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A TUTORIAL ON QUALITY FUNCTION DEPLOYMENT

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ABSTRACT

Quality function deployment (QFD) helps to introduce the idea of quality in early phases of the design cycle and to reevaluate quality considerations throughout the system's entire life cycle. This article presents a tutorial example of using QFD to design a product. It shows which quality controls in the manufacturing process are most important to ensure customer satisfaction.

Introduction

Over the past 40 years, the Japanese have developed many techniques for improving quality in manufacturing processes. One of these, quality function deployment (QFD), is becoming very popular in both Japan and the United States. QFD started in Japan in the late 1960s and is now used by over half of Japan's major companies. It was introduced in American automobile manufacturing companies in the early 1980s; now many of our major corporations are using it, including John Deere, Ford, Chrysler, General Motors, Hughes Aircraft, Boeing, McDonnell Douglas, Martin Marietta, Texas Instruments, Hewlett Packard, Westinghouse, and 3M. QFD is the jewel of the collection of tools now being called total quality management (TQM).

QFD strives to get the idea of quality introduced in early phases of the design cycle and to reevaluate quality issues throughout the product's entire life cycle. In most implementations, QFD uses many matrices to discover interrelationships between customer demands, product characteristics, and manufacturing processes, as shown in Exhibit 1. For example, the first QFD chart compares the customer's demands to quality characteristics. The second chart then investigates the relationships between these quality characteristics and characteristics of the product. The third chart subsequently examines the relationships between these product characteristics and manufacturing processes. Finally, the manufacturing processes are compared to the quality controls that will be monitored during manufacturing. An example will now be given for each of these charts.

QFD presents the data in a user-friendly format. The Japanese philosophy is that everyone participates in improving the product. Therefore, all system design tools should be usable by the chief scientist with a doctor of philosophy degree and the janitor with a high school diploma. As a result, QFD tools are mathematically simple.

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ToothBrite Inc.: A Heuristic Case Study

At this point, we are going to branch away from the generic and focus on a specific example to illustrate the QFD process. Assume that you are the chief executive officer of ToothBrite Inc., a major toothpaste manufacturer,

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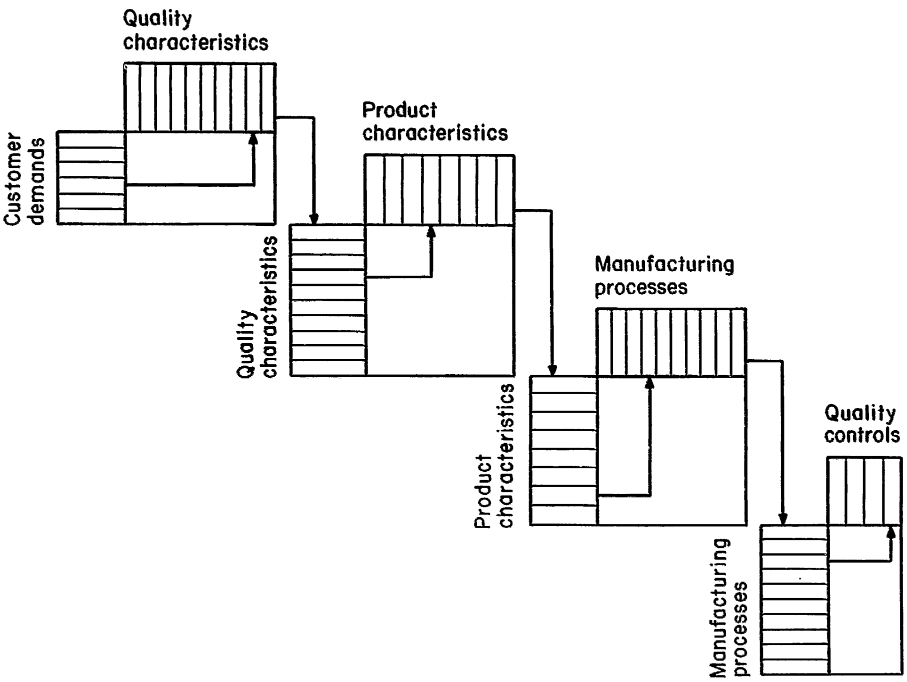

Exhibit 1. The QFD waterfall chart.

and your market share has suddenly dropped. You suspect this is the 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 want to cut open a Crest Neat Squeeze dispenser and see what is inside.) The function of Colgate®'s new Stand-Up Tube is similar. To recapture your market share, you decide to redesign your product. Therefore, you plan a QFD analysis of your product. To begin with, you must find out what your customers want. Our Marketing Department asked all people who should provide input for the system design what they thought was important. In the QFD literature, the aspects deemed important by the customer are variously called demands, wants, expectations, requirements, and needs. We will use only the term *customer demands*. Based on customer surveys, we derived the following customer demands:

Customer Demands:

Neatness
- Tidy Tip—The tip stays clean and neat.
- Retains Shape—The container retains its original shape.
- Stays Put—The container does not roll off the counter.

