste							9							9	29706
Screwing on Top	1							9						3	9141
Ultrasonic Weld Bottom										3	3	9		1	119641
Pasting or Printing Label													9	1	84576
Score	1474552		1913625	637875	637875	375957	267354	82269		400696	358923	1118542	761184	686380	
Rank	2		1	6	6	9	11	12		8	10	3	4	5	

(b)

Figure 5. The original (a) and the modified (b) ToothBrite Phase IV charts.

We have used the ToothBrite example (4) to list the Hows in the first chart as "How we can achieve it" instead of "How we can measure it." The customer requirements are the same for both charts (refer to Fig. 2). The Hows in the modified ToothBrite chart 1 of Figure 2b offer possible solutions for the customer requirements. For example, to meet the customer requirement of Neatness, in the original QFD chart, we have Amount of Mess, Amount of Pull-back, and Cost to Produce as significant measures (Hows). In the modified QFD chart, for Neatness, we are offering possible alternatives—we could possibly have a good suction device, or plastic walls, or rigid wall and a pump arrangement. For the Attractive Container requirement, the important measures in the original charts are Pleasing Appearance and Selling Price. For the same What, the modified QFD chart offers a solution—one can employ a graphic designer. Now, one can look at the scores at the bottom of the chart. Elastic Walls is the most important How in this case and, so, the designer of the toothpaste dispenser should consider elastic walls. Thus, this approach offers solutions after the first chart itself and the scores at the bottom of the chart are useful to determine which alternative should be considered seriously. For small tasks, if one wants to limit the QFD usage to the first chart, this approach still brings good results.

We have gone further to study how the effect of changing these Hows propagates through the four charts. Figures 3–5 compare the original ToothBrite charts with the modified charts. The results after progressing through four phases indicates that changing the Hows definition had almost no effect on the final outcome! Compare the two final charts from Figure 5. After progressing through the whole process, the ranks have hardly changed. Controlling the material temperature is still the most important task. This is an indication of the robustness of QFD analysis.

Bicknell (9) says the Hows " . . . should be controllable characteristics. They can be described in measurable terms to provide targets for specifications and desired product improvements." Janet Fiero (through personal communication) comments that the Hows of the first chart can be interpreted in different ways, depending on the problem in hand. Our example shows that it does not make a lot of difference.

Sensitivity Analysis

The next step in our research is to validate the robustness of the QFD process, by conducting a sensitivity analysis. We have used examples from the literature and industry to carry out the sensitivity analysis. Given the proprietary nature of these charts, some of them did not have complete information needed to carry out the sensitivity analysis. In such cases, we modified the charts by filling out the missing information to the best of our knowledge and experience without losing the original gist of the charts.

Figure 6 shows four charts of the Pencil example (7,10). These charts go through the design of a pencil as a new product. Figure 7 shows the four charts of a Door System example (American Supplier Institute, 1992). These charts are from the development of a car door system. Figure 8 shows three charts of a Video Game example (11). We have also used the modified ToothBrite example discussed earlier for this sensitivity analysis.

We have used two approaches to conduct this sensitivity analysis. In the first approach, the correlation weights were changed throughout all four charts and the effect of that on the final outcome was observed. In the second approach, we used a two-level fractional factorial design to vary the customer importance weights in different combinations (e.g., for L16, it will be 16 different combinations) and conducted an analysis to see the effect on the final outcome.

Change in Correlation Values

Deciding on the correlation values can be a very time-consuming process, especially when the chart has many Whats and Hows. The relationships between the Whats and the Hows are defined to be Strong, Medium, Weak, or None. These traditionally have point values of 9, 3, 1, and 0, respectively. It is important to analyze what effect these values have in the final outcome for two reasons. First, as explained earlier, the process gets tedious and there may be a tendency to fill up the rest of the boxes with minimum work and understanding, due to a loss in concentration. If this occurs, the QFD chart may not reflect the outcome as it should be. Second, there may be a conflict in deciding the relationship values. What one team member sees as a strong relationship may look like a medium relation or weak relation to the other team member.

