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Quality Function Deployment (QFD)

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Quality Function Deployment

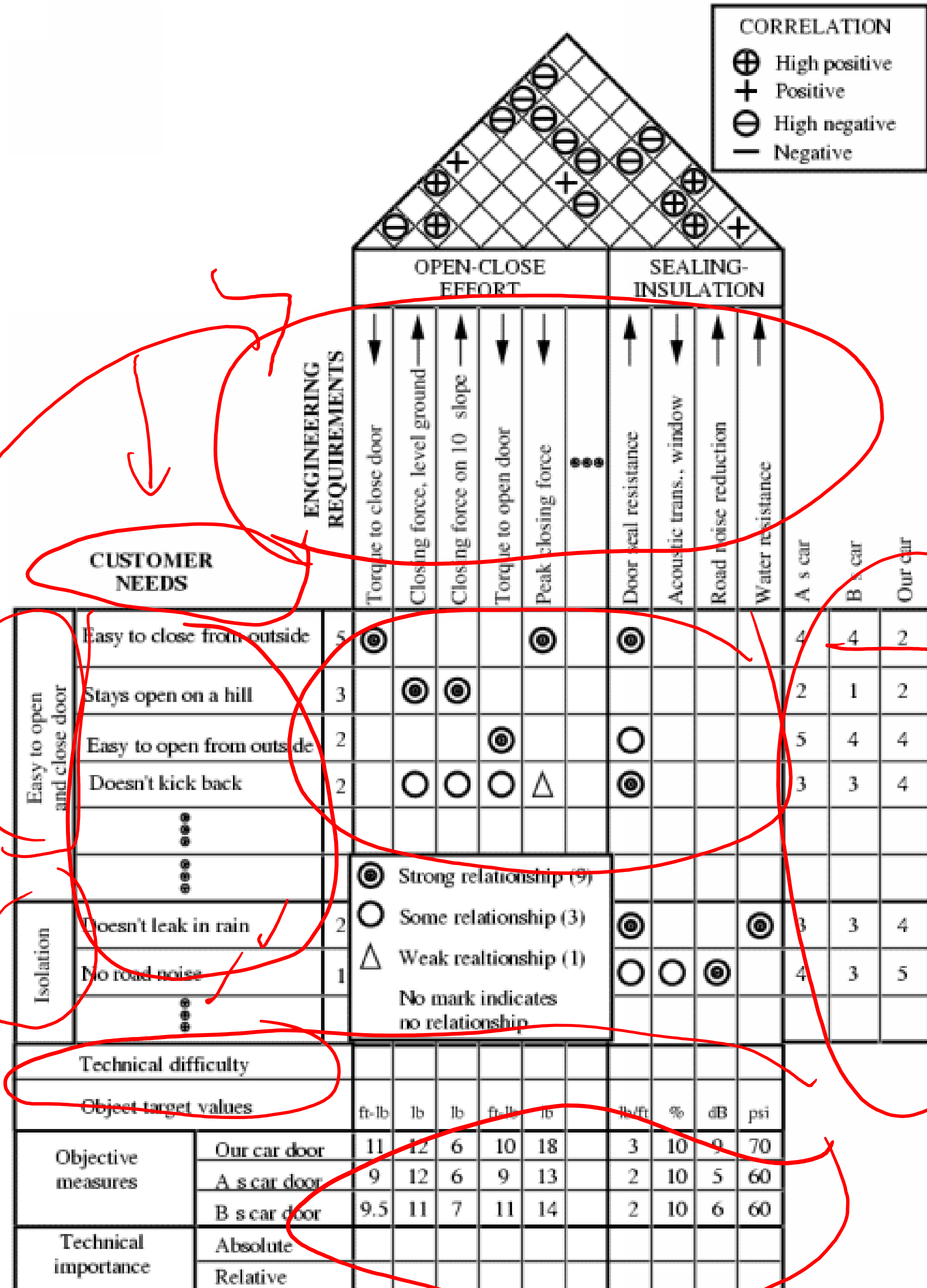
Hin Shitsu	品質 **Quality**
Ki No	機能 **Function**
Ten Kai	展開 **Deployment**

"A group of courageous people working in harmony pursuing the finest detail to unlock the organization and roll out products that the multitudes in the marketplace will value."

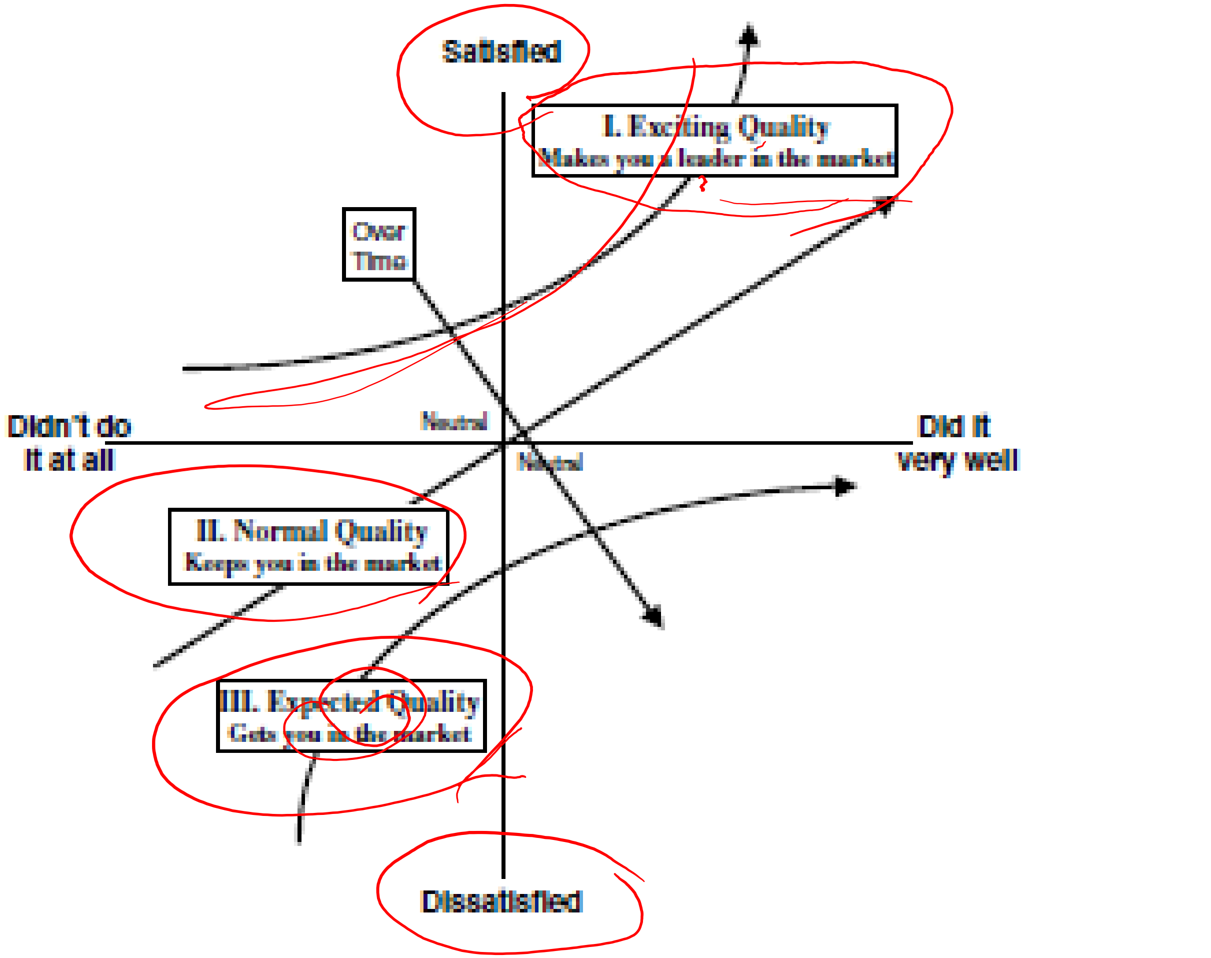
Glenn Mazur

Quality Function Deployment

- Structured method intended to transmit and translate customer requirements
- Voice of the Customer
- Through each stage of the product development and production process, that is, through the product realization process
- These requirements are collection of customer needs, including all satisfiers, exciters/delighters, and dissatisfiers


CORRELATION
High positive
Positive
High negative
Negative
OPEN-CLOSE EFFORT
SEALING-INSULATION
ENGINEERING REQUIREMENTS
Torque to close door
Closing force, level ground
Closing force on 10 slope
Torque to open door
Peak closing force
Door seal resistance
Acoustic trans., window
Road noise reduction
Water resistance
A s car
B s car
Our car
CUSTOMER NEEDS
Easy to open and close door
Easy to close from outside
Stays open on a hill
Easy to open from outside
Doesn't kick back
Isolation
Doesn't leak in rain
No road noise
Strong relationship (9)
Some relationship (3)
Weak realtionship (1)
No mark indicates no relationship
Technical difficulty
Object target values
ft-lb
lb
lb
ft-lb
lb
lb/ft
%
dB
psi
Objective measures
Our car door
A s car door
B s car door
Technical importance
Absolute
Relative

Kano Model - VOC



JRE 11.6 The kano model. (From Wm. Eureka and N. Ryan, The Customer Driven pany, American Supplier Institute, Livonia, MI, 1988. With permission.)

3 main goals in implementing QFD

1. Prioritize spoken and unspoken customer wants and needs.
2. Translate these needs into technical characteristics and specifications.
3. Build and deliver a quality product or service by focusing everybody toward customer satisfaction.

Return on Investment from Using QFD

Companies using QFD to reflect *"The Voice of the Customer"* in defining quality have a competitive advantage because there is/are:

1. Fewer and Earlier Design Changes
2. Fewer Start-up Problems
3. Shorter Development Time
4. Lower Start-up Costs
5. Warranty Cost Reductions
6. Knowledge Transfer to the Next Product
7. Customer Satisfaction

What Does QFD Do?

CONCEPT → CUSTOMER

Better Designs in Half the Time!

Plan | Design | Redesign | Manufacture

"Traditional Timeline"

Plan | Design | Redesign | Manufacture | Benefits

QFD Increase Productivity


HZ11 KHD

Brief History of QFD

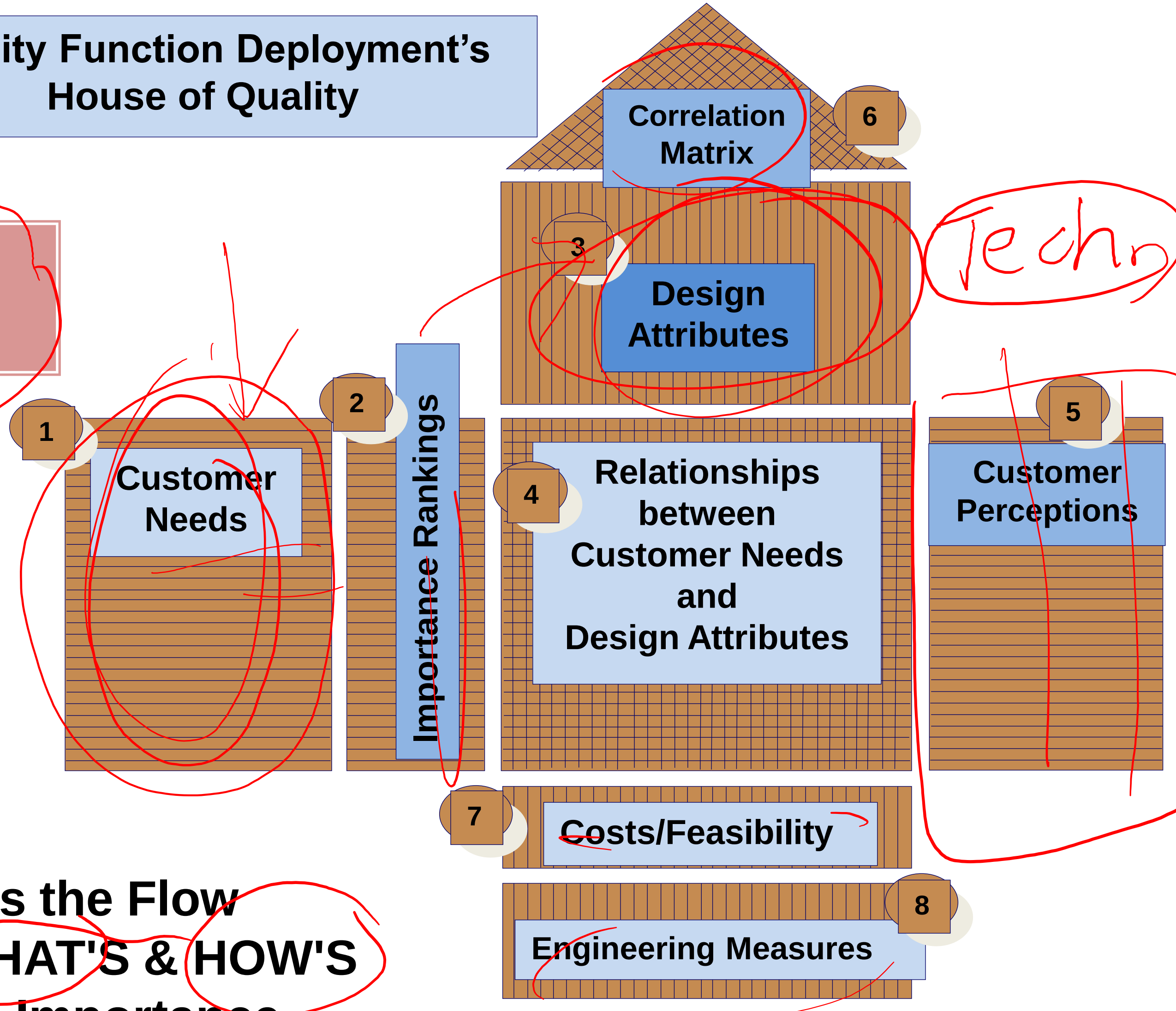
Origin - Mitsubishi Kobe Shipyard 1972

- Developed By Toyota and Its Suppliers
- Expanded To Other Japanese Manufacturers
  - Consumer Electronics, Home Appliances, Clothing, Integrated Circuits, Apartment Layout Planning
- Adopted By Ford and GM in 1980s
- Digital Equipment, Hewlett-Packard, AT&T, ITT

Foundation - Belief That Products Should Be Designed To Reflect Customer Desires and Tastes

Quality Function Deployment's House of Quality

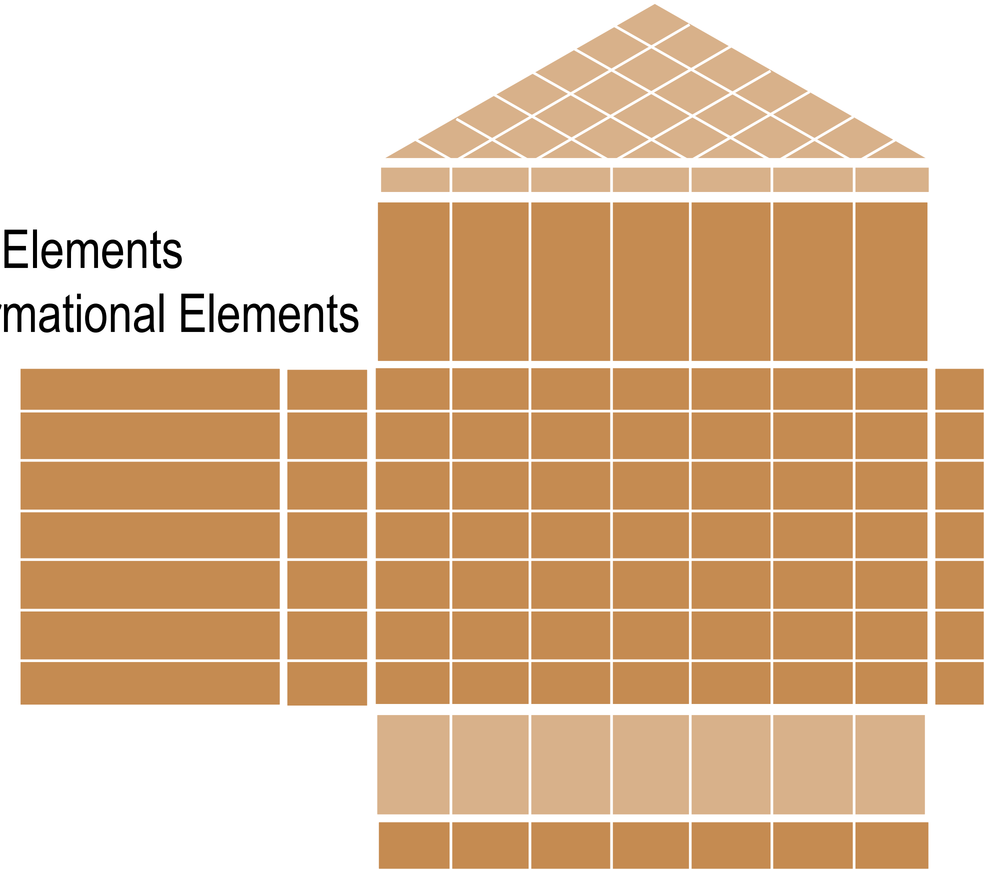
The House of Quality



- Establishes the Flow
- Relates WHAT'S & HOW'S
- Ranks The Importance

The House of Quality

- Key Elements
- Informational Elements



Two Types of Elements in Each House

QFD Deploy

Levels of details

Manufacturing Environment

Customer Wants

Technical Requirements

Part Characteristics

Manufacturing Process

Production Requirements

Software Environment

Customer Wants

Product Functionality

System Characteristics

Design Alternatives

Service Environment

Customer Wants

Service Requirements

Service Processes

Process Controls

Deployment Relating The Houses To Each Other

Building the House of Quality

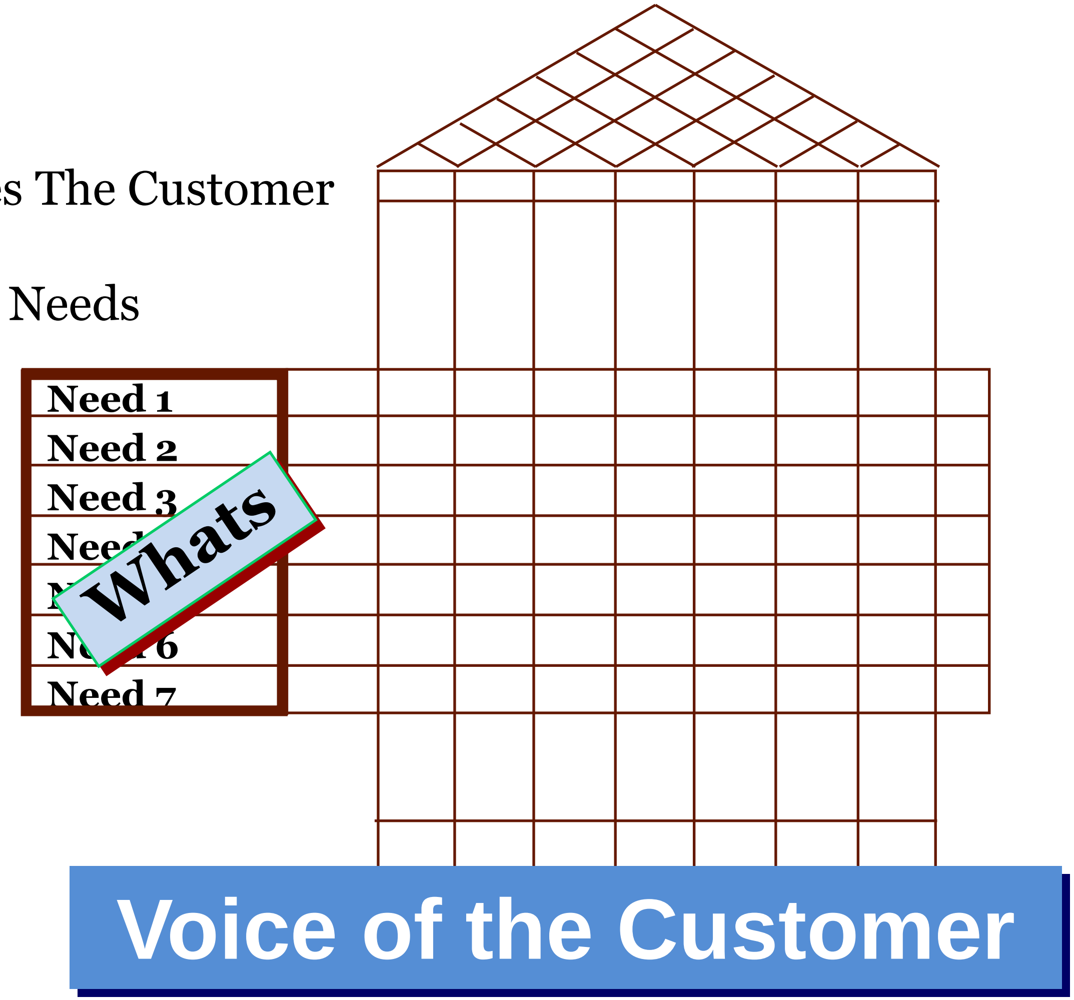
1. Identify Customer Attributes
2. Identify Design Attributes / Requirements
3. Relate the customer attributes to the design attributes.
4. Conduct an Evaluation of Competing Products.
5. Evaluate Design Attributes and Develop Targets.
6. Determine which Design Attributes to Deploy in the Remainder of the Process.