Hygienic—Toothpaste that touched the brush cannot be drawn back into container.

Squeezable—People want to squeeze the container, they do not want a pump.

Easy Open—The cap opens and closes easily.

No Waste—Almost all the toothpaste comes out but not all over the bathroom.

Small Footprint—Container takes up little counter space.

Reasonable Cost—It should cost about the same as present containers.

Attractive Container—The Sales Department says it must look good.

By *attractive container* we mean that is must look good on the shelf in the store and also on the counter in the bathroom. Perhaps we should have divided this up into two customer demands, but we did not. It is easy to continually second guess the categories. We advise that you review them once and move on. You can always go back and change things later.

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 the most important. Exhibit 2 shows the customer demands and the associated weights for the ToothBrite Project. Sometimes these weights are pulled out of the air by the customer's expert. Sometimes they result from group discussions. And sometimes they are derived using quantitative decision-aiding tools such as the analytic hierarchy process (Saaty, 1980; Bahill, 1991).

In this chart, it seems that our customer is the person that brushes his or her teeth with the toothpaste. However, the term *customer* includes all people who should provide input for the system design: buyers, store managers, mothers, stockholders, employees, company management, and the company's Manufacturing and Marketing departments. (Chapter 5 of Chapman, Bahill, and Wymore [1992] explains this more fully.) To suggest the possibility of including these other facets of the customer on this or parallel QFD charts, we now include two demands that are appropriate for the company:

Company Demands:

Time to Market—the amount of time needed before the product can be sold

Return on Investment—profit divided by money and value of facilities provided.

Next, we asked our Systems Engineering Department to derive measures to assure that these customer and company demands are satisfied. In the QFD literature, such measures are called quality characteristics; generally in systems theory, they are called figures of merit. Quality character-

	Importance (1 to 10)
Customer	
Neatness	
Tidy Tip	10
Retains Shape	4
Stays Put	4
Hygienic	7
Squeezable	4
Easy Open	6
No Waste	6
Small Footprint	5
Reasonable Cost	9
Attractive Container	8
Company	
Time to Market	5
Return on Investment	9

Exhibit 2. Customer demands with their associated weights.

istics should be quantitative and measurable. These are the quality characteristics for the ToothBrite Project:

Quality Characteristics:

Mess—amount of toothpaste scraped off tip when half empty
Pull-Back—amount of toothpaste pulled back when done dispensing
Pressure—pressure needed to get the toothpaste out
Effort—number of turns or time or effort needed to remove cap
Waste—amount of toothpaste left in 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
Pleasing Appearance—based on customer survey results
Cost to Produce—cost to manufacture the product
Selling Price—sales price for one item
Time to Develop—time needed to develop the product.

In general, QFD charts have something listed on the left and something listed along the top, as shown in Exhibit 3. The things listed on the left are called the Whats and the things listed along the top are called the Hows. To help determine the Hows we ask, "This is *what* the customer wants, now *how* can we measure it?"

The next step in a 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 central matrix as shown in Exhibit 3. Each element of the Whats is compared to each element of the Hows. 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. No relationship is given a 0, or the cell is left blank. The logarithmic 9-3-1 weighting was created by the Japanese and has been adopted by most QFD users. These correlations are sometimes represented with symbols and sometimes with numbers. In fact, sometimes we use both in the same chart, as in Exhibit 3. You should use whatever will make your customers most comfortable. Different symbols may even be used, because the foremost principle of QFD is "copy the spirit, not the form" (Akao, 1990). Each relationship can be either positive or negative. We want to know whether each customer demand can be measured by a quality characteristic, not whether it shows a positive or a negative relationship. If any row of this matrix is blank, then we cannot assure satisfaction of that customer demand; that demand, therefore, should either be eliminated or another quality characteristic should be added. Usually numerous customer demands are generated initially. And then, to save work, the least important ones are deleted. However, the deleted items should be recorded to assure future designers that these customer demands were indeed considered.

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 labeled "Score" in Exhibit 4. The total score for each column indicates 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 they will not be used in the product design: They may still be necessary for contractual or other reasons. To satisfy the customer, we must pay strict attention to the measures with the highest scores. This attention to 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 256) and the *selling price* (with a score of 249) were the most important measures.