The scale of 9–3–1 resulted from Weber's law. This is a logarithmic scale with a base of 3. Through discussions, we have found that some people feel the need of using different scales and so we did some experiments. We have examined the sensitivity of the QFD method using four different changes:

1. Replace the 9–3–1 scale with a 7–3–1 scale: This deemphasizes the Strong relationship.

CHART: 1

	Length of Pencil	Time Between Sharpening	Lead Dust Generated	Incline Angle Roll	Pages Per Pencil	Pressure Cycles to Erase	Eraser Dust Generated	Importance
Easy to Hold	3	0	0	0	0	0	0	3
Does Not Smear	0	3	9	0	9	1	0	4
Point Lasts	1	9	3	0	9	0	0	5
Does Not Roll	0	0	0	9	0	0	0	3
Easy to Erase	0	0	0	0	1	9	9	3
Score	14	57	51	27	84	31	27	

CHART: 2

	Graphite	Eraser	EraserHolder	Body	Paint	Graphics	Weights
Length of Pencil	1	0	0	3	0	3	14
Time Between Sharpe	9	0	0	0	0	0	57
Lead Dust Generated	9	0	0	0	9	0	51
Incline Angle Roll	0	0	0	9	0	0	27
Pages Per Pencil	9	0	0	0	9	0	84
Pressure Cycles to Era	3	9	1	3	0	0	31
Eraser Dust Generated	3	9	0	0	0	0	27
Score	1916	522	31	378	1215	42	

CHART: 3

	Mold Body	Insert Graphite	Assemble Body	Add Clip	Apply Graphics	Weights
Graphite	0	9	1	0	0	1916
Eraser	0	0	9	0	0	522
EraserHolder	0	0	9	0	0	31
Body	9	1	9	3	3	378
Paint	0	1	3	0	0	1215
Graphics	0	0	0	0	9	42
Score	3402	18837	13940	1134	1512	

CHART: 4

	Length of Mold	Diameter	Break Strength	Tension of Pocket Clip	Sharpness of Figures	Abraidability of Embossing	Depth of Embossing	Weights
Mold Body	9	9	0	0	1	0	1	3402
Insert Graphite	0	0	9	0	0	0	0	18837
Assemble Body	0	0	0	9	0	0	0	13940
Add Clip	0	1	0	9	0	0	0	1134
Apply Graphics	0	0	0	0	9	9	9	1512
Score	30618	31752	2E+05	1E+05	17010	13608	17010	

Figure 6. Pencil example.

2. Replace the 9–3–1 scale with a 5–3–1 scale: This deemphasizes the Strong relationship even further.
3. Replace the 9–3–1 scale with a 9–3–0 scale: This deemphasizes the Weak relationships.
4. Replace the 9–3–1 scale with a 4–2–1 scale: This changes the base of the logarithmic scale from 3 to 2.

We have analyzed the worst-case situations in the above four changes. We normalized each of the scores by dividing by the largest score and multiplying by 100. For example, if the 9's are replaced with 7 in the first modified ToothBrite chart (Fig. 2b), then the score for Dashpot and Air Chamber drops to 200 and the score for Elastic Walls drops to 251. Normalizing these scores (by dividing by 251, this being the highest score) yields 79 and 100, as shown in Table 1 (third column). These are compared to the original QFD scores by finding the root mean square (RMS) change. The Root mean square change is calculated using the following formula:

$$\text{RMS change} = \left\{\left(\frac{1}{n}\right)\sum_{i=1}^{i=n} [\text{Normalized score (original)} - \text{Normalized score (replacement)}]^2\right\}^{1/2}$$

where n is the number of Hows in a chart.

Figure 9 is the plot of root mean square change rows from each chart in Table 1. The largest change is recorded when the weights are changed from 9–3–1 to 5–3–1. Changing 9–3–1 to 7–3–1 does not have a substantial effect on the outcome. If the scale is changed from 9–3–1 to 4–2–1, the change is minimal. This is an important result, as it indicates

CHART: 1

	Door Closing Effort	Pull Force (Inside)	Dynamic Hold Open Force	Static Hold Open Force	Water Leak Test	Importance
Easy Close from Outside	9	1	1	1	0	8
Easy Close from Inside	3	9	1	0	0	5
Doesn't Kick Back	0	0	0	9	0	2
Stays Open in Check	0	0	9	9	0	5
Doesn't Leak Water	0	0	0	0	9	9
Doesn't Drip with Door	0	0	0	0	9	5
Score	87	53	58	71	126	

CHART: 2

	Outside Diameter	Inside Diameter	Shape	Material Specification	Material Density	Vent Hole Diameter	Weights
Door Closing Effort	3	3	3	9	9	9	87
Pull Force (Inside)	3	3	3	9	9	9	53
Dynamic Hold Open Force	0	0	0	0	0	0	58
Static Hold Open Force	0	0	0	0	0	0	71
Water Leak Test	9	9	9	9	9	1	126
Score	1554	1554	1554	2394	2394	1386	