1. Identify Customer Attributes

- These are product or service requirements *IN THE CUSTOMER’S TERMS*.
  - Market Research;
  - Surveys;
  - Focus Groups.
- “What does the customer expect from the product?”
- “Why does the customer buy the product?”
- Salespeople and Technicians can be important sources of information – both in terms of these two questions and in terms of product failure and repair.
- OFTEN THESE ARE EXPANDED INTO Secondary and Tertiary Needs / Requirements.

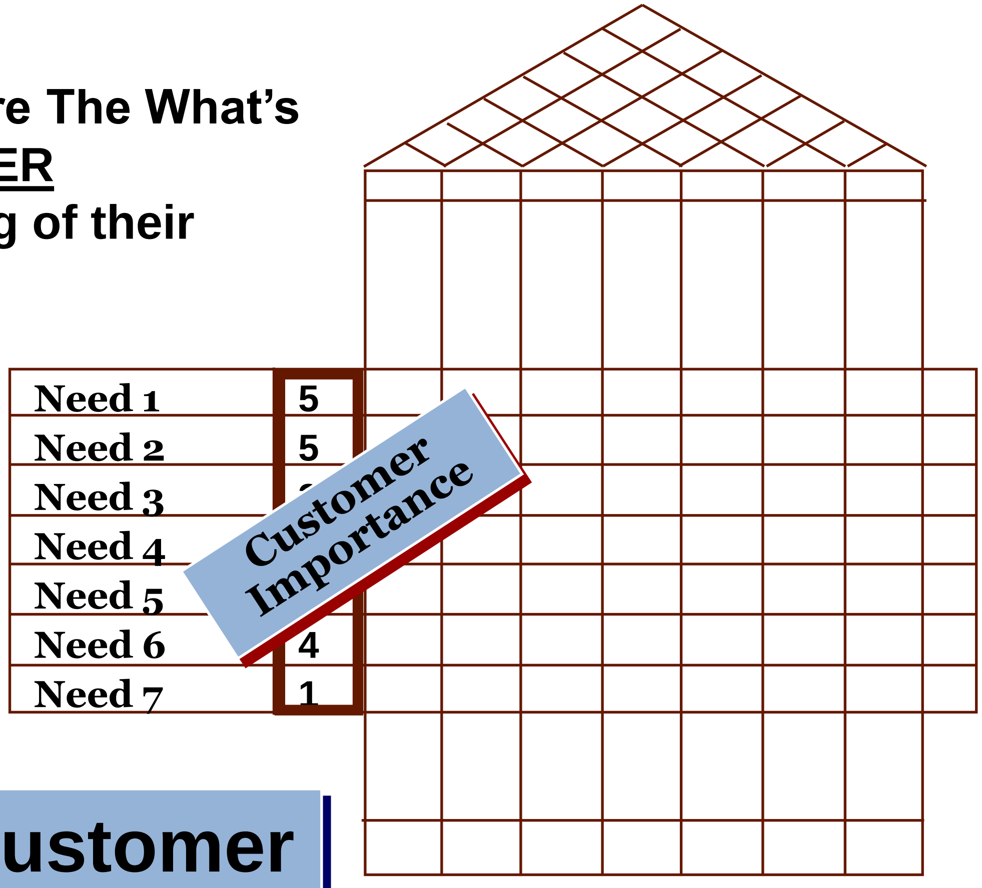
Key Elements - “Whats”

- What Does The Customer Want
- Customer Needs
- CTQs
- Ys



Key Elements: Customer Requirements

- How Important Are The What's <u>TO THE CUSTOMER</u>
- Customer Ranking of their Needs



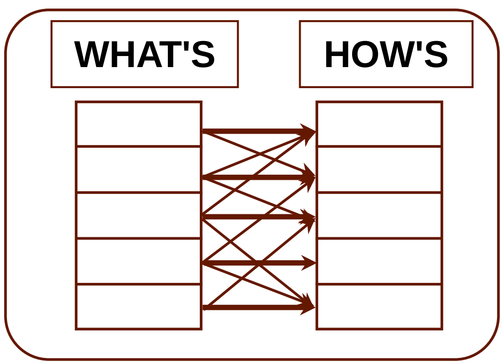
Voice of the Customer

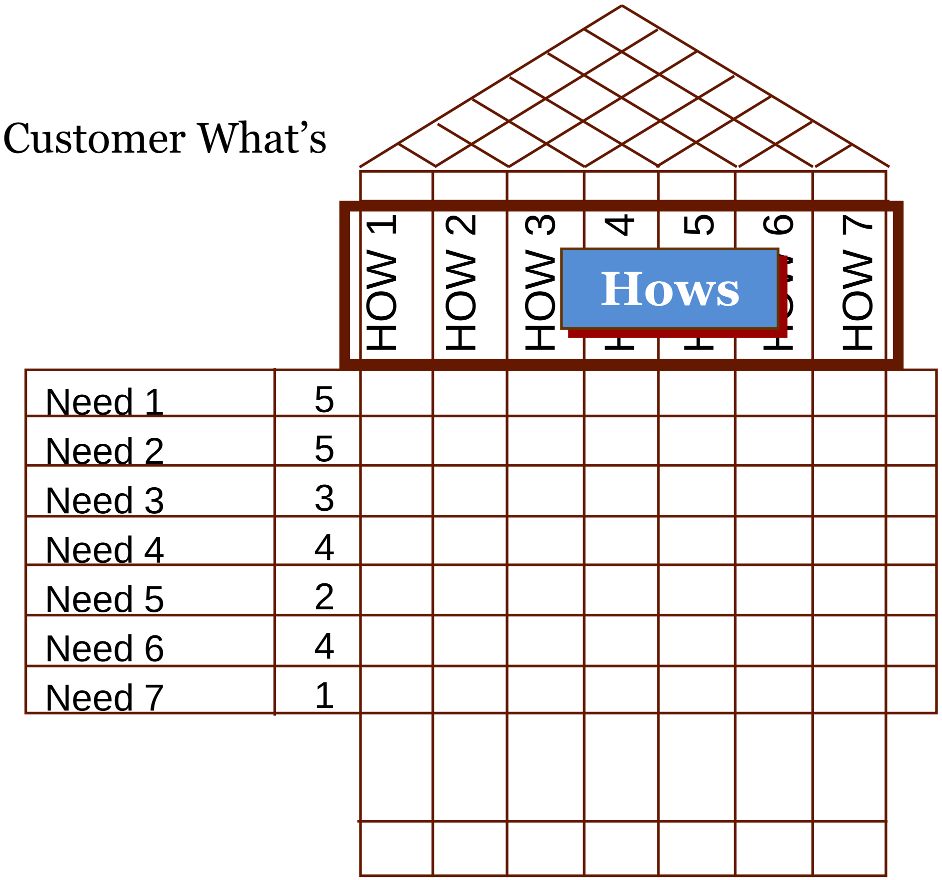
2. Identify Design Attributes.

- Design Attributes are Expressed in the Language of the Designer / Engineer and Represent the **TECHNICAL** Characteristics (Attributes) that must be Deployed throughout the **DESIGN**, **MANUFACTURING**, and **SERVICE PROCESSES**.
- These must be **MEASURABLE** since the Output will be Controlled and Compared to Objective Targets.
- The **ROOF** of the **HOUSE OF QUALITY** shows, symbolically, the Interrelationships between Design Attributes.

Key Elements - "How's"

- How Do You Satisfy the Customer What's
- Product Requirements
- Translation For Action
- X's





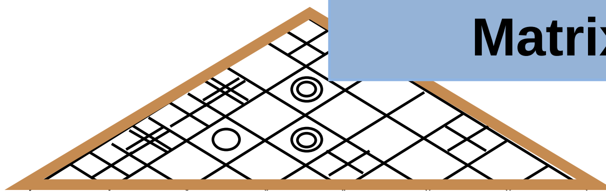
Satisfy the Customer Needs

Information – Correlation Matrix

- Impact Of The How's On Each Other

Strong Positive
Positive
Negative
Strong Negative

Correlation Matrix



		HOW 1	HOW 2	HOW 3	HOW 4	HOW 5	HOW 6	HOW 7	
		↑	↓	↓	↑	↓	↓	○	
Need 1	5	**H**	**L**			**L**		**M**	65
Need 2	5			**H**					45
Need 3	3				**M**	**M**	**L**		21
Need 4	4		**H**						36
Need 5	2			**L**				**M**	8
Need 6	4	**M**			**L**	**H**			52
Need 7	1			**L**			**M**		4
		3 lbs	12 in.	3 mils	40 psi	3	8 atm	1 mm	
		57	**41**	**48**	**13**	**50**	**6**	**21**	

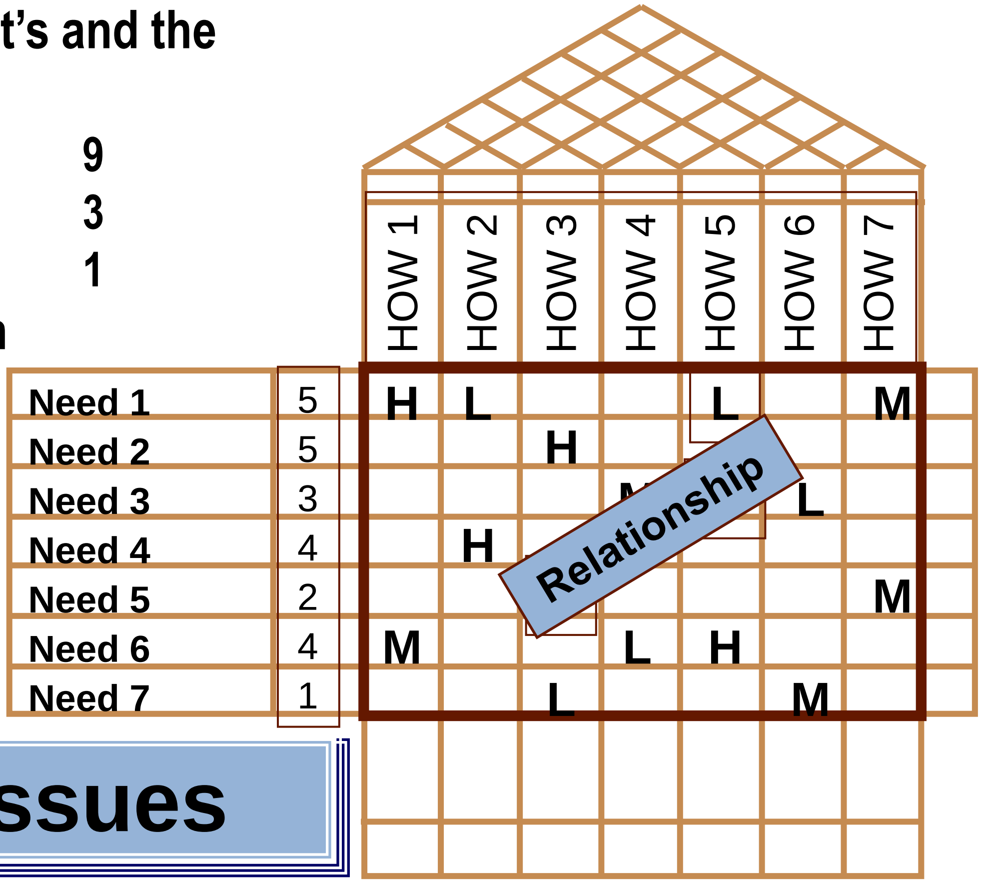
Conflict Resolution

3.Relating Customer & Design Attributes

- Symbolically, determine whether there is NO relationship, a WEAK one, MODERATE one, or STRONG relationship between each Customer Attribute and each Design Attribute
- PURPOSE is to determine whether the final Design Attributes adequately cover Customer Attributes.
- LACK of a strong relationship between *A* customer attribute and any design attribute shows that the attribute is not adequately addressed or that the final product will have difficulty in meeting the expressed customer need.
- Similarly, if a design attribute DOES NOT affect any customer attribute, then it may be redundant or the designers may have missed some important customer attribute.

Key Elements: Relationship

- Strength of the Interrelation Between the What's and the How's
  - H Strong 9
  - M Medium 3
  - L Weak 1
- Transfer Function
- Y = f(X)



Solving the issues

4. Add Market Evaluation & Key Selling Points

- This step includes identifying importance ratings for each customer attribute AND evaluating existing products / services for each of the attributes.
- Customer importance ratings represent the areas of greatest interest and highest expectations AS EXPRESSED BY THE CUSTOMER.
- Competitive evaluation helps to highlight the absolute strengths and weaknesses in competing products.
- This step enables designers to seek opportunities for improvement and links QFD to a company’s strategic vision and allows priorities to be set in the design process.

5. Evaluate Design Attributes of Competitive Products & Set Targets.

- This is USUALLY accomplished through in-house testing and then translated into MEASURABLE TERMS.
- The evaluations are compared with competitive evaluation of customer attributes to determine inconsistency between customer evaluations and technical evaluations.
- For example, if a competing product is found to best satisfy a customer attribute, but the evaluation of the related design attribute indicates otherwise, then EITHER the measures used are faulty, OR else the product has an image difference that is affecting customer perceptions.
- On the basis of customer importance ratings and existing product strengths and weaknesses, TARGETS and DIRECTIONS for each design attribute are set.

Information: How Much

- Target Values for the How's
- Note the Units

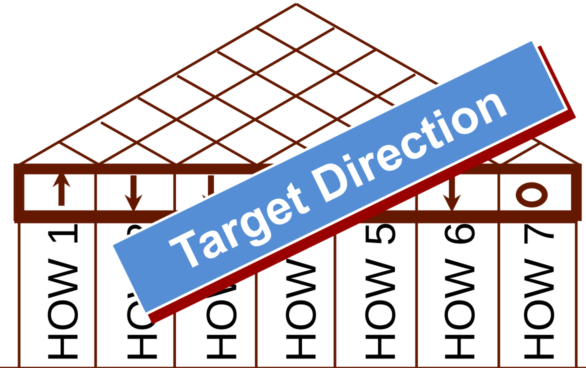
		HOW 1	HOW 2	HOW 3	HOW 4	HOW 5	HOW 6	HOW 7	
		↑	↓	↓	↑	↓	↓	o	
Need 1	5	H	L			L		M	65
Need 2	5			H					45
Need 3	3				M	M	L		21
Need 4	4		H						36
Need 5	2			L				M	8
Need 6	4	M			L	H			52
Need 7	1			L			M		4
		3 lbs	12 in.	3 mils	40 psi	3	8 atm		
		57	**41**	**48**	**13**	**50**	**6**	**21**	

How Much

Consistent Comparison

Information :Target Direction

- Information On The HOW'S
  - More Is Better
  - Less Is Better
  - Specific Amount



		HOW 1	HOW 2	HOW 3	HOW 4	HOW 5	HOW 6	HOW 7	
Need 1	5	H	L			L		M	65
Need 2	5			H					45
Need 3	3				M	M	L		21
Need 4	4		H						36
Need 5	2			L				M	8
Need 6	4	M			L	H			52
Need 7	1			L			M		4
		57	41	48	13	50	6	21	

The Best Direction

6. Select Design Attributes to be Deployed in the Remainder of the Process

- This means identifying the design attributes that:
  - have a strong relationship to customer needs,
  - have poor competitive performance,
  - or are strong selling points.
- These attributes will need to be DEPLOYED or TRANSLATED into the language of each function in the design and production process so that proper actions and controls are taken to ensure that the voice of the customer is maintained.
- Those attributes not identified as critical do not need such rigorous attention.