WHATs vs. HOWs

Strong Relationship:	●	9
Medium Relationship:	O	3
Weak Relationship:	Δ	1

	Amount of Mess	Amount of Pull-back	Amount of Pressure	Amount of Effort	Amount of Waste	Counter Space	Amount of Deformation	Pleasing Appearance	Cost to Produce	Selling Price	Time to Develop	Importance (1 to 10)
Customer												
Neatness												
Tidy Tip	●	O			Δ			5	●			10
Retains Shape			Δ		Δ	O	●	Δ	Δ			4
Stays Put						O	O					4
Hygienic	Δ	●							●			7
Squeezable			●		Δ		O		Δ			4
Easy Open	Δ			●					O			6
No Waste	O	Δ	O		●		Δ					6
Small Footprint						●	Δ					5
Reasonable Cost								Δ	O	●		9
Attractive Container	O					Δ	O	●	Δ	●		8
Company												
Time to Market								Δ	O	O	●	5
Return on Investment									O	●	O	9

Exhibit 3. The first QFD chart—customer demands versus quality characteristics.

The Roof and Porch of the House of Quality. In addition to the relationships between the Whats and the Hows, Exhibit 5 also shows interrelationships between the Hows in the top triangle. When this top triangle is added, the QFD chart begins to resemble a house, hence the name House of Quality. The top triangle is called the "roof." There are five possible relationships between the Hows: strong positive (indicated with a black disk with a white dot inside or +9); weak positive (indicated with a circle or +3); none (a blank square or 0); weak negative (indicated with an X or -3); and strong negative (indicated with # or -9). Relationships between the Hows help to identify correlations between the quality measures. For example, the *amount of mess* is strongly related to *pleasing appearance*. As one measure increases, the other decreases.

The "porch" (the leftmost triangle) of our House of Quality shows correlations between customer demands. We use the same symbols as for the correlations in the roof: a black disk with a white dot, a circle, a blank square, an X, and a #. Because the porch is original we will now discuss it in detail.

Principles of psychology suggest that humans understand properties best if they are stated in a positive manner and if properties are chosen so that "more is better" or that an "optimum is desired." One customer demand, *no waste*, in Exhibit 5's House of Quality is defined in a negative manner. As a result, the porch (the leftmost triangle) shows a positive correlation between *tidy tip* and *no waste*, because if we leave less toothpaste on the tip then we will waste less toothpaste, which means that *no waste* becomes bigger. Such use of a negative term might make it hard to follow logic like this. We used *no waste* instead of *amount of waste*, because in this case we thought that the "more is better" dictum was more important.

Negative correlations in the porch are important, because they point out conflicting customer demands that will make optimization difficult or perhaps make model validation impossible. For example, *stays put* and *small footprint* have a strong negative correlation. (A pencil balanced on its tip takes up very little counter space, but it is not likely to stay put for long.) Therefore we should worry about trade-offs between these two demands. There are no other strong negative correlations, so we do not have to trade off any other customer demands.

A valuable principle in studying correlations is "Do not analyze your customer's problems based on preconceived notions about the solution." For example, the first time we filled out the chart of Exhibit 4, we were thinking about the Crest Neat Squeeze dispenser, so we put a blank in the cell correlating *retains shape* with *small footprint*. However,

WHATs vs. HOWs

Strong Relationship:	●	9
Medium Relationship:	O	3
Weak Relationship:	Δ	1

	Amount of Mess	Amount of Pull-back	Amount of Pressure	Amount of Effort	Amount of Waste	Counter Space	Amount of Deformation	Pleasing Appearance	Cost to Produce	Selling Price	Time to Develop	Importance (1 to 10)
Customer												
Neatness												
Tidy Tip	●	O			Δ			5	●			10
Retains Shape			Δ		Δ	O	●	Δ	Δ			4
Stays Put						O	O					4
Hygienic	Δ	●							●			7
Squeezable			●		Δ		O		Δ			4
Easy Open	Δ			●					O			6
No Waste	O	Δ	O		●		Δ					6
Small Footprint						●	Δ					5
Reasonable Cost								Δ	O	●		9
Attractive Container	O					Δ	O	●	Δ	●		8
Company												
Time to Market								Δ	O	O	●	5
Return on Investment									O	●	O	9
Score	145	99	58	54	72	77	95	140	256	249	72	
Rank	3	5	10	11	8	7	6	4	1	2	8	

Exhibit 4. The first QFD chart with the addition of calculated scores.

one of our students pointed out that we were confounding our preconceived notion of the solution with the statement of the problem. If we thought about alternative solutions, we would realize that *retains shape* should be negatively correlated with *small footprint* with regard to counter space.