CHART: 3

	Melt Temperature	Extrude Temperature	Extrude Speed	Cure Temperature	Punch Diameter	Punch Sharpness	Weights
Outside Diameter	3	9	9	9	0	0	1554
Inside Diameter	9	9	9	9	0	0	1554
Shape	3	9	9	9	0	0	1554
Material Specification	0	0	0	0	0	1	2394
Material Density	0	0	0	0	0	3	2394
Vent Hole Diameter	0	0	0	0	9	9	1386
Score	23310	41958	41958	41958	12474	22050	

CHART: 4

	Quality Control Chart .	Preventative Maintenance	Mistake Proofing	Education & Training	Weights
Melt Temperature	9	0	0	9	23310
Extrude Temperature	9	0	0	9	41958
Extrude Speed	9	0	0	9	41958
Cure Temperature	0	9	0	9	41958
Punch Diameter	0	0	0	9	12474
Punch Sharpness	0	0	9	9	22050
Score	965034	377622	198450	1653372	

Figure 7. ASI Door System example.

that changing the base of the logarithmic scale used has little impact on the QFD process. Changing the relationships from Weak to None (changing the scale from 9–3–1 to 9–3–0) also has very little effect.

Similar analysis is carried out for the remaining three examples discussed. Table 2 shows the resulting RMS change values for different charts of all three examples. The RMS change is small in all the three charts.

We can also evaluate the change in rankings of the fourth chart Hows. These rankings are important because most teams use them to prioritize their action items. We are using the following formula to show the change in rankings. Say that if the original ranking was $[A_1, A_2, \ldots, A_n]$ and it changed to $[B_1, B_2, \ldots, B_n]$ due to change in correlation values, then the change in rank could be calculated as

$$\text{Change in rank} = \left[\left(\frac{1}{n}\right)\sum_{i=1}^{i=n} (A_i - B_i)^2\right]^{1/2}$$

where n is the number of Hows in the final chart of the QFD experiment.

To understand this better, refer to Table 3. The original ranks for the Hows of Chart 4 for the modified ToothBrite example (from the bottom row of Fig. 5b) were [2, 1, 6, 6, 9, 11, 12, 8, 10, 3, 4, 5]. After changing the correlation values from 9–3–1 to 7–3–1, these ranks changed to [2, 1, 6, 6, 10, 11, 12, 8, 9, 3, 5, 4]. So, using the above formula, we calculated the change to be 0.58, which is very small. Similarly, the changes in ranks were calculated for different combinations of correlation values experiments and for all four examples as shown in Table 3. The maximum change in ranks in all four examples was only 1.78!

To summarize, this analysis validates the fact that the QFD process is robust and is not affected by minor differences of opinion in deciding the correlation values or change of scales. Thus, the QFD process remains a useful tool in the product development process, even when it is used by

Table 1. Results of Changing the Correlation Values for the Modified ToothBrite Example

Results of changing correlation values for the first modified ToothBrite chart

Chart: 1 HOWS	Original 931	Replace 931 with 731	Replace 931 with 531	Replace 931 with 930	Replace 931 with 421
Dashpot & Air Chamber	80	79	79	80	79
Elastic Walls	100	100	100	100	100
Rigid Walls and Pump	18	20	22	15	23
Plastic Walls	66	65	63	65	65
Paste Viscosity Req.	30	33	38	26	38
Fixed Amount Dispensed	31	35	40	30	38
New Cap Design	29	33	40	20	42
Flat Top or Bottom	38	39	40	38	39
Squeezable Top & Bottom	34	38	44	28	45
Inexpensive Materials	31	32	34	29	34
Simple Manuf. Processes	33	34	36	29	37
Graphic Designer	37	41	47	34	45
Tamper Proof Package	22	24	28	20	28
Root Mean Square Change	0.00	2.57	6.50	3.69	6.54

Results of changing the correlation values for the second modified ToothBrite chart

Chart: 2 HOWS	Original 931	Replace 931 with 731	Replace 931 with 531	Replace 931 with 930	Replace 931 with 421
Double Lead Threads	12	13	14	7	13
Size of the Hole in the Tip	30	36	46	29	42
(Tube) Material Thickness	44	50	60	42	54
(Tube) Material Type	100	100	100	100	100
Size of the Dashpot	33	33	32	32	34
Viscosity of the Dashpot	53	51	47	54	49
Weight of the Container	4	5	7	1	7
Size of the Container	25	28	32	22	31
Printing on Label	23	26	29	19	28
Shape of the Container	49	51	54	43	52
Root Mean Square Change	0.00	3.16	8.20	3.19	5.84