Key Elements: Technical Importance

- Which How's are Key
- Where Should The Focus Lie
- "CI" = "Customer Importance"
- "Strength" is measured on a 9, 3, 1, 0 Scale

	CI	HOW 1	HOW 2	HOW 3	HOW 4	HOW 5	HOW 6	HOW 7
Need 1		45	5			5		15
Need 2	5			45				
Need 3	3				9	9	3	
Need 4	4		36					
Need 5	2			2				6
Need 6	4	12			4	36		
Need 7	1			1				
		57	4[illegible]	[illegible]	13	50	6	21

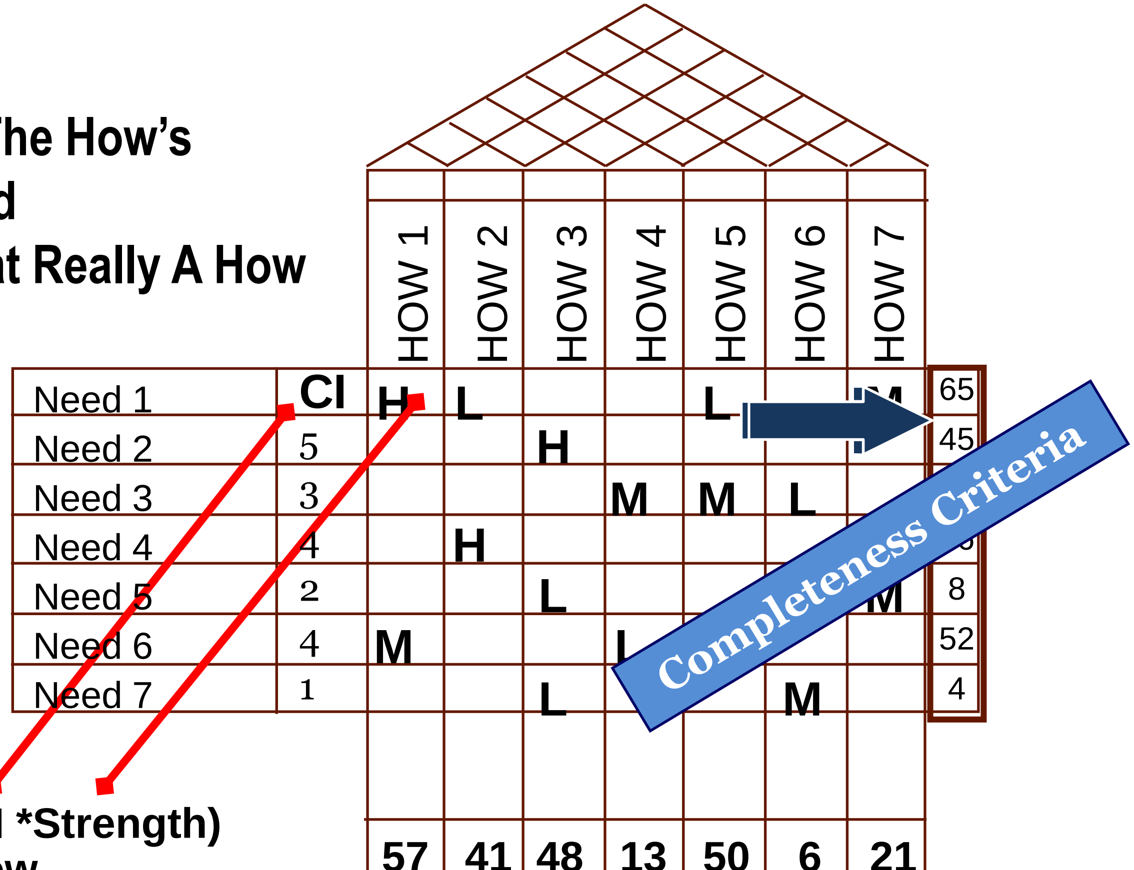
Technical Importance

$$TI = \sum_{column} (CI * Strength)$$

Ranking The HOW'S

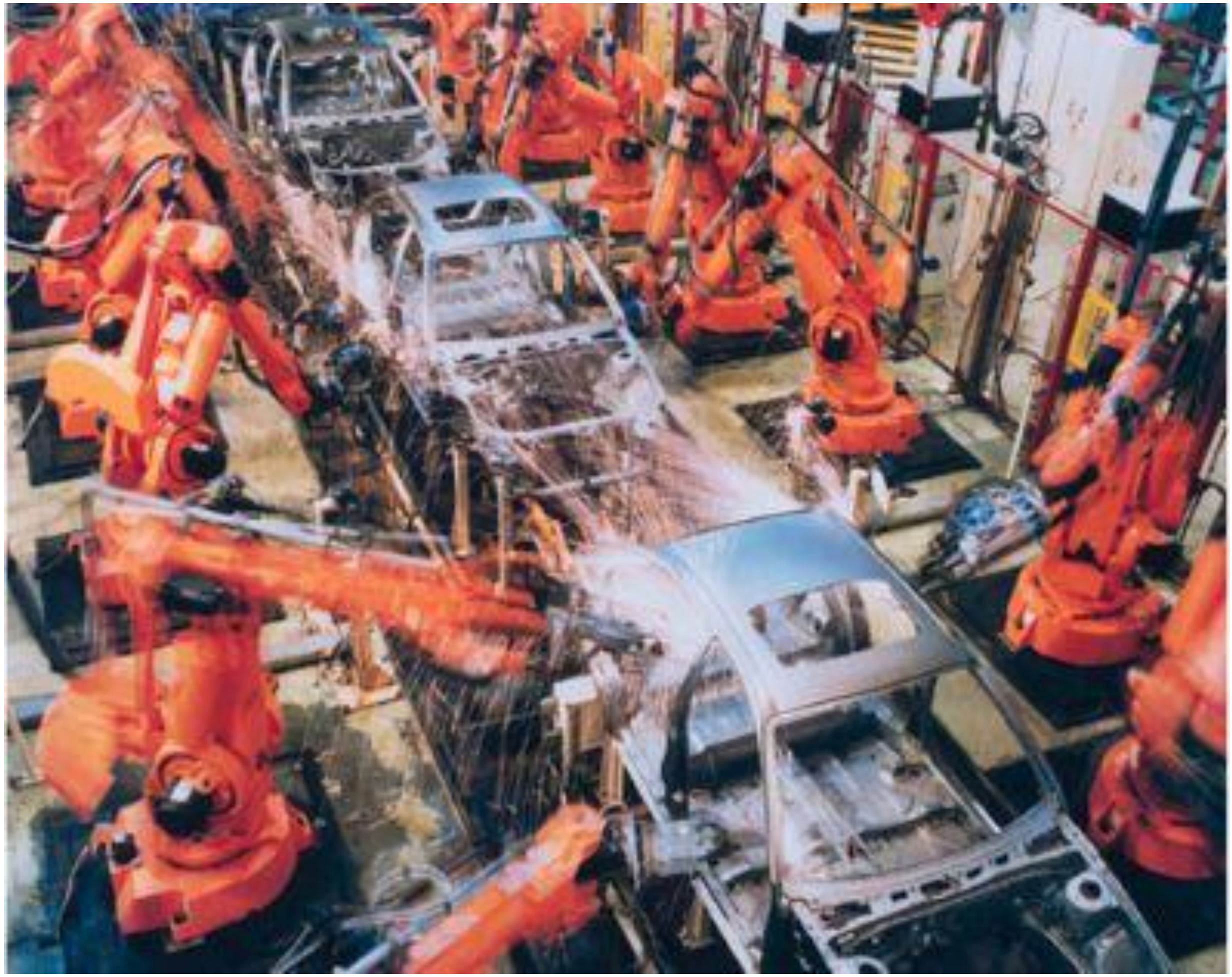
Key Elements : Completeness

- **Are All The How's Captured**
- **Is A What Really A How**



$$CC = \sum_{row}(CI * Strength)$$

Have We Captured the HOW'S



Using the House of Quality

The voice of the customer MUST be carried *THROUGHOUT* the production process.

Three other House of Quality are used to do this and, together with the first, these carry the customer’s voice from its initial expression, through design attributes, on to component attributes, to process operations, and eventually to a quality control and improvement plans.

1 **Design Attributes**

Customer Attributes

2 **Component Attributes**

Design Attributes

3 **Process Operations**

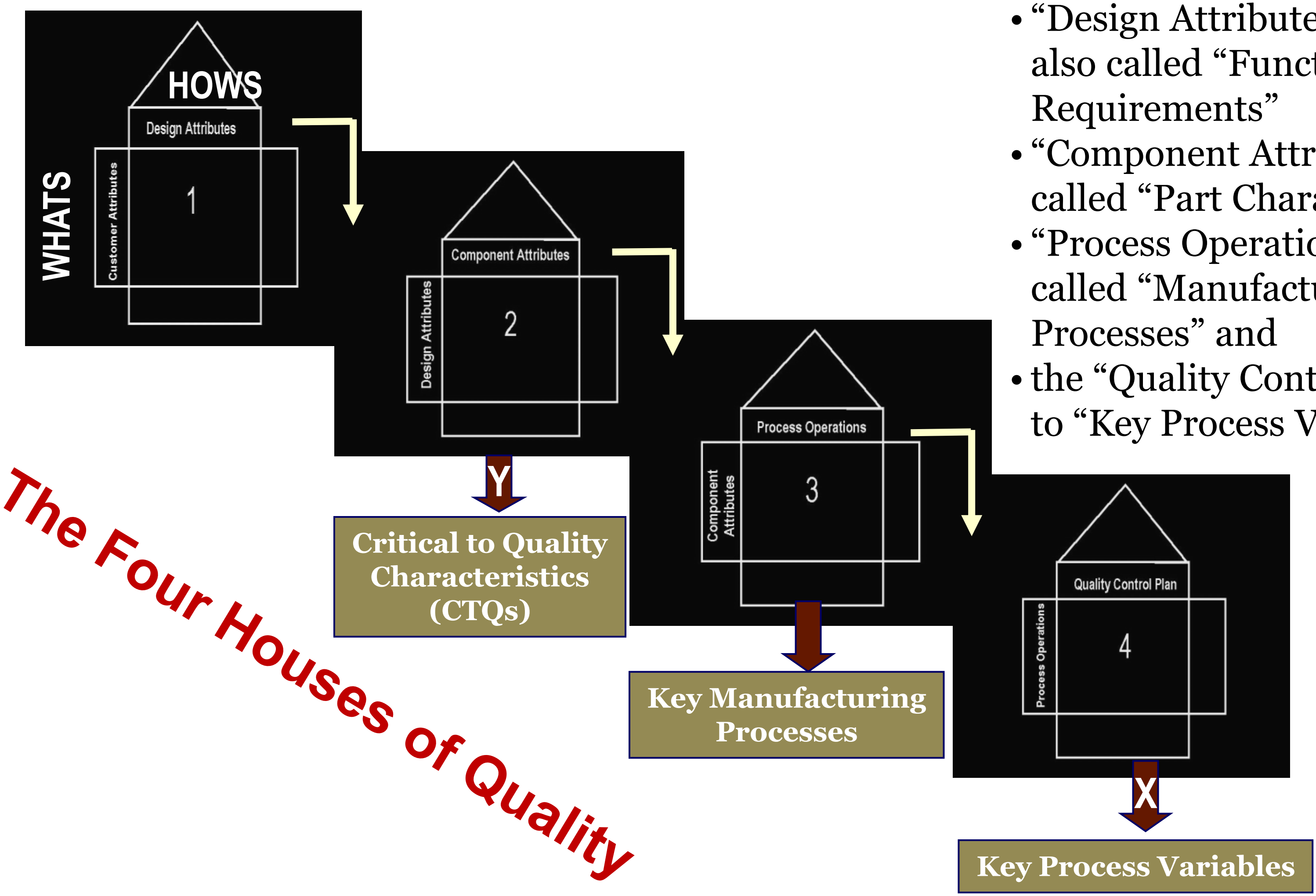
Component Attributes

4 **Quality Control Plan**

Process Operations

The How's at One Level Become the What's at the Next Level

The Cascading Voice of the Customer



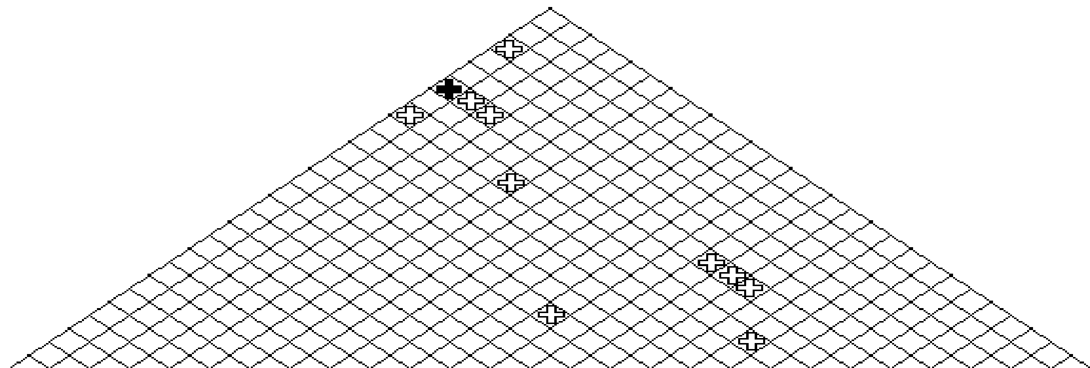
NOTES:

- "Design Attributes" are also called "Functional Requirements"
- "Component Attributes" are also called "Part Characteristics"
- "Process Operations" are also called "Manufacturing Processes" and
- the "Quality Control Plan" refers to "Key Process Variables.

Common QFD Pitfalls

- QFD On Everything
  - Set the “Right” level of details
  - Don’t Apply To Every Last Project
- Inadequate Priorities
- Lack of Teamwork
  - Wrong Participants
  - Lack of Team Skills
  - Lack of Support or Commitment
- Too Much “Chart Focus”
- “Hurry up and Get Done”
- Failure to Integrate and Implement QFD

Computer Server Product Planning Matrix



Interactions:
- ✚ Strong Negative
- ✣ Moderate Negative
- ● Strong Positive
- ○ Moderate Negative

	Customer Needs	Priority	Maximum Processors	Maximum memory controllers	Maximum I/O bridges	SPECint_rate95	Transactions/minute (24 proc.)	HTTPops	Clock rate	Wire data rate	Memory bandwidth	Memory latency	Maximum card cages	System interconnect	I/O	No. of fail-over sys. controllers	Availability	Mean Time Between Failures	Mean Time to Repair (MTTR)	FRU replacement	Maximum FRU weight	OS	System Monitor	Mfg. Cost (24 proc. ref. config.)	Annual support cost (24 proc.)	Rack size (H x W x D)	Cooling	Operating temp.	
	Goal		O	O	O	↑	↑	↑	↑	↑	↑	↓	O	O	O	O	↑	↓	↓	↓	↓	O	O	↓	↓	O	↑	↑	
Power	High performance	5	5	3	3	5	5	5	5	3	3	3			3												3		
Power	Balanced system design	4		3	3					5	5	5			3														
Power	Rapid modular sys. expansion	4											5	3													3		
Avail	Redundancy	2	3	3	3								3	5		5													
Avail	High availability	5	1	1	1									3		5	5	5	5	5	5						3		
Oper.	Compatible with existing apps	3																				5							
Oper.	Easy system management	3																					5						
Oper.	Low total cost of ownership	4															1	3	3	1	1			5	5				
Envir	Fits in standard rack	3																								5	1		
Envir	No special environmental rqmts	2																									3	5	

Customer Needs	Competitive Evaluation (1-Low, 5-High): 1	2	3	4	5	Sales Points	Improvement Ratio
High performance			IH	S		1.2	1.1
Balanced system design			SIH			1.0	1.1
Rapid modular sys. expansion		H		SI		1.2	1.0
Redundancy			SH	I		1.0	1.1
High availability				HI	S	1.5	1.0
Compatible with existing apps		S		IH		1.0	1.2
Easy system management		H	S	I		1.0	1.0
Low total cost of ownership		S	IH			1.0	1.1
Fits in standard rack					SIH	1.0	1.0
No special environmental rqmts			SH	I		1.0	1.0

Technical Evaluation	Maximum Processors	Maximum memory controllers	Maximum I/O bridges	SPECint_rate95	Transactions/minute (24 proc.)	HTTPops	Clock rate	Wire data rate	Memory bandwidth	Memory latency	Maximum card cages	System interconnect	I/O	No. of fail-over sys. controllers	Availability	Mean Time Between Failures	Mean Time to Repair (MTTR)	FRU replacement	Maximum FRU weight	OS	System Monitor	Mfg. Cost (24 proc. ref. config.)	Annual support cost (24 proc.)	Rack size (H x W x D)	Cooling	Operating temp.	
5							S							S						H				SIH			
4	SI	SI		I			I	SIH	SI	SI	S	I		I	S	S	I	S		I	I	I	I		I	I	
3	H	H	SIH	SH	SI	SH	H		H	H	IH	SH	SIH	H	H	IH	SH	H	SH	S	S	H	SH		SH	SH	
2					H	I									I			I	I		H	S					
1																											

S - Sun
I - IBM
H - HP

Technical Requirement	Specification Target Value	Technical Difficulty (1-Low, 5-High)	Importance Rating
Maximum Processors	24	2	47
Maximum memory controllers	24	2	47
Maximum I/O bridges	12	1	47
SPECint_rate95	35.5	3	33
Transactions/minute (24 proc.)	80,000	3	33
HTTPops	38,000	3	33
Clock rate	500 Mhz	2	33
Wire data rate	1 Gbit/s	3	42
Memory bandwidth	2 Gbit/s	4	42
Memory latency	<185 ns	2	42
Maximum card cages	4	2	35
System interconnect	RAPTOR protocol	1	51
I/O	PCI, PCI-66, cPCI & SIO	1	33
No. of fail-over sys. controllers	2	2	49
Availability	99.995% (25 min/yr)	4	42
Mean Time Between Failures	40,000 hrs	5	51
Mean Time to Repair (MTTR)	30 min.	5	51
FRU replacement	100% hot swappable	4	42
Maximum FRU weight	25 lbs.	3	42
OS	Solaris 7.3, Linux2.4	1	18
System Monitor	Enhan. Solstice SyMon	2	15
Mfg. Cost (24 proc. ref. config.)	$220,000	5	22
Annual support cost (24 proc.)	$22,000	3	22
Rack size (H x W x D)	H72" x W19" x D35"	1	15
Cooling	Air - 4 fans 55CFM	2	69
Operating temp.	5°C to 35°C	2	10
		0	0

Points to Remember

- Process may look simple, but requires effort
- If there are NO “tough spots” the first time: It Probably Isn’t Being Done Right!!!!
- Focus on the end-user customer.
- Charts are not the objective. Charts are the means for achieving the objective.
- Find reasons to succeed, not excuses for failure.
- Remember to follow-up afterward

11 Quality Function Deployment (QFD)

Charles A. Cox

11.1 INTRODUCTION

QFD is a way to capture, organize, and deploy the voice of the customer — both the external and internal customers of the organization. QFD has often been associated with product development activities, but has manufacturing applications as well. The QFD concepts and tools are useful to people involved in manufacturing in its long-run and short-run applications.

In a long-run situation, when a new product is designed, QFD requires that the organization's customers including an important internal customer, manufacturing, have input into the design process. The customers' choices and priorities are then converted to technical statements and quantified, which aids the design process. Once the product has been designed, the QFD process is extended to help design the manufacturing process as well. More recently, through integrated process and product design (IPPD), both the product and the process that will be used for producing it are developed in tandem. This results in a much shorter "concept-to-cash" cycle that uses fewer resources for the design and launch. This approach allows greater flexibility and responsiveness to the market.