In assessing correlations, avoid tertiary links. For example, *attractive container* is correlated with *retains shape*, and *retains shape* is correlated with *small footprint*. However, the link between *attractive container* and *small footprint* is only a tertiary link, so for this square in the porch of Exhibit 5 we were careful to indicate no correlation.

Analyzing correlations in the porch of the house can help organize the Whats into appropriate subcategories. Whats that have similar correlations with the other Whats should be grouped together. For example, because we thought they were related, we initially grouped the three customer demands *tidy tip*, *retains shape*, and *stays put* into one customer demand category, called *neatness*. However, after looking at the porch of the QFD chart we see that they are independent. Therefore they should not be subcategories, but should be moved up to the main level. However the customer demands *hygienic* and *tidy tip* are strongly correlated and their rows are similar. Therefore they seem to be dependent and could be made subcategories. No other rows are similar, so all the other customer demands seem to be independent. To further illustrate the need to use the porch to help group similar entries, let us consider a new example.

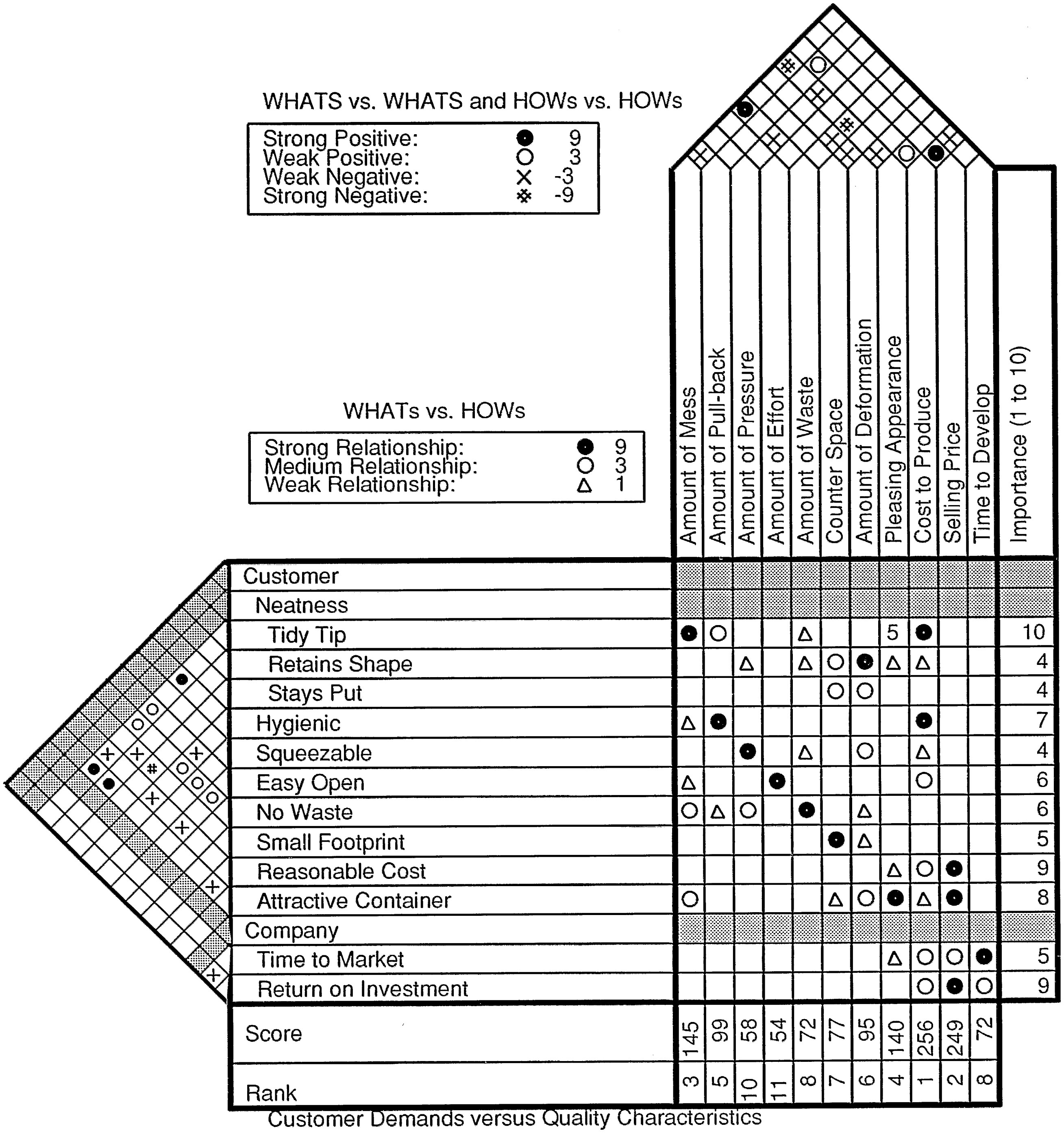

Exhibit 5. The full House of Quality.