Results of changing the correlation values for the third modified ToothBrite chart

Chart: 3 HOWS	Original 931	Replace 931 with 731	Replace 931 with 531	Replace 931 with 930	Replace 931 with 421
Create Mold	67	70	74	60	74
Blow Material	100	100	100	100	100
Remove Container	20	26	36	16	33
Insert and Bond Liner	19	24	33	17	31
Inserting Toothpaste	13	16	21	13	16
Screwing on Top	4	5	7	0	9
Ultrasonic Weld Bottom	56	60	68	56	67
Pasting or Printing Label	39	43	50	37	47
Root Mean Square Change	0.00	3.74	10.24	3.34	8.52

Results of changing the correlation values for the fourth modified ToothBrite chart

Chart: 4 HOWS	Original 931	Replace 931 with 731	Replace 931 with 531	Replace 931 with 930	Replace 931 with 421
Mold Dimensions	77	85	100	66	83
Temperature	100	100	96	100	100
Pressure (Matt. Control)	33	42	57	33	50
Time	33	42	57	33	50
Linear Attachment Inspect	19	24	31	17	19
ToothPaste Flowrate	13	16	20	13	13
Cap Attachment Torque	4	5	6	0	4
Intensity	20	29	46	18	33
Duration	18	25	39	18	28
Pressure (Welding Control)	58	64	72	56	61
Labeling Pressure	39	43	48	37	39
Cleanliness & Hygiene Ctrl	35	47	68	13	62
Root Mean Square Change	0.00	6.99	19.10	7.29	11.62

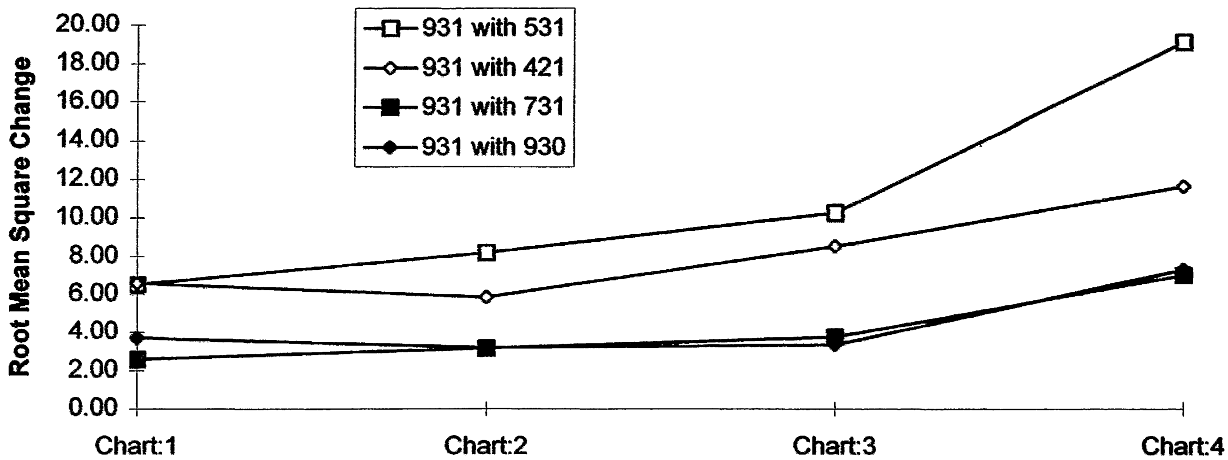

Figure 9. Root mean square change due to global changes in correlation values of the modified ToothBrite charts.

heterogeneous groups (consisting of various engineering and management disciplines), where the group members can have different styles of thought process.

Change in Weights of Customer Demands

Some QFD professional facilitators state that determining the importance of the customer demands is the most time-consuming activity in constructing the first chart. Also, what one customer sees as an important requirement may not be so important for another customer. So, there is a probability of conflict generation while determining the importance of the customer demands (Whats). In this situation, it will be useful to discover what effect this can have in the final outcome. Typically, these importance values are assigned on a scale of 1 to 10, 10 being the most important.