In the short run, the use of QFD helps the manufacturing team do a superior job of characterizing the process, especially in understanding the linkages between different segments of the process. An important QFD tool, the matrix, when applied as a simple cause-and-effect matrix (see Figure 11.1), shows the process's input–output relationships with the varying strengths between the different inputs and outputs. This structure takes a process map and makes it come alive for ongoing control efforts and further improvement efforts. The figure shows the relationships between ten different inputs in five steps of a plastics molding process to the three key outputs of dimensional stability, uniform density, and smooth finish.

Equipped with a process map and the information in a cause-and-effect matrix, people involved in manufacturing operations can create a process control plan (Figure 11.2) that is appropriate for the operations within their organization.

A high-level framework for conceptually viewing a process and the inputs-to-outputs conversion of a process is available in the SIPOC (Supplier–Input–Process–Output–Customer) chart (Figure 11.3).

In today's complex manufacturing environment, an internal process is often affected by elements outside the organization — from the supply side and customer side. To capture the relationships on both sides of the SIPOC, QFD helps to show

		Output #1	Output #2	Output #3	
		Dimensional Stability	Uniform Density	Smooth Finish	Process Outputs
		10	8	6	Importance
Process Step	Process Input	Correlation of Input to Output			Total
1	Pre-Heat Temp.	0	3	0	24
2a	Barrel Temperature	9	3	0	114
2b	Auger Speed	3	9	0	102
2c	Gate Size/Config.	9	3	0	114
3a	Mold Temperature	3	9	3	120
3b	Gate Distribution	3	9	1	108
4a	Dwell Time	3	1	9	92
4b	Dwell Temperature	3	0	3	48
5a	Extraction Pressure	9	0	3	108
5b	Cool down slope	0	0	9	54

FIGURE 11.1 The cause-and-effect matrix. Correlation of Input to Output: 0, no relationship; 1, possible relationship; 3, medium; 9, strong relationship.

Control Plan No.:	Key Contacts/Phone	Date (Orig.)	Date (Rev.)	Effective:
Part No./Latest Chg. Level	Core Team		Customer Eng'g. Approval/Date	
Part Name/Description	Supplier/Plant Approval/Date		Customer Quality Approval/Date	
Supplier/Plant	Supplier Code	Other Approval/Date	Other Approval/Date	

Part/ Process Number	Process Name/ Operation Desc.	Machine, Device, Jig Tools for Mfg.	Characteristics			Special Class.	Methods					Reaction Plan
			No.	Product	Process		Product/Process Spec/Tolerance	Evaluation Measurement Technique	Sample Size	Sample Freq.	Control Method	

FIGURE 11.2 Process control plan. (Reprinted with permission from the *APQP Manual* (DaimlerChrysler, Ford, General Motors Supplier Quality Requirements Task Force).)

and integrate the supply chain management and customer relationship management elements with the internal SIPOC (Figure 11.4).

Managing this chain of events and relationships that extends from our suppliers through our own operations to our customers is essential for our success. QFD

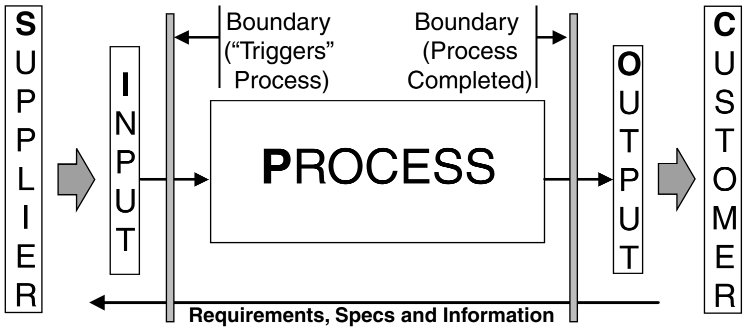


FIGURE 11.3 The SIPOC chart.

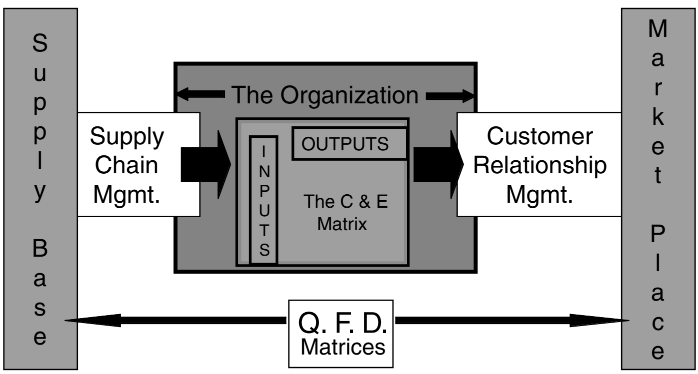


FIGURE 11.4 The span of quality function deployment vs. the cause and effect matrix.

concepts and tools assist in this by providing a structure to capture all the elements and prioritize them, enabling us to focus our limited resources in the most gainful way, i.e., from our customers' perspective.

Manufacturing can use QFD concepts and structure in three situations:

1. With the current product and process
2. With the current product and a new or redesigned process
3. With a new product and the current process

Because new product launches (situation 3) are rare compared with manufacturing operations' everyday need to address characterizing, monitoring, and improving the current processes, manufacturing's first use of a QFD tool is often the cause-and-effect matrix (for situation 1).

The cause-and-effect matrix shows how multiple inputs have varying levels of impact on the desired outputs sought from the process. For a process to consistently deliver satisfactory or even superlative output with no defects, it is essential to define the relationships among all of its inputs and outputs.

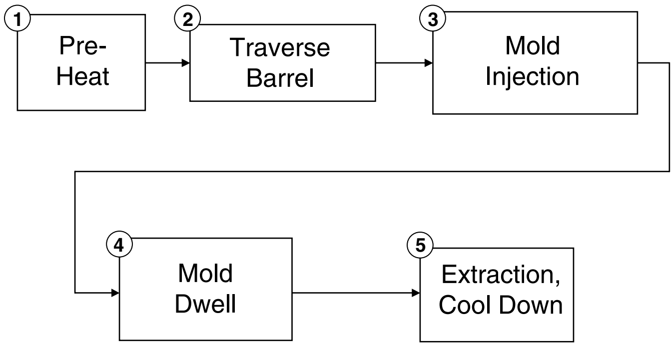


FIGURE 11.5 Process map example.

The cause-and-effect matrix does this most efficiently. Take a common manufacturing process: plastic molding. In a five-step plastic molding process (Figure 11.5), there are several inputs that affect the desired outputs.

As always when studying a process's input–output relationships, the desired outputs are determined first. The molding process's customers have indicated that dimensional stability, uniform density, and smooth finish are the most important output characteristics and have assigned weights of 10, 8, and 6, respectively, to those outputs. A group of plastic molding operators, supervisors, technicians, and engineers then review elements in all five steps and decide on ten that affect the desired outputs. These are entered into the cause-and-effect matrix and the degree of effect that each makes on the output is noted. A strong effect is rated 9, a medium effect 3, a slight effect 1, and no effect, 0. The strength of the effect of each relationship is then multiplied by the importance those effects are given by the customers to get a total value. The total value is used to guide the allocation of resources, monitoring, and improvement efforts. The five inputs — 2a, 2c, 3a, 3b, and 5a — are the most important out of the ten listed.

The completed cause-and-effect matrix is a valuable input for the process control plan. The latter defines the monitoring system to be used to maintain consistent production as well as the set of measures that will be used to highlight (1) the need for adjustments to production parameters and (2) opportunities for further process improvements.

With respect to situation 2, the expected outputs are well known and it is up to manufacturing to decide on how each of the outputs is to be met with the new or redesigned process. Again the cause-and-effect matrix is used. In this case, with the outputs defined, it is essential that the new process's inputs meet or exceed the performance of the old process.

The most complete use of QFD concepts and tools happens when situation 3 occurs. In many cases, there is an entirely new product to be manufactured by a series of known process steps. It is in this situation where there are many different steps using technologies of varying degrees of maturity that QFD can assist the manufacturing manager the most. This situation is the one of greatest complexity, but QFD helps to organize and overcome that. In fact, the initial application of QFD principles often shortens the concept-to-launch time up to 30%. In addition, if the same (but updated) matrices are used when launching the second generation or a follow-on product, there are additional time savings.

Because markets and the competitive environment are changing at a faster pace and innovation is causing technical obsolescence, many products now have a shorter life cycles. In addition, many organizations are decentralizing their activities and creating specialized approaches for interfacing with inputs (supply side) and outputs (customer side). The manufacturing function is experiencing more change, and the traditional functions, which were all in-house, may now be spread among several different entities, both inside and outside the organization. Given these changes, there is a greater need for faster and more accurate communications with a broader variety of groups than manufacturing experienced in the past.

11.2 RISK IDENTIFICATION

How can an organization increase the accuracy and timeliness of its responses to market demands and at the same time reduce the economic risk associated with the substantial investments necessary for new and reengineered products? Risks arise from

1. Products that are (a) more complex, (b) involve more technologies, materials, and processes due to increasing innovation, (c) come from more suppliers (a supply-chain management issue), and (d) involve more customers and modes of usage (a customer relationship management issue).
2. Products that have previously been "hardware" only, now have an electronic component incorporated or, along with the associated sensor and human inputs, have some limited monitoring or feedback capabilities. The adaptation of electronics to traditional products makes some really gee-whiz features possible, but with these newfound capabilities come further complexities in the form of additional software or firmware. These kinds of applications have only recently been seen in common commercial and consumer products, but they are a growing trend.
3. The introduction and support of products that are more complex.
4. The fact that (most importantly) the manufacture of products is continuing to become more complex.

Just based on sheer numbers, there is the possibility of missing the combination(s) of inputs that will give the greatest economic return to the organization. Using QFD principles reduces the risk that something will be overlooked. It also helps all areas of an organization understand what knowledge needs to be gathered and shared to assist the overall (both design and manufacturing) engineering effort on a new product.

11.3 THE SEVEN-STEP PROCESS

The QFD methodology is a structured way of capturing the spoken and unspoken needs of a product's various customer groups. It typically follows a seven-step process:

1. Define the product's customers, specifically their expectations and where they are in the product's life cycle.
2. Analyze (a) current industry offerings, (b) industry trends, and (c) the expectations of customers from three quality perspectives: normal, expected, and exciting to derive customer expectations. The three levels of quality are from the Kano model and they affect how firms choose the means used to capture customer input (more on the Kano model later).
3. Organize and prioritize these inputs: the voice of the market (2a and b, above) gathered through market research and the voice of the customer (2c, above) collected via *verbatims*.
4. Translate these "voices" into technical objectives. This is where QFD bridges a major gap between the users of the product and the designers and manufacturers. This is an extremely useful exercise because it gives the technologists (design and process engineers and technicians) specifics on which design or production efforts have the most value to the customer and which are less important.
5. Draw on the initial translation of the technical objectives to determine how each of the customers' expectations can best be satisfied. The technologists are in charge of this — the concept coming from design engineering, with input from process engineering. To the extent that the production and ultimate use of the concept are kept in mind during the design, ease of manufacture and early acceptance in the marketplace are assured.
6. Plan for production. The objectives focused on for the concept and design drive the manner of production. The QFD structure invites early consultation and input from the people involved in planning production. The collaboration of design and production activities is what makes the ramp up rapid and the initial and ongoing production smooth. If post-introduction demand increases, manufacturing operations have a much better chance of supplying consistent product quickly because of the guidance from QFD.
7. Update the original customer expectation QFD matrices as the product ages and the market changes. If the original QFD matrices are updated as new information becomes available, product launch time can be further reduced and new products can be introduced in progressively shorter cycles. This allows the organization more learning cycles and much greater flexibility, both in meeting market opportunities and in introducing innovation.

To maximize the synergy among marketing, design engineering, and production, a good project management structure is essential. Just as essential is a structure that provides clear information for the project team. There is always the chance of poor results from the GIGO (garbage in, garbage out) effect. To avoid these results, it is essential that two principles be stressed:

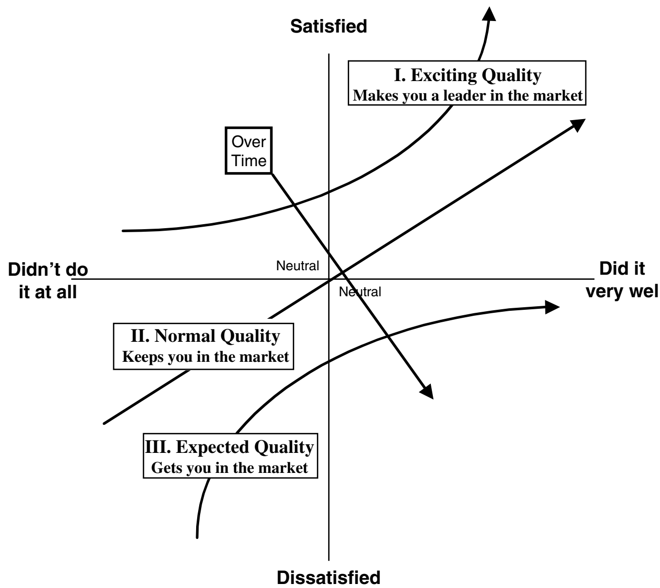


FIGURE 11.6 The kano model. (From Wm. Eureka and N. Ryan, The Customer Driven Company, American Supplier Institute, Livonia, MI, 1988. With permission.)

1. There is a well-defined process for gathering data and organizing it into information.
2. The people involved are the right (best) sources for the data or information.

Both are equally important if you are to capture the necessary knowledge from your different sets of customers and answer their spoken and unspoken needs.

11.4 KANO MODEL

The Kano model (Figure 11.6) helps define the process for gathering data and organizing it. The model stratifies each customer group's perceptions of the product into three types of quality: expected, normal, and exciting. Each of these types of quality requires a different approach for gathering data. The easiest to gather data about is normal quality — it is the basis of most of our conversations about a given product group and is usually the basis for advertising. The issues involved in normal quality are known by most customers. For example, in the case of tires, two major issues are price and length of warranty. Because the issues are well known, it is possible to gather information from the customer using simple surveys — telephone, mail-in, or in person. Satisfying customer expectations for normal quality keeps a firm competitive.

Expected quality issues are those that no one thinks about because everyone takes them for granted — until, that is, they are not met. An example would be tire treads that delaminate at high speed, a tire that does not hold air, or a tire with sidewalls that give out within 5000 miles of purchase. In the case of expected quality, the customers interviewed have knowledge and can provide answers, but it often takes some digging because these are not top-of-mind issues. Some approaches used to get this information are one-on-one interviews and focus groups. Being able to satisfy the expected quality issues only gets the firm into the marketplace.

The third type of quality, exciting quality, is the most difficult to obtain information on because, unlike expected and normal quality, the customer is not aware of exciting quality issues. In many cases, a new feature or function may be technologically feasible, but the technical persons are not aware of how much value the customer would place on the feature. The customer, on the other hand, is not technologically sophisticated enough to pursue innovation. For tires, an example of exciting quality would be a tire that never went flat, or one that could be driven several miles even though flat. To expose exciting quality issues, it is necessary to have multiple conversations with progressive customers and innovative designers. These conversations are best conducted in facilitated focus groups. Success in providing exciting quality helps make a firm worldclass.

Whereas the Kano model (Figure 11.6) offers the background for gathering data from different customer groups, general and specialized marketing information (including benchmarking) is used for competitive analysis. For both customer expectations and competitive market data gathering, it is necessary to define who will be consulted (the right persons to involve). You want them to be a good representative sample of the various groups.

The Kano model graphic shows how addressing expected quality issues only minimizes customer *dis*satisfaction; it never contributes to customer satisfaction. Normal quality issues can be either satisfying or dissatisfying although offering provision for greater customer satisfaction. Exciting quality issues can never be customer dissatisfiers (how can they be if the customer does not even know they exist?), but they can have a tremendous impact on customer satisfaction. Over time, items that are exciting quality become normal quality, and normal quality items become expected.

When gathering information from various groups of customers, it is important for the design team to realize the importance of the definition of the original design concept. It is also critical to check the concept against all the customer inputs and validate before proceeding. The cost of changing concepts is small at the concept stage, then rises exponentially. This is the reason it is so important that manufacturing be part of the QFD effort from the earliest phase (concept selection). The concept to production graph, Figure 11.7, shows how rapidly a company can become financially committed to a concept.

11.5 VOICE OF THE CUSTOMER TABLE

Once the groups of customers have been defined, there will be inputs from each group about the three different types of quality as defined by the Kano model. The resulting collection of *verbatims* from the customer groups will be entered into the Voice of the Customer Table (Figure 11.8). Then the *verbatims* are reworded to fit

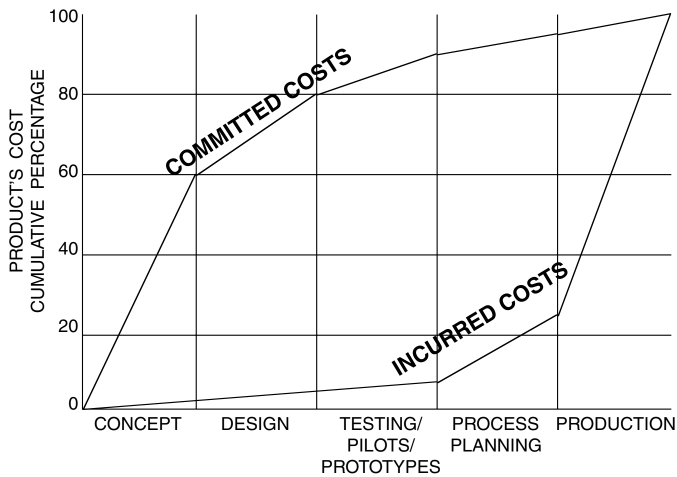


FIGURE 11.7 From concept to production. (From J. ReVelle, J. W. Moran, and C. Cox (Eds.), *The QFD Handbook,* J. Wiley & Sons, New York, 1998. With permission.)

Voice of the Customer Table 1

Customer Verbatim	Who	What	When	Where	Why	How

Voice of the Customer Table 2

Reworded Demands	Demanded Quality	Quality Characteristics	Function	Reliability	Other Issues

FIGURE 11.8 Voice of the customer tables. (From J. ReVelle, J. W. Moran, and C. Cox (Eds.), *The QFD Handbook,* J. Wiley & Sons, New York, 1998. With permission.)

into the categories in the Voice of the Customer Table 2. Figure 11.8 shows examples of VOCT 1 and 2 for a flashlight.

VOCT 1 categories are self-explanatory, but VOCT 2 categories are defined below:

- *Demanded quality* is a qualitative statement of the benefit the product gives the customer. These statements must be brief and phrased positively, for example, "can hold easily."