Our ToothBrite example shows how QFD can be used to help design a product or process. QFD can also be used to help select the best alternative concept, as suggested with the following example. Suppose a young couple wants to buy a new car. The man says his most important demand is *horse power*, and the woman says her most important demand is *gas mileage*. Although these are conflicting demands with a negative correlation, there is no problem. Their decision of what car to buy will probably be based on a trade-off between these two criteria. Now, however, assume there is another couple where the woman says her most important demand is safety (as measured by safety claims in advertisements), but the man says his most important demands are *lots of horse power*, *lots of torque*, *low time to accelerate 0 to 60 mph*, *low time to accelerate 0 to 100 mph*, *low time for the standing quarter mile*, *large engine size (in liters)*, and *many cylinders*. Assume the man agrees that the woman's demands are more important than his, so they decide to weight *safety* the heaviest: They give it the maximum importance value of 10. The man concedes that his demands are not as important as hers, so they only give his demands importance values of 3 and 4. What kind of a car do you think they will buy? In summary, dependent entries should be combined. However, similar, but independent, entries ought to be made into subcategories and grouped together.

Every QFD chart could have two triangular correlation matrices attached; we have called these the porch and the roof. They alert the system designer to interactions that have different consequences depending on the particular QFD chart. Consider a correlation matrix where the system components are listed. If a system is to be assembled from components made by different people, divisions, or companies, it is important to know which components affect which other components. Thus if one division changes the component they are building, they can notify the other divisions that will be affected by the change. In addition, these correlations can be used to determine interactions when doing sensitivity analyses.

Subsequent QFD Charts. To continue our QFD analysis, we will relate the quality characteristics of Exhibit 5 to characteristics of the product. One purpose of a QFD analysis is to investigate 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. If we wish to continue investigating alternative designs, we might have to create a second QFD chart for each. The following product characteristics, provided by the Design Engineering Department, seem to imply a suction type of tube:

Product Characteristics:

Double Lead Threads on Cap and Tip—this allows cap removal with one-half turn

WHATs vs. HOWs

Strong Relationship:	●	9
Medium Relationship:	○	3
Weak Relationship:	Δ	1

	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		Δ	Δ	○	○	○					145.0
Amount of Pull-back		○	○	●	○	●					99.0
Amount of Pressure		○	○	●		●					58.0
Amount of Effort	●	Δ		Δ							54.0
Amount of Waste		○	Δ	○		Δ		○		Δ	72.0
Counter Space							○	●	Δ	●	77.0
Amount of Deformation		Δ	Δ	●				Δ		Δ	95.0
Pleasing Appearance				Δ				○	●	○	140.0
Cost to Produce			Δ	●	Δ	○	Δ	○	○	●	256.0
Selling Price			Δ	○	Δ	Δ		Δ	○	○	249.0
Time to Develop				○	Δ	○			Δ	○	72.0
Score	486	981	1288	6380	1309	3153	487	2441	2924	4547	
Rank	10	8	7	1	6	3	9	5	4	2	

Quality Characteristics versus Product Characteristics

Exhibit 6. The second QFD chart—quality characteristics versus product characteristics.

Size of Dispensing Hole in Tip
Thickness of Sidewalls
Type of Material for Sidewalls
Size of Dashpot
Viscosity of Dashpot
Total Weight of Container
Size of Container
Printing on Label—must be colorful and easy to read
Shape of Container.

These product characteristics now become the Hows in our second QFD chart shown in Exhibit 6. The score of each quality characteristic as determined in the first chart is used as the weight in the second. The quality characteristics become the new Whats, and the product characteristics become the new Hows. The questions become, "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.

1. Fill out each cell based on how well each product characteristic is related to the quality characteristic. The relation values given in Exhibit 6 were the result of discussions with about 50 people over a 2-year time span. Most of them are obvious but some of them are subtle. For example, *selling price* is weakly related to the *size of the dispensing hole in the tip*, because most people put a certain length of toothpaste on their brush (not a certain amount); therefore with a larger tip they will use up the tube quicker and buy toothpaste more frequently. Such subtle relationships should be documented with notes in the database.