Table 2. RMS Change in Scores Due to Changing the Correlation Values for the Other Examples

Pencil Example	Original 9-3-1	Replace with 7-3-1	Replace with 5-3-1	Replace with 9-3-0	Replace with 4-2-1
CHART 1	0	3.1	7.8	2.6	5.7
CHART 2	0	1.5	3.8	0.8	2.9
CHART 3	0	3.1	3.6	3.6	6.8
CHART 4	0	3.6	10.4	3.4	8.3

ASI Door System Example	Original 9-3-1	Replace with 7-3-1	Replace with 5-3-1	Replace with 9-3-0	Replace with 4-2-1
CHART 1	0	1.9	6.2	6.4	7.8
CHART 2	0	3.7	9.6	2.5	6.7
CHART 3	0	2.9	8.3	4.4	7
CHART 4	0	0	0.9	1.5	1.2

Video Game Example	Original 9-3-1	Replace with 7-3-1	Replace with 5-3-1	Replace with 9-3-0	Replace with 4-2-1
CHART 1	0	1.4	3.6	1.8	3.3
CHART 2	0	4.4	11.2	3	9
CHART 3	0	3.3	8.9	4.4	8.1

Table 3. Change in Ranks Due to Change in Correlation Values

Modified ToothBrite Example - Change in Ranks at Chart 4	**HOWS of Chart 4**												
	Mold Dimensions	Temperature	Pressure (Matt. Control)	Time	Linear Attachment Inspect	ToothPaste Flowrate	Cap Attachment Torque	Intensity	Duration	Pressure (Welding Control)	Labeling Pressure	Cleanliness & Hygiene Ctrl	**Change in Ranks**
Original Rank at Chart 4	2	1	6	6	9	11	12	8	10	3	4	5	***
Rank after 7-3-1 experiment	2	1	6	6	10	11	12	8	9	3	5	4	**0.58**
Rank after 5-3-1 experiment	1	2	5	5	10	11	12	8	9	3	7	4	**1.15**
Rank after 9-3-0 experiment	2	1	5	5	9	10	12	7	7	3	4	10	**1.78**
Rank after 4-2-1 experiment	2	1	5	5	10	11	12	8	9	4	7	3	**1.26**

Pencil Example - Change in Ranks at Chart 4	**HOWS of Chart 4**							
	Length of Mold	Diameter	Break Strength	Tension of Pocket Clip	Sharpness of Figures	Abraidability of Embossing	Depth of Embossing	**Change in Ranks**
Original Rank at Chart 4	4	3	1	2	5	7	5	***
Rank after 7-3-1 experiment	4	3	1	2	5	7	5	**0**
Rank after 5-3-1 experiment	6	3	2	1	4	7	4	**1.07**
Rank after 9-3-0 experiment	3	3	1	2	5	5	5	**0.85**
Rank after 4-2-1 experiment	4	3	1	2	5	7	5	**0**

ASI Door System Example - Change in Ranks at Chart 4	**HOWS of Chart 4**				
	Quality Control Chart	Preventative Maintenance	Mistake Proofing	Education & Training	**Change in Ranks**
Original Rank at Chart 4	2	3	4	1	***
Rank after 7-3-1 experiment	2	3	4	1	**0**
Rank after 5-3-1 experiment	2	3	4	1	**0**
Rank after 9-3-0 experiment	2	3	4	1	**0**
Rank after 4-2-1 experiment	2	3	4	1	**0**

Video Game Example - Change in Ranks at Chart 3	**HOWS of Chart 3**						
	Coating Process	S/W I/F Demo	Field Operators - Respond Within 2 Minutes	Service Locator System	Training Procedures - Validated by Exam	Operational Analysis Procedures	**Change in Ranks**
Original Rank at Chart 3	5	2	4	6	3	1	***
Rank after 7-3-1 experiment	5	2	4	6	3	1	**0**
Rank after 5-3-1 experiment	4	3	5	6	2	1	**0.82**
Rank after 9-3-0 experiment	5	2	4	6	3	1	**0**
Rank after 4-2-1 experiment	4	2	5	6	3	1	**0.58**

Sometimes, the scale is restricted to 1–5 as in Figure 6 (the pencil example) and Figure 8 (the video example).

In this section, the importance of the customer demands were altered by (plus or minus) 1 and the impact was observed on all four charts. We used a design of experiments approach and a two-level fractional factorial design. We will use the pencil example from Figure 6 to explain this analysis. Looking at Figure 6, we realized that the highest number of parameters (either the number of Whats or the number of Hows) in the pencil example is 7. Using a two-level fractional factorial with eight trials (12), we can study up to seven factors (parameters); therefore, we will use a two-level fractional factorial with eight trials for the pencil example to conduct this analysis. The importance of the customer demands are the factors that are changed ± 1 from the original value. For example, look at Chart 1 in Figure 6. Easy to Hold has an importance value of 3. So, for this customer demand (What), the low and high values are 2 and 4. Therefore, in four instances, we will have the importance of the customer demands (for Easy to Hold) to be 2 and in the other four instances, it will be 4. Table 4 shows the two-level fractional factorial with eight trials for the pencil example. Because the first chart has only five factors (Whats), the remaining rows represent noise. As we progress through this analysis, we will realize that the effect of the noise on all the responses is 0.