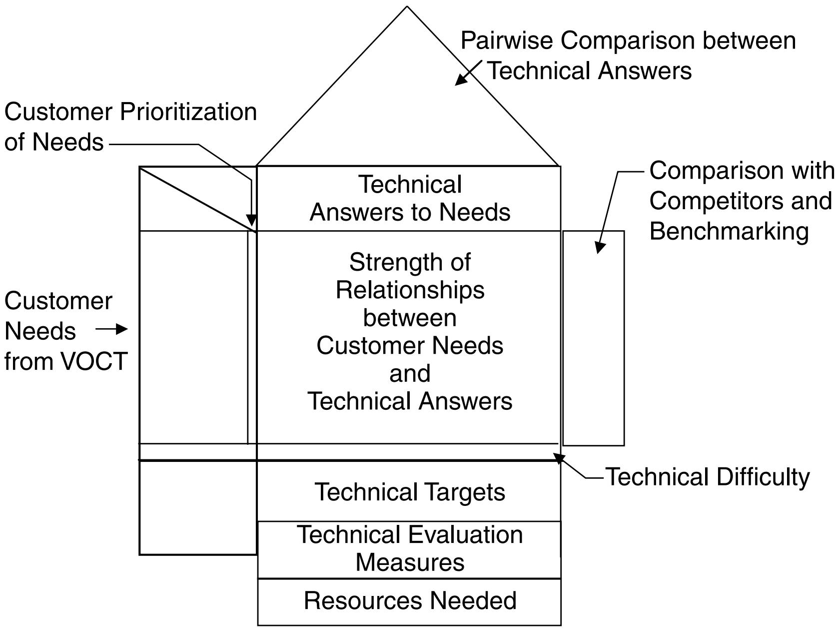


FIGURE 11.9A The house of quality (HOQ) matrix.

- *Quality characteristics* are quantitative — something that can be measured and that helps to attain demanded quality, for example, diameter.
- *Function* is the purpose of the product. Drawn from value engineering's standard practice, a function is stated as a verb plus an object, for example, "keeps aim."
- *Reliability* is the expected life of the product. Failure modes, typical warranty claims, or customer complaints can be included here. An example would be a complaint that the flashlight "won't light" or "won't turn on."
- *Other items* might be something emphasized in this particular design project, such as safety, environmental impact, price, or life-cycle cost.

11.6 HOUSE OF QUALITY (HOQ)

The results from the VOCT 2 are key inputs to the QFD beginning matrix shown in Figure 11.9A. Sometimes called the A-1 matrix, sometimes called the House of Quality (HOQ), this first matrix organizes the inputs from the various customer groups as well as marketplace intelligence, and has several elements or "rooms" that allow a tremendous amount of information to be organized.

The first "room" in the HOQ lists the wants of the various customer groups, which are referred to as WHATs. Each of them comes from the Voice of the Customer Table and has an importance rating (also from the customers) (see Figure 11.9B, #1).

The second room contains the HOWs and represents a technical, organizational response to explain how the WHATs will be achieved. It is possible that a single

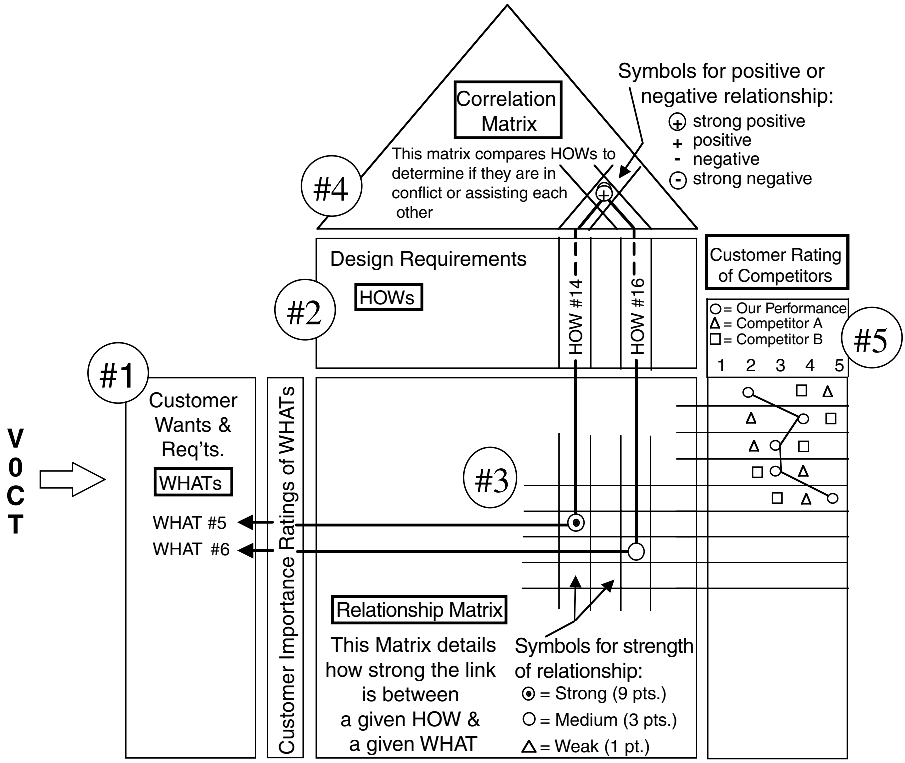


FIGURE 11.9B Five elements of the HOQ. (From J. ReVelle, J. W. Moran, and C. Cox (Eds.), *The QFD Handbook,* J. Wiley & Sons, New York, 1998. With permission.)

HOW can apply to several WHATs or that one WHAT may require several HOWs. (see Figure 11.9B, #2).

The third room is the relationship matrix located between the WHATs and the HOWs. It shows the extent to which the WHATs and HOWs are related and supplies a weight to the strength of the relationship. A strong relationship is rated 9, a medium relationship, 3, a weak relationship, 1, and no relationship is left blank (see Figure 11.9B, #3).

The fourth area of the HOQ is the "roof"(see Figure 11.9B #4). It is actually an L-shaped matrix which does a pair-wise comparison between each of the HOWs to seek out those pairs that are in conflict, but also notes those pairs which leverage each other. Again there is a multilevel rating system, in this case four leverage levels of relationships: strong positive, positive, negative, and strong negative. It is the strong positive and negative relationships that need to be noted and addressed. For strong negative relationships, the design team can look for ways to compromise, or the team can apply either TRIZ (Russian acronym for Theory of Inventive Problem Solving) or robust design. TRIZ refers to a technique, based on the study of thousands of patents, that allows these conflicts to be overcome without compromise. Robust design, on the other hand, is a methodology employed to make both product and processes robust, i.e., insensitive to conditions of use or manufacture.

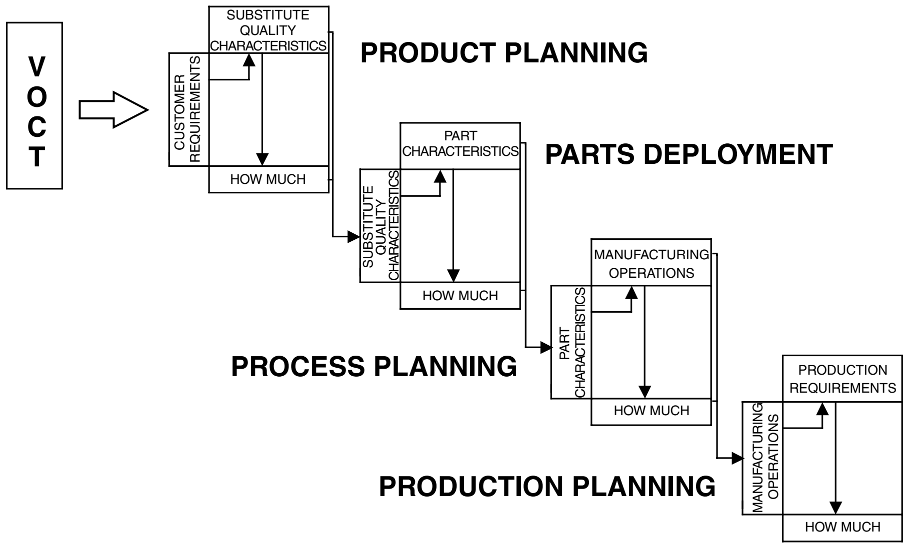


FIGURE 11.10 ASI four matrix approach — linking customer requirement to the production process(es) requirements. (From Wm. Eureka and N. Ryan, The Customer Driven Company, American Supplier Institute, Livonia, MI, 1988. With permission.)

The fifth room captures and presents the competitive intelligence, comparing our new product's features and functions with those of our competitors, and indicating the marketplace's perception on a feature-by-feature basis (see Figure 11.9B, #5).

11.7 FOUR-PHASE APPROACH

One series of matrices popularized by the American Supplier Institute (ASI) consists of four matrices (Figure 11.10). These start with high-level customer wants and requirements and finish with well-defined production requirements for manufacturing operations. The output from the voice of the customer tables feeds the first matrix, called the product planning matrix. Product planning changes the customer-defined requirements into substitute quality characteristics, which quantify the customer requirements and enable engineers and technicians to have design targets. The second matrix takes the high-level quantified concept and defines the components or parts of the system. The third matrix details the production process layout and the fourth matrix gives the measures and monitoring needed to assure consistent production.

An example of using the ASI approach might be in the design of a passenger vehicle. Among other wants, a potential buyer might say, "I want low cost of ownership," or "I want low fuel consumption." In the first matrix, these generalized wants, low cost and low fuel consumption, are quantified. The result would be agreement on a concept that included specifics on the coefficient of drag (the aerodynamics of the vehicle's movement through air at high speeds), targets for the mass of the vehicle, nature of the transmission (manual shift) and cubic displacement, breathing and fuel delivery configuration of the engine (multivalve, overhead cam, naturally aspirated or turbocharged, throttle-body or manifold fuel injection, etc.).

The results of the first matrix, product planning, would then feed the second matrix, parts deployment. In the example, if we focus on the mass-of-the-vehicle part of the vehicle's design in the parts deployment matrix, conclusions about the nature of the vehicle's structure (frame and body vs. unibody) and materials to be used can be decided. It may happen that a frame and body structure with a fiberglass skin is selected.

The output of the second matrix, parts deployment, serves as input to the third matrix, process planning. Knowing the type of vehicle structure (hence the sequence of production steps) will limit the options available for laying out the actual production operations. Once these decisions have been made, the results are transferred to the final matrix, production planning. Production planning addresses all the measuring and monitoring necessary to ensure that basic items (such as the fiberglass) are produced correctly. As a result of the last matrix, for example, there might have to be a very specific manufacturing procedure for mixing the resins that go into the fiberglass. Any requirement on the manufacturing floor would be directly traceable all the way back to some customer requirement (such as low fuel consumption).

11.8 MATRIX OF MATRICES APPROACH

The ASI four-phase approach can demonstrate a commonly used subset of a larger set of matrices, the matrix of matrices (popularized by GOAL/QPC), Figure 11.11. This larger set of matrices includes those that might be used when doing other types of analysis, such as value engineering, reliability planning, quality control, or cost analysis (all analyses that would also have an impact on manufacturing operations).

11.9 RECOMMENDATIONS

11.9.1 Software

- A longtime major software package for assisting the QFD process is *QFD Capture* from International TechneGroup, Inc., Milford, OH. 513-576-3900. <http://www.iti-oh.com>
- Another software package that is available is *QFD Designer* from QualiSoft Corp., West Bloomfield, MI. 248-357-4300. <http://www.qualisoft.com>

11.9.2 Books

- Cohen, L., *Quality Function Deployment: How to Make QFD Work for You*, Addison-Wesley, Reading, MA, 1995.
- Day, R. G., *Quality Function Deployment: Linking a Company with Its Customers,* ASQC Quality Press, Milwaukee, WI, 1993.
- King, B., *Better Designs in Half the Time: Implementing QFD in America,* GOAL/QPC, Methuen, MA, 1989.

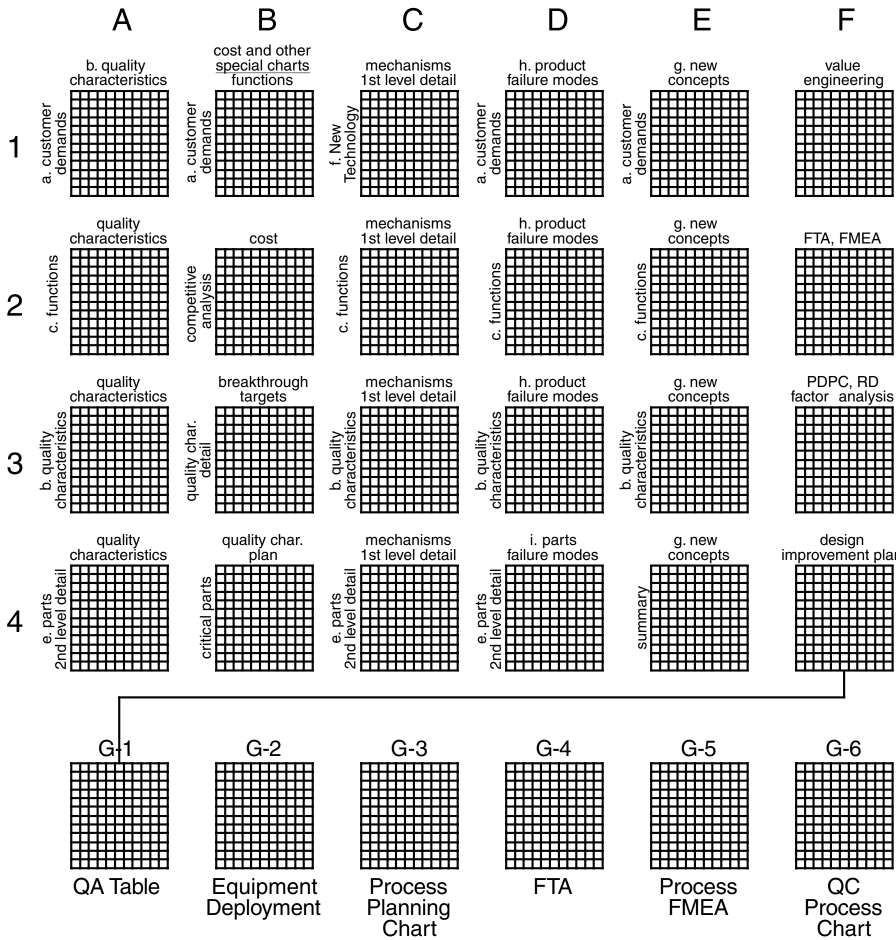


FIGURE 11.11 The matrix of matrices approach. Use for value engineering, reliability/durability, or other focuses in the product/service development process. (From B. King, *Better Designs in Half the Time,* Goal/OPS, Salem, NH, 1989. With permission.)

- ReVelle, J., Moran, J., and Cox, C., *The QFD Handbook*, Wiley, New York, 1998.
- Terninko, J., *Step by Step QFD: Customer-Driven Product Design*, CRC/St. Lucie Press, Boca Raton, FL, 1997.

11.9.3 Web Sites

Note: These references are listed in order of complexity.

- A quick 26-slide overview of QFD is available at (http://www.mines.edu/Academic/courses/eng/EGGN491/lecture/qfd/>

- A well-thought-out three-exercise tutorial from the Software Engineering Research Network at the University of Calgary is available at <http://sern.ucalgary.ca/~dweening/SENG613/Exercises/Exercise1.html#HouseOfQuality>
- A detailed write-up is available at <http://www.proactdev.com/pages/ehoq.htm>
- A *very* detailed write-up, which includes how the various features of the *QFD Capture* software can be utilized, is available at <http://www.iti-oh.com/cppd/qfd/qfd_basics.htm>
- An overview and commentary (part of the E. B. Dean/NASA series on Design for Competitive Advantage) on other good sources of information are available at <http://mijuno.larc.nasa.gov/dfc/qfd.html>
- A listing of many varied QFD resources and multiple bibliographies is available at <http://www.postech.ac.kr/ie/qelab/QFD_resource.html>

3 Quality Function Deployment

3.1 INTRODUCTION

The origins of quality function deployment (QFD) have not yet been exactly defined in terms of time. The general, basic concepts that are fundamental in this methodology have been known for over 40 years, even though the actual modular forms used in QFD appeared in the United States and in the Western world no earlier than 1986.

The first article to relate a short history of QFD appeared in *Quality Progress*, a magazine published by the American Society for Quality Control (ASQC) [Kogure and Akao, 1983]. The article shows that the first reports about QFD written in Japanese date back to 1967, even though before the end of the 1970s several dozen reports had been presented on the subject.

The previously mentioned article by Kogure and Akao pinpoints the official birth date as 1972, when with the help of consultants Mizuno and Furukawa engineers Nishimura and Takayanagi first developed a *quality chart* used in the shipyards of Mitsubishi Heavy Industries Ltd., in Kobe, Japan. The Kobe experiment involved the use of a matrix where the customer's requirements were listed on the page, with the columns showing the methods that had to be applied to meet these demands.

Basically the idea was that, as a result of in-depth discussions held between marketing, planning, and production, the matrix should be gradually filled in with the customer's most important requisites and with the product technical specifications expounded in the greatest possible detail. Next, various symbols were introduced to indicate whether a strong, a medium, or a weak relationship existed between the customer's requirements and the technical specifications.

Although the QFD method was extremely simple, it was hailed as a considerable step forward in respect to the hitherto virtually nonexistent aids to the design. In particular, QFD produced a galvanizing effect within the corporation in the efforts of the personnel involved to collaborate even more closely.

Two years later, Professor Yoji Akao (Deming prizewinner on QFD) founded and headed a research committee of the Japanese Society for Quality Control (JSQC) on QFD. As head of the committee he was responsible, at the end of the 1970s, for promulgating QFD as the technique used for improving the transition from design to production. Again Akao, in a successive article [Akao, 1989], declared himself to be founder of the methodology, because he was — he asserted — the first person in Japan to introduce (in 1967) the concept of QFD as a new approach to quality assurance from design right through to manufacturing. The article supplies the first operative definition of QFD as a tool in which "responsibilities for producing a quality item must be assigned to all parts of a corporation."

Even though Akao declares that he introduced the concept of QFD in 1967, Schubert ascribes to Mizuno the fatherhood of the methodology [Schubert, 1989]. According to Clausing and Pugh [1991], however, the basic ideas developed in QFD are not new, because they are rooted in *value analysis/value engineering* (VAVE), combined with marketing techniques.

The QFD diffusion throughout the United States began no earlier than 1986, almost 15 years after the experiment at the Kobe shipyards, thanks to the commitment of Don Clausing, professor at Massachusetts Institute of Technology (MIT), who was doing research work on the various ways of developing new products. At the time he was the *principal engineer* for advanced development activities at Xerox Corp., and he was first introduced to using QFD during a March 1984 visit to the Fuji Xerox Ltd. plant in Tokyo.

On his return from Japan, Clausing used his newly acquired knowledge to develop some projects at Ford Motor Co. in Dearhorn, Michigan. After that, the American Supplier Institute (ASI) organized a series of study missions in Japan aimed at focusing greater attention on the potentials and the ways of employing QFD. Now the instrument has been officially introduced to the designers' worktables in Western companies.