2. Multiply the weights by the numerical values for the relationships and sum the columns to give the scores at the bottom of the chart.

3. The column scores now indicate how well each product characteristic is related to the customer's demands. For

WHATs vs. HOWs

Strong Relationship:	●	9
Medium Relationship:	O	3
Weak Relationship:	Δ	1

	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		●	●	O		Δ	Δ			486.0
Size of Hole in Tip		●	●	O		●				981.0
Material Thickness			●					O		1288.0
Material Type		Δ	●	Δ	O		Δ	●	O	6380.0
Size of Dashpot		O			Δ			O		1309.0
Viscosity of Dashpot		●	●	O				O		3153.0
Weight of Container		O			Δ					487.0
Size of Container		●			Δ	O		Δ	O	2441.0
Printing on Label									●	2924.0
Shape of Container		●	●	O	O			O	●	4547.0
Score		116240	151515	33881	37018	16638	6866	90752	93702	
Rank		2	1	6	5	7	8	4	3	

Product Characteristics versus Manufacturing Processes

Exhibit 7. The third QFD chart—product characteristics versus manufacturing processes.

WHATs vs. HOWs

Strong Relationship:	●	9
Medium Relationship:	O	3
Weak Relationship:	Δ	1

	Mold Dimensions	Material Controls	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	●													Δ	116240.0
Blow Material			●	O	O										151515.0
Remove Container	O													Δ	33881.0
Insert and Bond Liner	Δ					●				Δ		Δ			37018.0
Inserting Toothpaste							●							●	16638.0
Screwing on Top	Δ							●						O	6866.0
Ultrasonic Weld Bottom										O	O	●		Δ	90752.0
Pasting or Printing Label													●	Δ	93702.0
Score	1191687.0		1363635.0	454545.0	454545.0	333162.0	149742.0	61794.0		309274.0	272256.0	853786.0	843318.0	504915.0	
Rank	2		1	6	6	8	11	12		9	10	3	4	5	

Manufacturing Processes versus Quality Controls

Exhibit 8. The fourth QFD chart—manufacturing processes versus quality controls.

our 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 Exhibit 7, compares the product characteristics to manufacturing processes provided by the Manufacturing Department.

Manufacturing Processes:

Molding Process (Cap, Body, and Bottom)—Assume a blow molding process.
Create Mold
Blow Material—Assume use of polycarbonate material.
Remove Container
Insert and Bond Liner—The liner is the bag that holds the toothpaste.
Insert Toothpaste
Screw on Cap
Ultrasonic Weld—Assume bottom is attached to sides by ultrasonic welding.
Paste or Print Label—Minimizing extraneous packaging is an important consideration.

These manufacturing processes are listed in the approximate order in which they are done. 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 manufacturing process. Creating the mold is the second most important process.

Finally our fourth QFD chart, shown in Exhibit 8, compares the manufacturing processes to the quality controls provided by the Quality Control Department. These are the things that will be monitored and controlled during the manufacturing process.

Quality Controls:

Mold Dimensions
Material Controls—properties to be controlled during the molding process
 Temperature
 Pressure
 Time
Liner Attachment Inspection
Tooth Paste Flow Rate—how fast the toothpaste is inserted into the tube
Cap Attachment Torque
Welding Controls—parameters to be controlled during ultrasonic welding
 Intensity
 Duration
 Pressure
Labeling Pressure
Cleanliness and Hygiene Controls.

For the *liner attachment inspection*, we assume that some quality control technique will be used to remove some units from the assembly line for destructive testing to monitor assembly strength. The other tests can be made on-line.

As we progressed through this ToothBrite Project, the QFD charts became more and more specific. This fourth QFD chart is specific to the particular alternative, materials, and manufacturing process chosen. This last chart tells us that in order to satisfy the customer, we should pay very special attention to the *material temperature* and the *mold dimensions* during manufacturing. This may not have been obvious to the manufacturing engineers before this QFD analysis.

Our QFD analysis is now complete. Throughout the entire design and production cycle, the QFD charts have been used to ensure that the customer's concerns were addressed. The chief responsibility of engineering management is to allocate scarce human and financial resources to ensure that these customer needs are met. The first chart shows that the *cost to produce*, *the selling price*, and the *amount of mess* should be the chief concerns for the designers. The second chart shows that the *type of material*, the *shape of the container*, and the *viscosity of the dashpot* are the most important product characteristics; the manager should allocate talent and money to trade-off studies on these product characteristics. On the third chart, the manufacturing processes of importance are *blowing the material* into the mold, *creating the mold*, and *pasting or printing the label*. The manufacturing manager now knows which processes to develop and spend capital on. The final matrix shows that the *material temperature*, the *mold dimensions*, and the *ultrasonic welding pressure* are the critical quality controls and deserve special experimentation and investment to ensure a quality product.