The importance column of chart 1 of Figure 6 is $(3, 4, 5, 3, 3)^T$. The superscript T represents the vector transpose operation; that is, we are representing a column with a horizontal row. This column changes in the eight experiments. In the first experiment, this column will become $(2, 3, 4, 2, 2)^T$, which is column 2 of Table 4, the two-level fractional factorial with eight trials. When these numbers are used in Chart 1 of Figure 6, the row labeled Score becomes (10, 45, 39, 18, 65, 21, 18), which becomes the top row of Table 5. Eight experiments are run. The last one uses an importance column of $(4, 5, 4, 4, 2)^T$, which is the ninth column of Table 4 and produces a Score row of (16, 51, 57, 36, 83, 23, 18), which becomes the eighth row of Table 5. The effect Easy to Hold can be computed by averaging the four values when importance was low (10, 10, 12, 12) ⇒ average 11, subtracting this from the average when the importance was high (18, 18, 16, 16) ⇒ average 17, and dividing by 2, giving $(17 - 11)/2 = 3$. This is the effect of the importance of Easy to Hold on the Length of Pencil. The other 48 cells of Table 5 are computed in a similar manner. As a check on the arithmetic, we note that all entries in the noise rows must be zero and the rest of the lower portion of Table 5 must be identical to chart 1 of Figure 6.

Now, the results of these eight experiments provide values to replace the Weights column in chart 2 of Figure 6. We will carry out eight different experiments for chart 2, as was explained for chart 1. Refer to chart 2 of Figure 6. The nominal weights column is $(14, 57, 51, 27, 84, 31, 27)^T$. For the first experiment, this will be replaced by (10, 45, 39, 18, 65, 21, $18)^T$, which is the first row of Table 5. This process will continue for the remaining charts. Tables 6–8 show the fractional factorial analysis for the remaining charts of the pencil example.

So, how do we analyze these four tables? And what does this analysis tell us? Because all four tables are linked and a change in Table 5 will propagate through to Table 8, we will concentrate on Table 8. Let us consider the factor Length of Mold from chart 4 of Figure 6. The effects of Whats from chart 4 are the Effect rows of Table 8. The average effect will be the average of these seven entries in column 1. So, if you average 729, 243, . . . , 2187, 0, 0, then you will get the number 1423. Now, the original score from chart 4 of Figure 6 for Length is 30,618. So the % effect is 4.65% [(1423)(100/30,618)]. This means that changing the importance of the customer demands in chart 1 by ±1 unit produces an average change in the score for the How Length of Mold in chart 4 of only 4.65%. These effects are small. Similarly, the % effect for Break Strength is calculated to be 3.36%. These are shown in Table 9.

A similar analysis was carried out for the modified ToothBrite charts, the ASI Door System charts, and the Video Game charts. These results are shown in Table 10.

Table 4. Two-Level Fractional Factorial with Eight Trials Array for Pencil Example

Experiment Number >>>	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Easy to Hold	2	2	2	2	4	4	4	4
Does Not Smear	3	3	5	5	3	3	5	5
Point Lasts	4	4	6	6	6	6	4	4
Does Not Roll	2	4	2	4	2	4	2	4
Easy to Erase	2	4	2	4	4	2	4	2

Table 5. Two-Level Fractional Factorial Analysis—First Chart of Pencil Example

Experiment Number	Length of Pencil	Time Between Sharpening	Lead Dust Generated	Incline Angle Roll	Pages Per Pencil	Pressure Cycles to Erase	Eraser Dust Generated
1	10	45	39	18	65	21	18
2	10	45	39	36	67	39	36
3	12	69	63	18	101	23	18
4	12	69	63	36	103	41	36
5	18	63	45	18	85	39	36
6	18	63	45	36	83	21	18
7	16	51	57	18	85	41	36
8	16	51	57	36	83	23	18
Effect Easy to Hold	3	0	0	0	0	0	0
Effect Does Not Smear	0	3	9	0	9	1	0
Effect Point Lasts	1	9	3	0	9	0	0
Effect Does Not Roll	0	0	0	9	0	0	0
Effect Easy to Erase	0	0	0	0	1	9	9
Effect Noise 1	0	0	0	0	0	0	0
Effect Noise 2	0	0	0	0	0	0	0

We used a two-level fractional factorial with eight trials for the modified ToothBrite charts, a two-level fractional factorial for the ASI Door System charts, and a Plackett–Burman design for the Video Game charts.