According to a recent definition by the ASI, QFD constitutes

> …A system for translating customer requirements into appropriate company requirements at every stage, from research through production design and development, to manufacture, distribution, installation and marketing, sales and services [Asi, 1987].

QFD, as it has been defined, therefore constitutes a tool able to orient product design toward the real exigencies of the end user. In this sense it represents an *evident and powerful tool for laying project plans in a structured and finalized manner.* Normally, it is used before starting on the activities of development, engineering, and production of new products or services [Clausing and Pugh, 1991; Franceschini, 1993].

According to Sullivan [1996] QFD was developed as a tool contributing to the attainment of Japanese quality standards in industry. Its implementation requires the collaboration of all company staff, from top management through to workers in all the areas of a company's activities. Quality control executed in such a global manner is called company-wide quality control (CWQC).

Japanese CWQC [Akao, 1989] has contributed to enrich the American *total quality control* (TQC) approach. The new model was then accepted in the Western world with the name of *total quality management* (TQM).

QFD, therefore, represents a tool aiding TQM enabling us to avoid or at least reduce the possibility that any essential aspect of quality be neglected during the process of product design or during its revision. These concepts are effectively connected with the indications supplied by Garvin [1987], who points out that managers are often prone to neglecting one or more crucial dimensions of quality during systems design. In point of fact, quality is a *multidimensional* entity and its evaluation must necessarily involve all those characteristics that are necessary to represent it in its entirety (performance, added characteristics (*optionals*), safety, reliability, compliance with specifications, lifetime, after sales service (*service*), aesthetics, ecology, maintenance, economy of usage, etc.) [Hauser and Clausing, 1988].

3.2 INTEREST AROUSED BY QUALITY FUNCTION DEPLOYMENT

To understand the kind of results attainable with QFD, it may be interesting to name an example [Hauser and Clausing, 1988] that compares the present-day situation with that preceding the industrial revolution.

When, over 400 years ago, a knight went to a specialized blacksmith to get a new suit of armor made, the armor characteristics and design were agreed on at that time; for example, they could decide to make the armor of metal plate instead of chain mail.

The blacksmith would then transform these specifications into so many details of his production plan. He could, merely by way of example, decide on the thickness of the plate to render it less flexible; obviously this kind of decision would have had to meet the knight's approval.

Subsequently, the armorer, in considering the details of his production plan, could decide which production process would best be suited to obtain the characteristics that had been agreed on, for example, tempering the plate to harden the steel to the right point.

Finally, the armorer would determine from the production process a detailed production plan, by deciding, for example, that the fire in the forge had to be lit at 6 o'clock in the morning so that by midday it reached a sufficiently high temperature to allow him to hammer the armor into shape.

The moral of this story set in medieval times is that the definition (and *deployment*) of the armor characteristics and requisites was something extremely simple; it could be finalized by only two men: the armorer and the customer. A good deal of the process took place in the armorer's head, because he was custodian of all technical knowledge at the time.

Should we wish to reconstruct a similar situation in today's complex industrial world, we would need to be able to take customers into the plant and put them into direct contact with the workers, to have them to communicate their requirements. It does seem pretty obvious that the lifestyle found in the example is totally unfeasible in today's highly sophisticated production setting.

Nowadays, companies employ specialists having a sound technical knowledge, which has actually brought substantial advantages to end users by way of better and cheaper products, even though all this has created considerable problems in development and production processes. There again, specialists tend to shut themselves off within their specialized fields. Individually, they possess an impressive amount of technical knowledge, but there are notable difficulties in integrating them to meet customers' requests. Hence, it is necessary to develop techniques able to integrate the multiplicity of functions and so aid the two participants talking to one another, at the same time fully utilizing the enormous wealth of specific knowledge accumulated by the specialists.

The role of QFD is illustrated in the circle of company communications shown in Figure 3.1. The customer's requirements follow the circle of company commu-

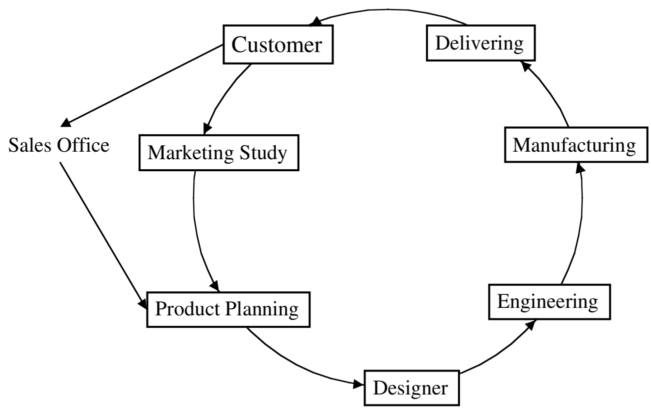


FIGURE 3.1 The circle of company communications distorts customer information.

nications and return to the customer in the form of a new product. All too often, however, in this sort of word-of-mouth communication process within a company, we find that customer requirements are not adequately translated in the passing from one function to another.

QFD is an instrument that prevents such drawbacks by having the new products pass through the various company functions, thus contributing to improvement of the company's horizontal organization.

3.3 QUALITY FUNCTION DEPLOYMENT APPROACH

The QFD process begins when we endeavor to pinpoint *customer requirements* (or *needs*), which are usually expressed in terms of qualitative characteristics, broadly defined as, for example, pleasing to look at, easy to use, working properly, safe, long lasting, stylish, comfortable, etc. During the process of product development, customer requirements are successively converted into internal company requisites, called *design specifications* (Figure 3.2).

These specifications are generally the global characteristics of a given product (usually measurable characteristics) which, if correctly developed, will have to satisfy customer requirements. Then the general specifications of the system are translated into detailed technical specifications for the subsystems or the *critical* parts (meaning those parts that will permit the realization of the essential functions constituting the reason why the product was designed).

The use of the word *parts* is considered particularly appropriate for those products that are assembled from various mechanical components. In any case, QFD can be applied just as successfully on other types of products and services in the most disparate market sectors.

Determining which *operations* are necessary for the *manufacturing* process constitutes the next step, a step often closely bound to prior capital investments in plants and machinery. Within these operational limits the manufacturing processes best suitable to attaining the desired part characteristics are established.

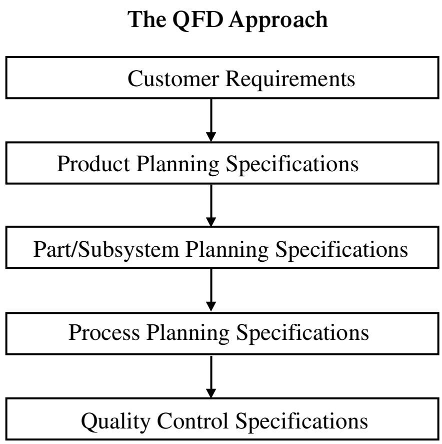


FIGURE 3.2 QFD translates customer requirements into specifications for product planning, part or subsystem planning, process planning, and quality control.

To effectively obtain the required quality characteristics, the identified manufacturing process specifications are translated into *quality control specifications*. Such specifications include, to name but a few, inspection plans for acquired materials, information needed to determine which activities will need monitoring with statistical process control (SPC), planned preventive maintenance on machinery (*total productivity maintenance* [TPM]), instructing and training operative personnel, and generally the totality of procedures and practical prescriptions in use when manufacturing a product.

This top-down (or hierarchical) approach is not, at least in appearance, dissimilar to that used by Western companies for a considerable number of years, with varying degrees of success. The differences become apparent, however, when we analyze in detail their organizational structure and their ways of dealing with customers to involve them in the product specification activities.

The structure of Western companies is usually highly pyramidal, hierarchical with rather clear backtracking reference lines. On commencement of a new project of some importance, the backtracking reference lines of many of the company functions should be widened to form the horizontal connections needed to bring the project to its conclusion. The vertical connections, however, are sometimes so strong that the corporate spirit of the various functions and the rigid respect of departmental rules form a sharp contrast to the requirements dictated by the project on hand.

The strong vertical and horizontal constraints are sometimes compared with the characteristics found in a piece of well-woven material: maximum strength of fiber, both vertical and horizontal (Figure 3.3).

3.4 STAGES OF DEVELOPMENT

From the point of view of procedure, QFD uses a series of forms called *quality tables*. The philosophy governing how QFD is to be applied is that of *management*

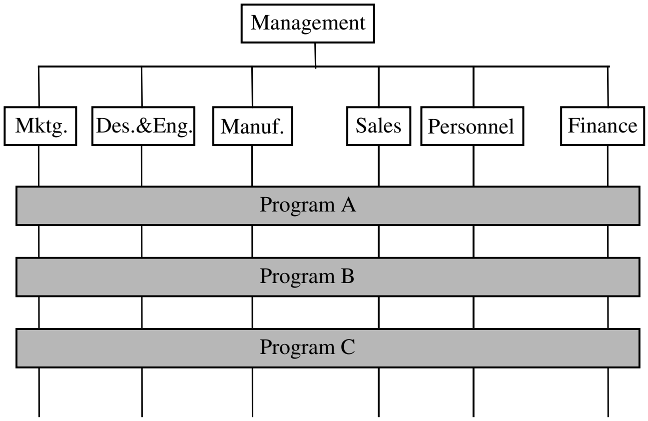


FIGURE 3.3 QFD organization**.** QFD helps to strengthen both the organization's vertical lines as well as the program's horizontal connections, thus improving the efficiency of the product development process. (From Sullivan, L. [1986], *Qual. Prog.*, 19(6), 39–50. With permission.)

by objectives (MBO) and *management by processes* (MBP): the emphasis is placed on both what needs to be done and how it is to be done (Conti, 1989).

Quality tables enable us to represent the variables that concur to define a given project. They show the various relationships existing among them, supplying useful indications of the levels at which they interact and of the way they interact. They consist of a series of forms with a particular layout, where the information considered important for the project development is set down. Normally, four forms are used, each one enabling the user to focus, with a varying degree of detail, on the key aspects and on the interactions occurring between the various functions.

Several different types of forms are currently in use in QFD applications [Crow, 1992; Sullivan, 1986]. They differ only in that some details may or may not be required, but the information gathered therein remains substantially equivalent.

The importance of QFD as a tool stems from the fact that both the customer and the company are compelled to make the effort to organize the project in compliance with the instructions set down in the proffered forms. As a result the documents thus obtained constitute the *common point of reference* for design revisions and successive analysis of details.

Form 1 (product planning matrix) — This compares the customer's foremost requirements (*user requirements*) with product characteristics (*product attributes*), which are the technical requisites needed to render product specifications coherent with customer expectations. The matrix thus obtained defines the relationships occurring between the two elements and their reciprocal priorities. Furthermore, it enables the user to develop comparisons between product characteristics and the best available competitor performances found on the market (*benchmarking*).

Form 2 (part deployment matrix) — This compares product characteristics with the requirements of the more important components (subsystems) into which the product can be broken down (*critical part characteristics*).

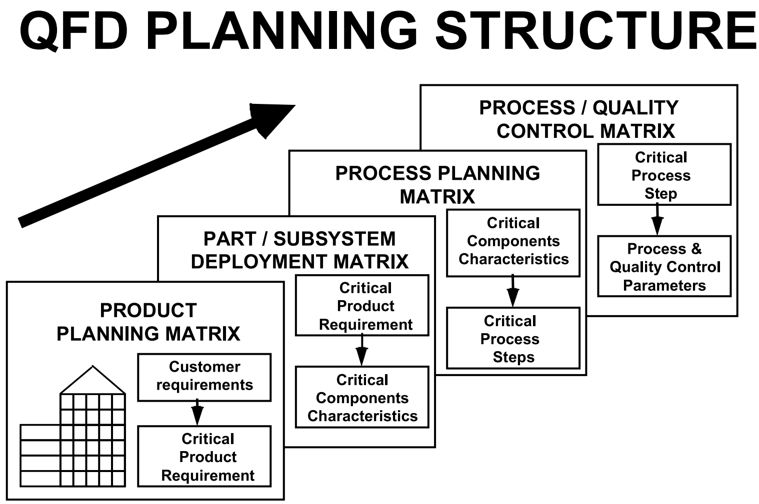


FIGURE 3.4 The logical sequence of QFD forms. The first two modules (house of quality and part characteristics) refer to product planning; the second two refer to manufacturing process planning and quality control. (From Crow, K.A. [1992], Seminar on Concurrent Engineering, DRM Associates, Rome.)

Form 3 (process planning matrix) — This relates the characteristics of the single subsystems with their respective production processes (*critical process steps*).

Form 4 (process and quality control matrix) — This defines inspection and quality control parameters and methods to be used in the production process of each process step (*quality control process steps*). In this form, in particular, each single *critical process step* is set down, as well as the relative *process control parameters*, *control points*, *control methods*, *sample size, frequencies*, and *check methods*. Figure 3.4 illustrates the structure as well as the logical sequence of the forms used. Besides the forms described earlier [Crow, 1992], others can be used for particular applications, for example, when the entity of the project is such that it must be necessarily broken down into a series of less complex subprojects.

3.5 HOUSE OF QUALITY

The first matrix to be used in QFD is known as the *house of quality* (HoQ). This matrix serves to describe the basic process underlying QFD: the transition (based on a strategy of input–output) from a list of customer requirements, the "what," through to a list of considerations as to "how" the requirements will be met (product characteristics).

The whats are the list of basic customer demands. These are generally rather vague requests, often expressed in imprecise terms requiring further detailed definitions. An example of a what could be the typical wish expressed by a coffee drinker: "to have a really good cup of coffee."

Customer demands, rationalized and organized according to hierarchical criteria (expectations tree) and summarized in a chart showing expected quality (*demanded*

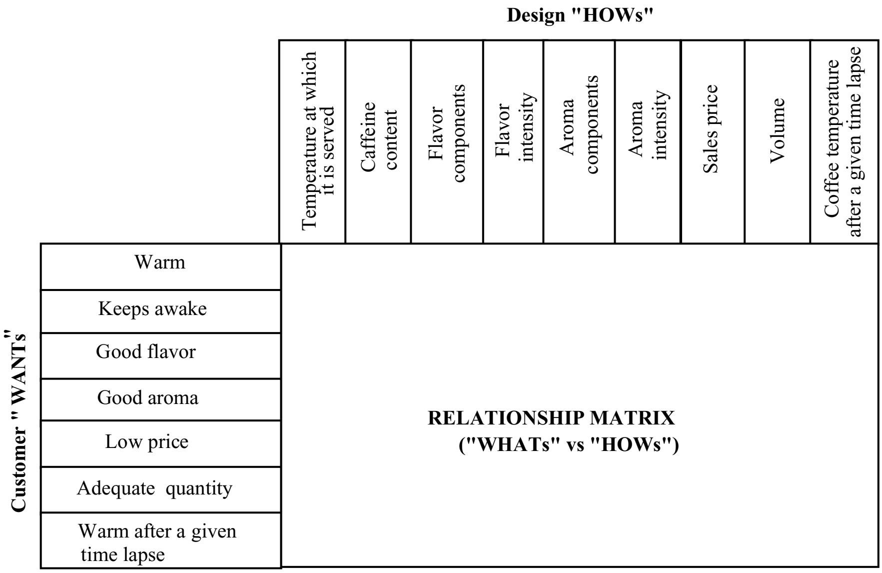


FIGURE 3.5 The whats are listed on the left of the relationship matrix. The hows are shown on the top of the relationship matrix.

quality chart) must as far as possible be kept in the customer's own words, so that they fully express the actual quality the customer asked for. The aim is to consolidate and to make available for use in successive stages of the methodology, the real as well as the latent needs as expressed by the customer, and to help in the process of transforming these needs into design specifications. The list of whats stemming from the request for a really good cup of coffee is shown in Figure 3.5.

It is necessary, at this point, to determine "how" to satisfy customer requisites, or how to meet customer expectations, from a technical point of view. Figure 3.5 also shows the technical characteristics thus identified. It is interesting to note that usually the hows impact more than the whats and that they, in turn, can reciprocally affect one another.

QFD proffers a way of unraveling this complex network of relationships through the use of a matrix, formed by hows and whats, which identifies their reciprocal relationships (*relationship matrix*).

The whats (customers' requirements or needs as defined by them) are listed horizontally on the left of the matrix, whereas the how factors (design specifications or measurable product characteristics) are shown vertically on the first line above the relationship matrix (Figure 3.5).

The relationships between the whats and the hows, that is to say the customer requirements and the measurable product characteristics, are represented by specific symbols placed at the intersections of the relationship matrix to indicate, weak, medium, or strong relationships, respectively. The symbols commonly used are a triangle for weak relationships, a circle for medium relationships, and two concentric circles for strong relationships (Figure 3.6).

Δ: weak relationship

O: medium relationship

o : strong relationship

Customer "WHATs" \ Design "HOWs"	Temperature at which it is served	Caffeine content	Flavor components	Flavor	Aroma components	Aroma intensity	Sales price	Volume	Coffee temperature after a given time lapse
Warm	**o**								
Keeps awake	O	O							
Good flavor	Δ	Δ	**o**	O					
Good aroma					**o**	O			
Low price							**o**	O	
Adequate quantity							O	**o**	
Warm after a given time lapse	O								**o**

FIGURE 3.6 Specific symbols are used to indicate relationships existing between customer requirements (whats) and design specifications (hows). These unique symbols are used to define weak, medium, or strong relationships, respectively.

If no relationship is apparent, the corresponding intersections in the matrix are left blank. Rows or columns left completely blank indicate zones where the transformation of hows into whats is inapplicable. The QFD ability to transform plans into actions, due to the very fact that it induces repeated cross-checks on the various analyzed elements, makes it a particularly suitable tool for testing congruity among the various aspects involved in the definition of a project.

Parallel to the how axis, on the bottom line of the matrix, a third area is brought into focus, the axis of the "how muches." These represent the measure of the hows and are kept separate from them, because when the hows are determined, the values of the how muches are not usually known. These values will be successively determined through further analysis.

The how muches supply both a means to a guarantee that the requirements are met, and a declaration of the intended *targets* during development. Thus, they constitute specific reference values that serve as guidelines for the successive planning stage and as a means of checking progress effectively made. As far as possible, the how muches must be measurable entities, because the latter supply a greater number of opportunities to analyze and to optimize planning than nonmeasurable entities would [Kuhn, 1981].

By returning to our example, the how muches involved in our design for a cup of coffee include a definition of the following elements:

- Temperature at which it is served
- Caffeine content
- Sales price
- Amount served

- Coffee temperature after a certain given time lapse
- Factors determining the aroma, flavor, and taste requested by the customer

The process of determining the whats, hows, and how muches represents the basis for almost all QFD applications, and constitutes the lighting spark within a planning process.

3.6 ORGANIZATIONAL STRUCTURE

3.6.1 Work Team

As inferred by the work expounded thus far, QFD is meant to be developed within a work team. First of all, customer requirements and the product or service characteristics to be ultimately achieved are freely discussed; subsequently, the same information is diffused throughout the company.