Generalizations

The phrase *quality function deployment* might imply that the tool is a technique for deploying good functions, but this is misleading. That phrase is just a loose translation of the Japanese phrase *HinShitsu KiNo TenKai*. The word *HinShitsu* can be translated as qualities, features, characteristics, or attributes; *KiNo* can be translated as function, method, or procedure; and *TenKai* can be translated as deployment, allocation, flowdown, or distribution. Hence a literal translation might be quality function deployment; but we think more meaningful translations would be *method for allocating features*, or *method for translating characteristics*. However, throughout this article we use the standard name, QFD.

The process of linking QFD charts together can continue until dozens of charts have been filled out, as suggested by the "waterfall" chart of Exhibit 1. For examples of using many QFD charts on one heuristic example, we recommend King (1989) and Chapman, Bahill, and Wymore (1992). For many examples derived from real manufacturing systems, see Akao (1990), which is arguably the most definitive work on QFD in the English language, and the *Transactions of the Symposia on Quality Function Deployment*.

QFD can also be applied to the overall system, then to its subsystems, and then to their components. The critical parameters should flow down from one QFD analysis to the next. 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: We used QFD/Capture (1990) and QFDplus (1991) to generate the exhibits of this article.

Creating QFD charts is a lot of work. The real productivity gain comes when parts of QFD charts are reused. If several versions of the same product are being built, then parts of earlier QFD charts can be reused in the design of later products in the line. Similarly, if QFD charts are reused in redesigning a product, then productivity is enhanced.

The important thing to remember about QFD is that the goal is to translate what the customer considers important into the product so that the customer is satisfied. Creating many charts or trying to optimize any chart is of little value. Discovering what is important to the customer is of great value. "The process of making QFD charts is more meaningful than the final results" (Akao, 1990).

Other QFD Charts

Exhibit 1 shows a temporal ordering of QFD matrices. It would be nice if we really could design a product in such a straightforward manner. However, more often everything has to be done simultaneously. We will now try to give a flavor for many other QFD charts that have been used. Most of them do not follow a temporal ordering. Some of the entities that have been used for the Whats and Hows include customer demands, quality characteristics, product characteristics, manufacturing processes, quality controls, alternatives, functions, parts, components, mechanisms, product failure modes, part failure modes, and new concepts. With just these 13 entities, more than 100 matrices could be formed. However, not all of these matrices are useful; King (1989) explains 30 of them that are in common use. We will now discuss eight of the most useful ones.

1. Customer Demands Versus Quality Characteristics. This is the House of Quality of Exhibit 5. Purposes: to learn customer priorities, to point out which customer demands are most important, to ensure that no customer demand is ignored, to identify key items to measure and control, and to develop an initial plan of how customer demands will be satisfied. This is the most widely used QFD chart. Often these charts are embellished with comparisons of the company's present product to that of the competition.

2. Customer Demands Versus Customer Demands. This is the porch of the house in Exhibit 5, although it could be constructed as a separate chart. Purpose: to alert the system designers to interactions. Dependent demands might be eliminated, and similar but independent demands might be grouped into subcategories. This chart is original; it is not mentioned in the QFD literature.

3. Functions Versus Quality Characteristics. Functions are usually written by engineers, so this chart is often called "Voice of the Engineer Versus Quality Characteristics." Purposes: to identify functions of the product that the customer may not be aware of and to identify missing quality characteristics. The functions of our toothpaste dispenser are *store toothpaste*, *dispense toothpaste*, *clear tip*, and *attract attention*. We made a QFD chart relating these functions to the quality characteristics. The *store toothpaste* function pointed out a possible new quality characteristic of *net weight*.

4. Quality Characteristics Versus Quality Characteristics. This is the roof of the house in Exhibit 5, although it is often constructed as a separate chart. Purposes: to alert the system designers to interactions, to tell the engineers who else must be notified if they make a design change, and to suggest groupings of quality characteristics.

5. Quality Characteristics Versus Parts. Purpose: to identify the parts associated with the most important quality characteristics. These critical parts might be highlighted for technological breakthroughs.

6. Customer Demands Versus Functions. This chart could also be called "Voice of the Customer Versus Voice of the Engineer." Purposes: to validate customer demands, to identify functions that should be the target of cost reductions, to identify conflicts between the Voice of the Customer and the Voice of the Engineer, and to search for latent demands that were not verbalized. For example, the fact that no customer demand related to the function *store toothpaste* suggested a new customer demand of *holds a reasonable amount of toothpaste*.