Tables 9 and 10 indicate that changing importance of the customer demands by one point (in either direction) does not have a large effect on the final outcome. This is an important conclusion, as the customer can have differences of opinion in what they see as the most important customer demand. As long as these differences are not too large, the QFD process is robust enough to withstand the change.

In another experiment, which we will report in a future article, we found that the most important decisions in completing QFD charts were deciding whether each strong and each medium should indeed be a strong or a medium.

Table 6. Two-Level Fractional Factorial Analysis—Second Chart of Pencil Example

Experiment Number	Graphite	Eraser	Eraser Holder	Body	Paint	Graphics
1	1468	351	21	255	936	30
2	1594	675	39	471	954	30
3	2232	369	23	267	1476	36
4	2358	693	41	483	1494	36
5	1980	675	39	333	1170	54
6	1854	351	21	441	1152	54
7	1984	693	41	333	1278	48
8	1858	369	23	441	1260	48
Effect Length of Pencil	3	0	0	9	0	9
Effect Time Between Sharpeni	192	9	1	3	162	0
Effect Lead Dust Generated	190	0	0	3	108	3
Effect Incline Angle Roll	0	0	0	81	0	0
Effect Pages Per Pencil	63	162	9	27	9	0
Effect Pressure Cycles to Erase	0	0	0	0	0	0
Effect Eraser Dust Generated	0	0	0	0	0	0

Table 7. Two-Level Fractional Factorial Analysis—Third Chart of Pencil Example

Experiment Number	Mold Body	Insert Graphite	Assemble Body	Add Clip	Apply Graphics
1	2295	14403	9919	765	1035
2	4239	15771	15121	1413	1683
3	2403	21831	12591	801	1125
4	4347	23199	17793	1449	1773
5	2997	19323	14913	999	1485
6	3969	18279	12627	1323	1809
7	2997	19467	15421	999	1431
8	3969	18423	13135	1323	1755
Effect Graphite	81	36	84	27	108
Effect Eraser	27	1893	795	9	9
Effect Eraser Holder	27	1821	541	9	36
Effect Body	729	81	729	243	243
Effect Paint	243	603	1872	81	81
Effect Graphics	0	0	0	0	0
Effect Noise 1	0	0	0	0	0

Table 8. Two-Level Fractional Factorial Analysis—Fourth Chart of Pencil Example

Experiment Number	Length of Mold	Diameter	Break Strength	Tension of Pocket Clip	Sharpness of Figures	Abraidability of Embossing	Depth of Embossing
1	20655	21420	129627	96156	11610	9315	11610
2	38151	39564	141939	148806	19386	15147	19386
3	21627	22428	196479	120528	12528	10125	12528
4	39123	40572	208791	173178	20304	15957	20304
5	26973	27972	173907	143208	16362	13365	16362
6	35721	37044	164511	125550	20250	16281	20250
7	26973	27972	175203	147780	15876	12879	15876
8	35721	37044	165807	130122	19764	15795	19764
Effect Mold Body	729	756	324	999	1053	972	1053
Effect Insert Graphite	243	252	17037	7236	108	81	108
Effect Assemble body	243	252	16389	4950	351	324	351
Effect Add Clip	6561	6804	729	8748	2916	2187	2916
Effect Apply Graphics	2187	2268	5427	17577	972	729	972
Effect Noise 1	0	0	0	0	0	0	0
Effect Noise 2	0	0	0	0	0	0	0

Table 9. Pencil Example—Results of Two-Level Fractional Factorial Analysis

Hows of Chart 4 --> (Refer to Figure 6 - Chart 4)	Length of Mold	Diameter	Break Strength	Tension of Pocket Clip	Sharpness of Figures	Abraidability of Embossing	Depth of Embossing
Ultimate Effect (In %)	4.65	4.65	3.36	4.16	4.54	4.51	4.54

Table 10. Results of Two-Level Fractional Factorial Analysis for the Remaining Examples

Results of Changing Importance of the Customer Demands for the Modified ToothBrite Charts

Hows of Chart 4 --> (Refer to Figure 5)	Mold Dimensions	Temperature	Pressure	Time	Linear Attachment Inspection	ToothPaste Flowrate	Cap Attachment Torque	Intensity	Duration	Pressure	Labeling Pressure	Cleanliness & Hygiene Controls
Ultimate Effect (In %)	1.8	1.7	1.7	1.7	1.8	1.9	1.7	1.7	1.7	1.7	1.80	1.8