The emphasis that QFD puts on teamwork results in an involvement of all company functions in the planning process, including:

- Marketing
- Design (technical management)
- Quality
- Technical assistance
- Technologies
- Production
- Suppliers

Compared with a traditional design phase review, the procedure differs: it is no longer a case of contacting only those individuals involved in the successive phase; on the contrary, everyone contributes right from the start and at every stage of product development, keeping in mind customer expectations.

To develop a project *ex novo* utilizing QFD, therefore, interdisciplinary work teams are formed, each having roughly five to seven people [Dahlgaard, Kristensen, and Kanji, 1994], embodying all the key functions mentioned earlier and having the participation, if necessary, of suppliers. The project leader of this interfunctional work team, over and above having a sound knowledge of QFD methodology, should be an expert coordinator but not constitute a domineering presence. The methodology is in fact oriented toward consensus and attains excellent results in creative work teams that run on their own, so as to allow a structured synthesis of new ideas.

3.6.2 Technical and Management Problems

The greatest difficulties that companies encounter when they try to implement QFD are organizational. QFD works best in an environment favoring innovation, and encouraging creative initiatives and sharing of information. Departmentalization along with the consequent difficulty to work in a group on projects that may last several years, on the other hand, constitutes one of the obstacles precluding implementation of QFD on a large scale.

In addition to this, often companies perceive QFD as an added workload, instead of a better way to do things. So it happens that QFD becomes submerged in a tangle of daily chores, and is ultimately perceived merely as a tool that cannot be employed because of a chronic lack of time. If companies do not integrate QFD into their daily activities, it will continue to be considered an added task.

Difficulties of a technical nature, which the method entails, are expounded in Chapter 4, giving a detailed analysis of the operative steps required in the construction of a QFD table. A few of the principal disadvantages connected to QFD usage and some risks that may be incurred in compiling the various forms follow:

- Construction of excessively long tables, which therefore become difficult to handle and to analyze
- Confusion in defining customer requisites
- Risk of mistaking product characteristics for customer requirements
- Risk of getting lost in a host of details not conformant to the operative level of intervention
- Gathering of incorrect data: often the answers given by customers are difficult to classify as needs
- Difficulty in determining the true intensity of correlation between customer needs and technical characteristics of a given product

Obviously these risks are to be kept well in mind to avoid penalizing project results.

3.7 BENEFITS OBTAINABLE FROM QUALITY FUNCTION DEPLOYMENT USAGE

According to Clausing [Eureka and Ryan, 1988], QFD was originally developed to solve three problems generally diffused in Western industry: (1) the customer's voice was held to be of no account; (2) a considerable loss of information occurred during the cycle of product development; and (3) the different interpretations were given to technical specifications by the various departments involved. Furthermore, QFD supplies the solution to two problems closely related to those mentioned earlier: the *subdivision into departments* and the *temporal serialization of activities.*

The application of QFD on a horizontal plane within the organization reduces the negative effects of departmental subdivisions. The members of a QFD team work *together* and not as separate entities.

One of the most renowned benefits of QFD is its ability to *generate and maintain involvement within the work team* over the whole product development cycle. The results of the ensuing synergy are greater than the sum of those obtained by single components. Pooling knowledge within the work team leads to improved decisional capabilities and favors the disappearance of personal prejudices [Dahlgaard, Kristensen, and Kanji, 1994].

The short-term benefits brought by QFD include shorter product development cycles, fewer modifications in planning, fewer initial problems, and improved quality and reliability.

Many companies, especially in Japan and in the United States, have benefited from QFD in that it has been instrumental in achieving notable improvements in planning cycles while at the same time attaining reduced product development times and costs. For example, Toyota Auto Body Co., Ltd., in Kariya, Japan, witnessed an overall reduction of 61% in the initial costs involved in introducing four new models of vans between January 1977 and April 1984 [Hauser and Clausing, 1988].

Furthermore, QFD contributes to the creation of a solid platform of *basic knowledge* in planning. Once the method has been successfully applied in a project, the platform of basic knowledge thus created becomes a data bank storing technical information of extreme importance. The tables and documents prepared during QFD constitute a work documentation that becomes a source of ready reference, from which to glean new and interesting ideas for future projects.

From a strictly operative point of view, QFD is best suited to attaining the following objectives:

- To define product characteristics that meet effective customer requirements (instead of presumed requirements)
- To assign, on specially structured forms, all the information deemed necessary for the development of a new product or service (a synthetic tool, albeit rich with information)
- To effect a comparative analysis of our product performances against those of competitors (comparative analysis of product profile, or *technical benchmarking*) (see Chapter 6)
- To guarantee coherence between manifest customer needs and measurable product characteristics without neglecting any point of view
- To ensure that all those in charge of each process step are constantly kept informed about the relationship between the output quality of that step and the quality of the final product
- To reduce the necessity of applying modifications and corrections during advanced stages of development, because, right from the start, everyone is conscious of all the factors that can influence project evolution
- To minimize time allotted to customer interaction
- To guarantee full coherence between product planning and planning of the relative production processes (by facilitating the integration between the various product functions and by emphasizing interactions and mutual conditionings)
- To increase the capability of a company to react, so that any errors that could stem from a faulty interpretation of priorities and objectives are kept to a minimum
- To have self-explanatory documentation on the project as it evolves
- To agree on specific reference documents, useful for the customer as well as for those involved in drawing them up, which limit to a minimum the formulation of ideas and requests that cannot be coded and, most importantly, may not find general consensus

In Chapter 4, we will analyze QFD in greater detail and see which operative steps a work team should take to organize the planning process or the replanning process that a new product or a service entails.

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5 Supporting Tools of Quality Function Deployment

5.1 INTRODUCTION

Although many maintain that quality function deployment (QFD) methodology is a very useful communications tool, others point out that the technique, in its traditional form, does not come to terms in a sufficiently rigorous manner with some problems that arise when we endeavor to apply it within a complex industrial context.

This effectively represents one of the QFD shortcomings when it is applied in its more traditional form. It often appears to be somewhat "coarse" in its tentative efforts to reach a swift and simple solution to problems that are generally rather complex.

In this chapter we intend to point out some of these weak points found in traditional QFD methodology, and to indicate possible ways of solving them through its integration with several other design-supporting techniques.

Nowadays, QFD methodology is considered to be useful, particularly for its benefits in planning. In the very near future it could come to constitute the cohesive element within a group of instruments able to create an integrated environment for decisional aids in the field of design.

5.2 ASSIGNING LEVELS OF IMPORTANCE TO CUSTOMER REQUIREMENTS

The first aspect we intend to deal with concerns the assignation of numerical values (or *weights*) to the levels of importance of the various needs expressed by the customer. This problem, as we have seen in Chapter 4, Sections 4.2.5 and 4.5.2, has been solved in the traditional QFD version in a rather Spartan manner by applying methods of direct attribution or similar means. On the other hand, we must remember that assigning relative importance values to evaluation criteria constitutes a classic problem in the field of decision-aiding methods.

From this point of view QFD may be considered as a tool aiding designers' decisions when it is utilized to determine an evaluation of importance among various potential processes involved in planning (product or service characteristics).

Customers establish the criteria on which such an evaluation is based. These criteria are the very needs (expressed or latent) connected to that particular product or service. The *decision makers* in this process are, therefore, the customers themselves, and QFD is a means of keeping their preferences in mind during the planning process. The information obtained from the weights assigned to the various requirements–criteria serves, within this context, to aggregate the preferences of customers–decision makers and must reflect their system of values.

The problem of determining the value to be assigned to the weight of each need is, therefore, particularly important because it causes QFD to make the jump from its standing as a purely organizational instrument to the rank of a decisional supporting tool. Among the various methods used to determine the level of importance to be attributed to customer requirements, as seen in Chapter 4, we undoubtedly encounter the analytical hierarchy process (AHP) method [Saaty, 1990a].

5.2.1 General Principles of the Analytical Hierarchy Process Method

The AHP is a technique aiding decision makers, perfected by Saaty during the 1970s. The methodology is particularly useful for the evaluation of complex alternatives having a multiplicity of decisional attributes, where *subjective* criteria are also involved.

The axiomatic fundamentals of the AHP method are described by Saaty [1986]. Essentially, the method organizes the decision into three distinct operative phases:

1. The breakdown of the initial decisional problem into a number of subproblems, which may be more easily understood and evaluated through the construction of a hierarchy of criteria, subcriteria, alternatives, etc., on which the decision is based
2. The determination of a scale of priorities for each level of the decisional hierarchy against which to compare the various elements
3. The evaluation of the consistency of evaluations formerly expressed

5.2.1.1 Hierarchy of Attributes

The construction of hierarchies is one of the basic elements in the process of human comprehension. A decisional problem can be functionally broken down into a functional hierarchy made up of criteria, subcriteria, alternatives, etc., emphasizing their fundamental interactions. The highest level of the hierarchy is univocal (this is *the focus*, or *goal*), whereas the other levels usually comprise several elements. There is no limit set to the number of levels in the hierarchy: when two levels of the hierarchy cannot be directly compared with one another, then another more detailed level has to be created. The hierarchies are flexible in the sense that they can be updated to take into account possible additional criteria.

5.2.1.2 Priorities among Attributes

Once a hierarchy has been established, it is necessary to determine the priorities among elements standing at the same hierarchical level, verifying the consistency of the expressed opinions.

In the AHP method, the priorities are calculated according to the assertions made by a decision maker, who is requested to compare all the elements found on a given decisional level, two at a time. The estimation of their importance (relative preference) is made in relation to the element on the level directly preceding it (above it) in the hierarchy. For example, individual decision makers are asked to judge how important attribute A is compared with attribute B (where A and B are attributes both belonging to the same level in the hierarchy) to guarantee attainment of the objective indicated by the successive element on the next higher level.

If a given level in the hierarchy includes n elements for comparison, $n(n-1)/2$ comparisons of pairs of elements will have to be made. The comparisons are carried out thinking of evaluations expressed on a *ratio scale*. The very fact that it is possible to compare pairs on the basis of ratio scales constitutes one of the axioms of this method.

The evaluation scale $E = (1 \text{ to } 9)$ used by Saaty finds application in many other operative contexts and is rooted in the field of cognitive psychology. Experiments have proved that Saaty's scale of nine elements captures fairly well the preferences of an individual. However, the scale can be altered to suit any individual's needs [Harker and Vargas, 1987].

This scale permits us to express options of preference between two objects in terms of: equal importance (1), moderate importance of one over another (3), essential or strong importance (5), very strong importance (7), extreme importance (9). The values 2, 4, 6, and 8 express the intermediate values between two adjacent judgments.

The operative steps that must be taken to establish priorities are as follows:

1. To effect comparisons among all the various elements found on the same hierarchical level
2. To construct a matrix showing comparisons among pairs
3. To show in matrix **A** the comparisons of the pairs by using the numbers in the scale from 1 to 9
4. To set the elements of the matrix diagonal at 1
5. To show that if k is the value associated to the comparison between the i-th and the j-th alternatives (the coefficient a_{ij} of matrix **A**), then it follows that $a_{ji} = 1/k$ (matrix **A** is a reciprocal matrix)

5.2.1.3 Synthesis of Priorities

Once we have determined the element priorities standing on the same hierarchical level, it becomes important to synthesize the priorities expressed on all levels.

The priorities on each level are weighed against the priority of the attribute on the next higher level used to effect the comparison. Every comparison between a pair of entities (alternatives, subcriteria, or criteria) represents an estimate of the relationship between the priorities or the weights of the two elements that are compared. By applying Saaty's method to these data, we are able to calculate the evaluations of their weights (priorities) on each level of the hierarchy.

5.2.2 Intuitive Justification of the Method for Calculating Weights

A rigorous mathematical justification of the AHP method starting from the definition of the axioms on which it is based will not be given in this book; however, it can be found in various texts shown in the references [Saaty, 1990a]. To understand this method we do, however, present an intuitive justification [Saaty, 1990b].

Let $C_1, C_2, \ldots, C_n$ be a set of n objects (alternatives or criteria) of the same level on a hierarchy. The judgments arising from a comparative evaluation of the single objects are given on an n by n matrix:

$$\mathbf{A} = \{a_{ij}\} \qquad (i, j = 1,\ 2,\ \ldots,\ n)$$

The coefficients of the matrix **A** are defined according to the following rules:

1. If $a_{ij} = \alpha$, then $a_{ji} = 1/\alpha$, with $\alpha \neq 0$, and possibly $\alpha \in E = (1 \text{ to } 9)$.
2. If C_i is as important as C_j, then $a_{ij} = 1$, $a_{ji} = 1$; in particular, $a_{ii} = 1$ $\forall i = 1, 2, \ldots, n$.

Thus, for matrix $\mathbf{A} \in R^{n,n}$ (reciprocal) of the comparisons on pairs:

$$\mathbf{A} = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix}$$

the problem lies in the assigning to the n objects C_1, C_2, …, C_n, a set of numerical weights w_1, w_2, …, w_n, which reflect the judgments expressed in **A**.

If, for example, the preferences expressed were the result of typically physical measurements (length, mass, etc.), the weight would express the ratio between the determined values:

$$w_i/w_j = a_{ij} \qquad (\forall i,\ j = 1,\ 2,\ \ldots,\ n)$$

With this position matrix **A** becomes:

$$\mathbf{A} = \begin{bmatrix} w_1/w_1 & w_1/w_2 & \cdots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & \cdots & w_2/w_n \\ \vdots & \vdots & \ddots & \vdots \\ w_n/w_1 & w_n/w_2 & \cdots & w_n/w_n \end{bmatrix}$$

In this case the coefficients of matrix **A** satisfy the following properties:

$$(*) \quad a_{ij} \cdot a_{jk} = \frac{w_i}{w_j} \cdot \frac{w_j}{w_k} = \frac{w_i}{w_k} = a_{ik} \quad \text{(Consistency)}$$

$$(**) \quad a_{ji} = \frac{w_j}{w_i} = \frac{1}{w_i / w_j} = \frac{1}{a_{ij}} \quad \text{(Reciprocity)}$$

Let us now consider the resolution of a linear system:

$$\mathrm{A} \cdot \mathbf{x} = \mathbf{y} \tag{5.1}$$

with

$$\mathbf{x} = \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix}$$

$$\mathbf{y} = \begin{bmatrix} y_1 \\ \vdots \\ y_n \end{bmatrix}$$

By making Equation (5.1) explicit we find:

$$\sum_{j=1}^{n} a_{ij} \cdot x_j = y_j$$

$$i = 1, \ \ldots, \ n$$

On the other hand, the equation $a_{ij} = \frac{w_i}{w_j}$ can be rewritten, by multiplying both terms by $\frac{w_j}{w_i}$ in the following manner:

$$a_{ij} \cdot \frac{w_j}{w_i} = 1$$

$$(\forall i, \ j = 1, \ \ldots, \ n)$$

By summing with respect to j we obtain:

$$\sum_{j=1}^{n} a_{ij} \cdot \frac{w_j}{w_i} = n$$

$$i = 1, \ \ldots, \ n$$

or

$$\sum_{j=1}^{n} a_{ij} \cdot w_j = n \cdot w_i$$

$$i = 1, \ \ldots, \ n$$

which is equivalent to:

$$\mathrm{A} \cdot \mathbf{w} = n \cdot \mathbf{w} \tag{5.2}$$

This expression shows the concept that **w** (vector of the weights that qualifies each single alternative) is an *eigenvector* of **A**, with n one of its *eigenvalues*.

$$\begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix} \cdot \begin{bmatrix} w_1 \\ \vdots \\ \vdots \\ w_n \end{bmatrix} = n \cdot \begin{bmatrix} w_1 \\ \vdots \\ \vdots \\ w_n \end{bmatrix}$$

If we now analyze a practical example where the coefficient a_{ij} expresses an *intensity of preference* between two alternatives not based on exact (physical) measures, but on subjective judgments, normally a_{ij} will derive from the ideal relationship $\frac{w_i}{w_j}$ and the relationship A·**w** = n·**w** will no longer hold.

At this point two important concepts in the matrix theory intervene:

1. If $\lambda_1, \ldots, \lambda_n$ are the n solutions (eigenvalues) of the linear system:

$$\mathrm{A} \cdot \mathbf{x} = \lambda \cdot \mathbf{x} \tag{5.2a}$$

$$\begin{cases} \mathbf{A} \in \Re^{n,n} \\ \mathbf{x} \in \Re^{n,1} - \{\mathbf{0}\} \\ \lambda \in \Re \end{cases}$$

and if $a_{ii} = 1$; $\forall i = 1, 2, \ldots, n$, then:

$$\sum_{i=1}^{n} \lambda_i = n \tag{5.3}$$

If Equations (5.2) and (5.3) are true, then all the eigenvalues of **A** are null, except the greatest whose value is n (because **A** is reciprocal).

2. If we vary slightly the coefficients a_{ij} of a reciprocal matrix **A**, the autovalues will also vary slightly.

In combining the results in 1 and 2 by the very fact that our matrix **A** has only unit values on its principal diagonal $a_{ii} = 1$; $\forall i = 1, 2, \ldots, n$, and if **A** is consistent (i.e., if $a_{ik} = a_{ij} \cdot a_{jk}$), then small variations of the a_{ij} keep the largest eigenvalue λ_{max} close to n, whereas the other eigenvalues will remain close to zero.

Once the matrix of pairwise comparisons **A** has been assigned with the objective of defining the vector of priorities, it is simply a case of determining the eigenvector **w** associated to the eigenvalue λ_{max} that satisfies the equation:

$$\mathrm{A} \cdot \mathbf{w} = \lambda_{\max} \cdot \mathbf{w} \tag{5.4}$$

Once $\mathbf{w} = \begin{bmatrix} w_1 \\ \vdots \\ w_n \end{bmatrix}$ has been determined, the weights are successively normalized, for easier interpretation:

$$w_i' = \frac{w_i}{\sum_{i=1}^{n} w_i} \qquad \text{with} \sum_{i=1}^{n} w_i' = 1 \qquad \forall i = 1, 2, \ldots, n \tag{5.5}$$

The weights w_i' represent the relative importance of the entities that have been compared.

5.2.2.1 Consistency Evaluation

An important consideration to be made when utilizing the AHP method is the notion of consistency. Customers who answer that a certain characteristic A is twice as important as characteristic B, and that B is three times more important than D, will be supplying a consistent evaluation if they also answer that the characteristic A is six times more important than characteristic D. Any other value assigned by customers when comparing the characteristics A to D will render their opinions not

TABLE 5.1
Average RI Values

N	1	2	3	4	5	6	7	8
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41

From Saaty, T.L. (1990a), *Multicriteria Decision Making: The Analytical Hierarchy Process*, 2nd ed., RWS Publications, Pittsburgh. With permission.)

coherent or not consistent. The method involving eigenvalues allows us to evaluate quantitatively the distance from condition of consistency. As small variations in a_{ij} imply small variations in λ_{max}, the difference ($\lambda_{max} - n$) can be taken to be a measure of consistency of the evaluations expressed in matrix **A**.