7. Customer Demands Versus Product Failure Modes. Purposes: to prioritize product failure modes for reliability engineering and to ensure that some important customer demands have not been discarded. For the ToothBrite Project, the product failure modes were 1) stripping the threads, 2) rupturing the mylar sack containing the toothpaste, and 3) losing the hermetic seal of the dashpot by splitting the case, puncturing the case, or having the orifice fall off. This QFD chart (not presented in this article) showed that losing the hermetic seal of the dashpot was the most important failure mode.

8. Product Failure Modes Versus Functions. Purpose: to help engineers focus on the key functions. For the ToothBrite Project, we found that the functions *dispense toothpaste* and *clear tip* were affected most by possible failures.

Other Modern Manufacturing Tools

We have used several of the other recently popularized quality engineering tools. We found that Pareto diagrams are useful if the product is already being manufactured and statistical data about the process are available. We found three tools that are good for brainstorming to help solve problems in the manufacturing process, namely, Ishikawa fishbone diagrams (also called cause-and-effect diagrams), affinity diagrams, and force field analysis.

We found three tools that could be used to select the best alternative concept: Pugh charts (Pugh, 1990), QFD, and matrix analysis (Chapman, Bahill and Wymore, 1992). However, Pugh charts do not provide a quantitative recommendation for the best alternative; they merely give a bunch of +'s and -'s. Therefore, this tool seems more appropriate for brainstorming than for selecting the best alternative concept. Perhaps this tool is best used as a bridge between brainstorming and selecting the best alternative concept. It could be used late in the brainstorming process after many ideas have already been formalized but early in the concept selection process when designs are still being extensively modified. Pugh (1990) has deprecated QFD, saying it is only good for redesign of old, static products. He said, for example, that for the last 90 years, all automobiles have been designed with an engine and a steering system mounted on a box with one wheel at each corner; for such systems, the customer demands and their weights are well known.

Indeed, the most spectacular successes of QFD in the literature have been by automobile companies. We found that QFD was very useful for analyzing an old design, but it was less useful for a brand new design. Most QFD tools have provisions for comparing competitive designs. However, only the customer demands are used, not the performance or cost figures of merit. (The performance and cost figures of merit are also called design requirements or quality characteristics; they are the Hows of the first QFD chart.) Furthermore, none of these QFD tools gives a quantitative summary of the data. Therefore, we think the best way to use QFD to evaluate alternative designs is to fill in a House of Quality QFD chart for each design and study the scores at the bottom of each chart. This way the system judged best is the one that best satisfies the customer demands as well as the performance and cost figures of merit. However, in selecting the best alternative design, we have had the best results using matrix analysis.

In general, QFD charts have the Whats listed on the left and the Hows listed along the top, as shown in Exhibit 3. With a systems engineering approach, we determine the Hows by asking, "This is What the customer wants, now How can we measure it?" However, there is an alternative use for the Hows. We could ask, "This is What the customer wants, now How can we provide that?" If we used this approach for the ToothBrite Project, we would have created Hows such as *incorporate a suction chamber*, *make the tube walls resilient*, *use double lead threads*, etc. This approach is not consistent with the systems engineering process. We suggest that it not be used with QFD unless its consequences are first demonstrated.

Advantages of Using QFD

Japanese and American manufacturers (King, 1989; Akao, 1990; and our companies) have found the following advantages of using QFD:

Customer needs were understood and prioritized better.
Documentation of system requirements was improved.
There was increased commitment from the customer toward finalizing the design.
Design time was reduced (usually by one-fourth to one-half).
Planning became more specific, thus making consensus-building within the company easier.
An informed balance between quality and cost was made.
Control points were clarified.
Duplication of effort was eliminated.
Each task was guaranteed to have someone assigned to it.
The number of engineering bottlenecks was reduced.
The design aim was communicated to manufacturing.
There were fewer manufacturing problems at start up.
There were fewer design changes late in development and during production.
Rework was greatly reduced.
Sales were increased.
Market share was increased.
Customer feedback was increased.
Human relations between divisions were improved.
Employee job satisfaction was improved.
Company organization was improved.
Company reputation for being serious about quality was enhanced.

There are three versions of every conversation: what you meant to say, what you actually said, and what the other person thought you said. QFD helps document what was actually said.

In summary, QFD charts are rapidly becoming popular, powerful, system-design tools. They help ensure that important items are not overlooked. They provide a convenient mechanism for communication between the customer and the engineer. And finally they help to streamline the design and manufacturing process.

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