Results of Changing Importance of the Customer Demands for the ASI Door System Charts

Hows of Chart 4 --> (Refer to Figure 7)	Quality Control Chart	Preventative Maintenance	Mistake Proofing	Education & Training
Ultimate Effect (In %)	2.1	2.1	2.2	2.1

Results of Changing Importance of the Customer Demands for the Video Game Charts

Hows of Chart 3 --> (Refer to Figure 8)	Coating Process	S/W I/F Demo	Field Operators - Respond Within 2 Minutes	Service Locator System	Training Procedures - Validated by Exam	Operational Analysis Procedures
Ultimate Effect (In %)	2.5	2.7	2.6	2.4	2.6	2.6

Summary

These experiments suggest that the QFD process is robust to small changes in the correlation values and the importance of the customer demands. The most significant changes were caused by changing the correlation values from 9–3–1 to 5–3–1: Eliminating the weak correlation or changing the importance weights by ±1 unit had little effect. QFD brings together members from various departments of the company. There are members from marketing, application engineering, design engineering, manufacturing engineering, quality engineering, and so forth. Each member has a different way of thinking and a different way of evaluating given the diversity of his or her background. Thus, there are going to be conflicts when it comes to deciding, say, correlation values or the scale for the correlation values in the first chart. Now, conflict generation is a healthy part of the group dynamics, but it can sometimes diminish the purpose and goals of the group. The above analysis indicates that QFD is robust to a certain extent to such conflicts. From the surveys that marketing or application engineering groups carry out as the first step of QFD process, we may see slight variation in what customers think is the most important need. Our analysis indicated that the QFD process supports such variations to a certain extent. So, even with minor conflicts, a group can utilize QFD outcomes effectively.

Acknowledgments

We would like to thank Jeff Cavanough, Curt Hoffmeister, and Tim Stacy at American Supplier Institute (ASI) for providing us the Door System QFD charts. We would also like to thank Professor John Ramberg at the University of Arizona for his helpful comments about the statistical aspects of this article.

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CHART: 1

	Software Design	Screen Resolution	Info. Access to Technical Matt.	Maintainance and Repair Time	Product Development Process	Manufacturing Operations	Importance
Easy to Use	9	0	3	0	9	1	4
Not Break Easily	0	0	0	9	0	3	3
Versatile Controls	9	0	3	0	9	1	2
Affordable	9	9	0	9	9	3	3
Good Visual Effects	3	9	9	0	3	3	5
Everybody Can Use It	0	1	0	1	1	0	3
Sturdy Controls	0	0	0	9	3	9	4
Interruptable Play	9	0	0	0	1	0	2
Wide Assortment of Action	9	3	3	0	1	0	5
No Eye Strain	9	9	0	0	1	9	3
Don't Get Hurt Using	0	3	0	1	1	9	4
Score	186	129	78	97	125	138	

CHART: 2

	Screen Material	S/W Planning Module	User Friendly Contact	# of Communication Links	Training for DFM and CAD	Definition of Mfg. Operations	Weights
Software Design	0	9	0	9	0	0	186
Screen Resolution	9	0	0	0	0	0	129
Info. Access to Technical Matt.	0	0	9	9	0	1	78
Maintainance and Repair Time	3	3	3	9	9	3	97
Product Development Process	3	1	1	3	9	3	125
Manufacturing Operations	3	0	0	0	9	9	138
Score	2241	2090	1118	3624	3240	1986	

CHART:3

	Coating Process	S/W I/F Demo	Field Operators - Respond Within 2 Minutes	Service Locator System	Training Procedures - Validated by Exam	Operational Analysis Procedures	Weights
Screen Material	9	0	0	0	0	9	2241
S/W Planning Module	0	9	0	0	0	1	2090
User Friendly Contact	0	0	0	9	0	1	1118
# of Communication Links	0	0	9	0	0	0	3624
Training for DFM and CAD	0	0	0	0	9	3	3240
Definition of Mfg. Operations	3	9	0	3	3	9	1986
Score	26127	36684	32616	16020	35118	50971	

Figure 8. Video game example.

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About the Authors: Kinnar Ghiya is a Senior Materials Engineer with Intel Corporation in Chandler, AZ.

A. Terry Bahill is a professor of systems engineering at the University of Arizona in Tucson.

William L. Chapman is a Principal Systems Engineer with Raytheon Systems Company in Tucson, AZ.