We define the *consistency index* as the ratio:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{5.6}$$

CI is compared with the *random index* (RI) randomly generated for reciprocal matrices, with reciprocals forced, having n varying from 1 to 15 and taking into account the average on a sample having an increasing number of units (from 100 to 500) (Table 5.1).

The ratio:

$$CR = \frac{CI}{RI} \tag{5.7}$$

defines the so-called consistency ratio (CR).

An empirical rule supplied by Saaty states that the CR of 0.10 or less is considered acceptable. When judgments are not far too coherent, decision makers should be given the opportunity to have another look at their pair comparisons.

5.2.3 Advantages and Disadvantages of Integrating Quality Function Deployment and Analytical Hierarchy Process

Many authors have suggested the use of the AHP method in applying QFD [Akao, 1990; Aswad, 1989]. AHP is used to assign a level of priorities to a hierarchy of requirements that constitute the customer's own criteria of evaluation. The hierarchy is that found in the tree or table of demanded quality. The customer's basic requirements constitute the strategic dimensions of the decisional problem, the second level includes the criteria of evaluation, and the lowest level includes the attributes or the subattributes.

The advantage of using AHP to determine the priorities of customer requirements is that it constitutes a *ready-made* model enabling us to deal with complex situations of order ranking, based on subjective criteria.

The calculation of the various weights is facilitated, for example, by the use of the computer program Expert Choice™, which implements Saaty's procedure. A considerable advantage of the method is that it supplies a measurement of the consistency of evaluations expressed by the customer–decision maker. Moreover, it points out which judgments are the more incoherent among those expressed by the customer, permitting reevaluations where necessary.

In this sense, if the number of customers–decision makers is limited and if they can be grouped, AHP can be used in a quite advantageous manner as a *group decision support system* (GDSS) making use of a *moderator* whose duty it will be to facilitate reaching a consensus on the evaluations expressed by the various customers.

The situation changes remarkably when dealing with a rather numerous but scattered group of customers, as may very often happen where some particular industrial products are involved. In any case, even here, the AHP method can be used.

Aczel and Saaty [1983] have in fact demonstrated that matrix $\mathbf{A}'$ of pairwise comparisons obtained by calculating the geometric average of the *judgments expressed by n* customers:

$$A' = \left\{a'_{ij}\right\}$$

with

$$a'_{ij} = \sqrt[n]{a_{ij}^{[1]} \cdot a_{ij}^{[2]} \cdot \ldots \cdot a_{ij}^{[k]} \cdot \ldots \cdot a_{ij}^{[n]}} \tag{5.8}$$

(where $a_{ij}^{[k]}$ is the evaluation of the k-th customer on the comparison between the pair of requisites i and j), maintains the property of reciprocity and its elements still belong to the ratio scale E = (1 to 9). It is, therefore, possible to apply the method of eigenvalues to matrix $\mathbf{A}'$ that synthesizes the evaluations of n customers.

Nonetheless, if the customers are numerous and cannot be easily contacted, we shall have to utilize a questionnaire (the program Expert Choice™ creates one automatically), which is rather difficult to compile and much more irksome for the customer. It requires a greater number of evaluations than does a traditional questionnaire, which does not require pair comparisons of requirements on the same level.

Furthermore, it must be pointed out that *the customer finds it extremely difficult to indicate precisely how many times* one alternative may be more important than another. Does the information supplied by customers have the properties of a ratio scale?

The danger of noncoherence between judgments then becomes quite evident, as the difficulty of adjusting them is equally evident. We could run the risk, too, of possessing a heap of data of somewhat scant significance and using them *uncritically or improperly.*

O: 9 points
O : 3 points
Δ : 1 point

		Technical Characteristics										
		S 1									S2	
Customer Needs	Degree of importance	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.1	2.2
R1	**10%**	**O**	**O**	**O**	**O**	**O**	**O**	**O**	**O**	**O**		
R2	**90%**										**O**	**O**
		90	90	90	90	90	90	90	90	90	810	810
	Absolute importance	810									1620	
	Relative importance	**33.3%**									**66.6%**	

FIGURE 5.1 The need for deployment normalization: an exaggerated example. (From Wasserman, G.S. [1993], *IIE Trans.*, 25(3), 59–65. With permission.)

5.3 PRIORITIZING THE TECHNICAL CHARACTERISTICS

We have seen in Chapter 4, Section 4.6 how it may be possible through QFD to determine the prioritization of technical characteristics. The information contained in the relationship matrix is used to draw up a list ranking the *level of attention* a designer will have to dedicate to each single product characteristic (keeping in mind the relative importance of customer requirements).

It is, therefore, of fundamental importance that customer requirements be considered without forcing or distorting the customer's intentions. In this respect, the traditional method described in Chapter 4 does present some drawbacks. In this chapter as well as the one following, we will deal with how the level of importance of a characteristic depends on the number of subcharacteristics used to describe it in detail. Such problems can be opportunely resolved by *normalizing* the relationship matrix.

Let us consider a case that has been purposely exaggerated. We have, for example, two customer requirements: *R*1, a requisite of relatively *little importance* (weighing 10%), and *R*2, a requisite relatively *important* (weighing 90%) (Figure 5.1).

We also have two design characteristics, *S*1 and *S*2, which completely characterize the product to be planned in terms of satisfaction of customer requirements. Note that *S*1 is a level one design characteristic that declines into no less than 9 subcharacteristics on a lower level, coded 1.1 to 1.9, respectively.

Each one of these subcharacteristics is strongly correlated to the requirement having little importance, *R*1. On the other hand, specification *S*2 declines into two subcharacteristics (2.1 and 2.2), each of which is strongly correlated to the important requirement *R*2.

If we apply the traditional *independent scoring method* [Akao, 1990] with its scale of 1 to 3 to 9, we will determine that the weight of the characteristic $S1$, connected to requisite $R1$ (and none other), is 33.3%, whereas the weight of characteristic $S2$, able to satisfy requirement $R2$, is 66.7%.

According to the levels of importance of each customer requirement, the contribution of the requisites $R1$ and $R2$ on an overall level of customer satisfaction is 10 and 90%, respectively. We should expect a similar proportion (1:9) between the levels of relative importance of the planning characteristics $S1$ and $S2$. On the contrary, we note that because the first characteristic is detailed by a greater number of subcharacteristics than the second characteristic, the level of relative importance is *artificially* heightened from 10 to 33.3%.

5.4 NORMALIZING THE COEFFICIENTS OF THE RELATIONSHIP MATRIX

5.4.1 LYMAN'S NORMALIZATION

To solve this problem, Lyman [1990] proposes the normalization of the coefficients in the relationship matrix **R**. The coefficients $\tilde{r}_{ij}$ of relationship matrix $\tilde{\mathbf{R}}$ are obtained by dividing each of the coefficients of **R** by the sum of the values on each line.

We will therefore obtain:

$$\tilde{r}_{ij} = \frac{r_{ij}}{\sum_{j=1}^{m} r_{ij}} \tag{5.9}$$

In this manner, the resultant matrix $\tilde{\mathbf{R}}$ will satisfy the property that the sum of the elements on each row is equal to 1. This property can be expressed in matrix form in the following manner:

$$\tilde{\mathbf{R}} \cdot \mathbf{1} = \mathbf{1} \tag{5.10}$$

as $1 = (1, 1, 1, \ldots, 1)^T$.

Figure 5.2 illustrates the effect of Lyman's normalization on the example shown in Figure 5.1. Normalization contributes to ensuring that the calculated weights of the design characteristics truly reflect the ranking order of customer requirements on the basis of their importance. This procedure does not take into account the fact that the technical characteristics of a product may be correlated to one another. In practice this happens very frequently. Sometimes it is possible to reduce the level of dependency between the design characteristics by eliminating those that appear to be redundant, or by devising planning alternatives to reduce correlation.

		Technical Characteristics											
		S 1									S2		
Customer Needs	Degree of importance	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.1	2.2	Row sum
R1	10%	O	O	O	O	O	O	O	O	O			81
R2	90%										O	O	18
		1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	45	45	
	Absolute importance	10									90		
	Relative importance	10%									90%		

FIGURE 5.2 The need for deployment normalization: an exaggerated example. (From Lyman, D. [1990], Deployment Normalization, 2nd Symposium on QFD cosponsored by ASCQ and ASI, pp. 307–315; Wasserman, G.S. [1993], *IIE Trans.*, 25(3), 59–65. With permission.)

5.4.2 Wasserman's Normalization

An extension of Lyman's normalization procedure has been suggested by Wasserman [1993] to solve the problem of interdependant planning characteristics. To model the dependency, we determine the vector space of technical characteristics and that of customer requirements. Let us assume that the vector space of customer requisites $\Im$ is generated by the unit vectors $\{\mathbf{u}_i\}$, $i = 1, 2, \ldots, n$. For the moment let us assume that the customer requirements are not correlated. Thus, the set of vectors $\{\mathbf{u}_i\}$, $i = 1, 2, \ldots, n$ forms an orthonormal basis spanning the customer requirements space $\Im$. This hypothesis is coherent with the way the customer requirements are usually treated during the QFD process.

If necessary, the interdependence of the customer requirements may be analyzed later. At this point we are able to write the vector $\mathbf{d}$ of customer importance rating in the following manner:

$$\mathbf{d} = d_1 \cdot \mathbf{u}_1 + d_2 \cdot \mathbf{u}_2 + \ldots + d_n \cdot \mathbf{u}_n \tag{5.11}$$

where d_i is the importance of the i-th requirement.

On the other hand, to model the vector space Ξ of product characteristics, let us assume that it is generated by the unit vectors $\{\mathbf{v}_j\}$ that do not necessarily constitute an orthonormal basis for Ξ, because they may be linearly dependent on one another. To represent the interdependence of the technical characteristics, we will introduce the notation γ_{jk} to indicate the element on the roof of the house of quality (HoQ) that describes the intensity of correlation existing between characteristic j and characteristic k. We can note this as:

$$\gamma_{jk} \equiv \mathbf{v}_j \cdot \mathbf{v}_k \left(\equiv \cos\left(\mathbf{v}_j, \mathbf{v}_k\right)\right) \tag{5.12}$$

obviously $\gamma_{jj} \equiv \mathbf{v}_j \cdot \mathbf{v}_j = 1, \ \forall j = 1, \ \ldots, \ m$

Coefficients γ_{jk} expressing the intensity of correlation between characteristics are assigned by the designers using a scale very similar to that used for the coefficients of the relationship matrix. However, it is necessary to make sure the scale levels remain between 0 and 1. Thus, a value of 0.9 will be assigned to a strong correlation, 0.3 to a medium correlation, and 0.1 to a weak correlation. In the example of the pencil (see Figure 4.10), the vectors $\{\mathbf{v}_j\}$ are

$$\gamma_{12} = \gamma_{21} = 0$$

$$\gamma_{13} = \gamma_{31} = 0$$

$$\gamma_{14} = \gamma_{41} = 0$$

$$\gamma_{15} = \gamma_{51} = 0$$

$$\gamma_{23} = \gamma_{32} = 0$$

$$\gamma_{24} = \gamma_{42} = 0$$

$$\gamma_{25} = \gamma_{52} = 0$$

$$\gamma_{34} = \gamma_{43} = 0$$

$$\gamma_{35} = \gamma_{53} = 0$$

$$\gamma_{45} = \gamma_{54} = 0$$

A generalization of Lyman's normalization referred to correlated planning characteristics is, therefore, as follows:

$$\left(r_{i,j}^{\text{norm}} \cdot \mathbf{v}_1 + r_{i,2}^{\text{norm}} \cdot \mathbf{v}_2 + \ldots + r_{i,n}^{\text{norm}} \cdot \mathbf{v}_n\right) \cdot \left(\mathbf{v}_1 + \mathbf{v}_2 + \ldots + \mathbf{v}_n\right) = 1$$

with

$$i = 1, \ 2, \ \ldots, \ n$$

which, as we have:

$$\left\{\sum_{i=1}^{n} \mathbf{v}_i\right\} \cdot \left\{\sum_{j=1}^{n} \mathbf{v}_j\right\} = \left\{\sum_{i=1}^{n} \sum_{j=1}^{n} \gamma_{ij}\right\}$$

is satisfied by calculating the normalized coefficients using the following formula:

$$r_{i,j}^{\text{norm}} = \frac{\sum_{k=1}^{m} \left(r_{i,k} \cdot \gamma_{k,j} \right)}{\sum_{j=1}^{m} \sum_{k=1}^{m} \left(r_{i,j} \cdot \gamma_{j,k} \right)}$$

Notice that this type of transformation is referable to Lyman's normalization where the design characteristics are independent from one to the other, such that:

$$\gamma_{jk} = 1 \quad \text{if } j = k$$

otherwise

$$\gamma_{jk} = 0$$

For example, the relation coefficient $r_{3,1}^{\text{norm}}$ in the example of the pencil is calculated in the following manner:

$$r_{3,1}^{\text{norm}} = \frac{\sum_{k=1}^{5} \left(r_{3,k} \cdot \gamma_{k,1} \right)}{\sum_{j=1}^{5} \sum_{k=1}^{5} \left(r_{3,j} \cdot \gamma_{j,k} \right)}$$

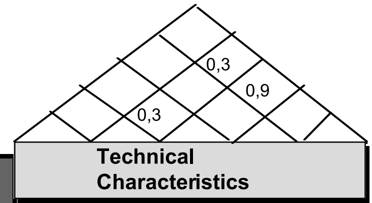
$$= \frac{r_{3,1} \cdot \gamma_{1,1} + r_{3,2} \cdot \gamma_{2,1} + r_{3,3} \cdot \gamma_{3,1} + r_{3,4} \cdot \gamma_{4,1} + r_{3,5} \cdot \gamma_{5,1}}{r_{3,1} \cdot \left(\gamma_{1,1} + \ldots + \gamma_{1,5} \right) + r_{3,2} \cdot \left(\gamma_{2,1} + \ldots + \gamma_{2,5} \right) + r_{3,3} \cdot \left(\gamma_{3,1} + \ldots + \gamma_{3,5} \right) + r_{3,4} \cdot \left(\gamma_{4,1} + \ldots + \gamma_{4,5} \right) + r_{3,5} \cdot \left(\gamma_{5,1} + \ldots + \gamma_{5,5} \right)}$$

$$= \frac{1 \cdot 1 + 3 \cdot 0 + 9 \cdot 0 + 0 \cdot 0 + 9 \cdot 0}{1 \cdot (1) + 3 \cdot (1.6) + 9 \cdot (2.2) + 0 \cdot (1) + 9 \cdot (2.2)} = \frac{1}{45.4} \cong 0.022$$

Figure 5.3 shows the example of the pencil after Wasserman's process of normalization. It should also be noted that with this transformation the absolute weights (calculated with normalized coefficients) coincide with the relative weights (in percentages).

Even in this simplified example, the effect of normalization is evident. An analysis of the relationship matrix reveals that "minimal erasure residue" and "lead dust generated" are essentially redundant characteristics. We can see from the roof of the HoQ that both characteristics have an equal impact on the customer requirements "does not smear" and "point lasts." Therefore, it may be sufficient to introduce only one of the two to satisfy both customer requirements.

This consideration is pointed out through the procedure of normalization. Before applying it, both specifications had been assigned a level of relative importance equal to 33% (see Figure 4.10). After it had been applied, the level of importance



	A Degree of importance	Relative importance	1) Length of Pencil	2) Time between sharpening	3) Lead Dust Generated	4) Hexagonality	5) Minimal Erasure Residue
1) Easy to hold	2	17%	0.25	0	0	0.75	0
2) Does not smear	3	25%	0	0.19	0.405	0	0.405
3) Point lasts	5	41%	0.022	0.185	0.396	0	0.396
4) Does not roll	2	17%	0.1	0	0	0.9	0
Total	12	100%					

	1)	2)	3)	4)	5)
Technical importance	6.74	12.3	26.4	27.5	26.4
Relative importance	6.78%	12.4%	26.6%	27.7%	26.6%

FIGURE 5.3 Wasserman's procedure for the normalization of the pencil example. (From Wasserman, G.S. [1993], *IIE Trans.*, 25(3), 59–65. With permission.)

of each of the two characteristics diminished to 26.7%, with a level of global importance fixed at about 54%. Furthermore, the characteristic "hexagonality," which appears to be a very important characteristic for "easy to hold" and "does not roll" customer requirements, is seen to increase its level of importance after normalization from 17 to 27.5%.

5.5 QUALITY FUNCTION DEPLOYMENT AND VALUE ANALYSIS

5.5.1 Simplified Model for Costing

Numerous authors [King, 1989; Akao, 1990] point out the usefulness of analyzing the costs involved in the QFD planning process.

From the very first stages of planning a new product, companies are obliged to define the market niche and the targeted sales price. Akao talks of a *deployment of costs* to be carried out in parallel with the *deployment* of the quality attributes defined by the customer. The aim of this deployment of costs should be to introduce a systematic procedure for the evaluation and optimization of the cost of the product, without diminishing the importance of its quality and its reliability. This necessity stems from the need to avoid the erroneous allocation of company resources on the one hand, and, on the other hand, the necessity to reduce thoughtless costs (because they are not proportional to the results obtained or because they may one day be the cause of possible unforeseen complaints).

We are then faced with the problem of determining which methodology will be able to indicate those product characteristics where cost reductions can be applied to the greatest advantage. This entails operating a distribution of economic resources that will enhance product quality. The analysis will obviously have to take into account the fact that planning is in the process of being defined, and that many operative details have not yet been frozen into their definite shape. The distribution of costs is, therefore, to be intended as a preliminary generalized attribution.

Let us consider once again the example of the pencil; supposing that a budget B of 2 cents has been fixed to cover the unit cost increase, whereas the basic cost is 10 cents [Wasserman, 1993]. If we carry out the normalization of values in the relationship matrix, we are able to interpret the normalized values as the marginal variation of the level of satisfaction of the *j*-th customer requirement where the technical characteristic is on level x_j. The decisional variables x_j, $j = 1, \ldots, m$, are assumed on a percentage basis, so that $x_j = 100\%$ means that the *j*-th design characteristic is at target (optimal) level. For the sake of convenience, let us suppose that the product's basic unit cost is set at the same level as the value of the cost obtained when the level of the decisional variables is set at zero, that is, when $x_1 = x_2 = \cdots = x_m = 0$. Wasserman [1993] suggests a linear cost constraint as described in the following equation:

$$c_1 \cdot x_1 + c_2 \cdot x_2 + \ldots + c_m \cdot x_m \leq B \tag{5.13}$$

The cost coefficients $c_1, c_2, \ldots, c_m$ represent the incremental change in unit cost associated to a variation of x_j.

The decisional variables (design characteristics) are to be so determined with a view to maximizing global CS. The following objective function is proposed:

$$CS = \max\left\{w_1 \cdot x_1 + w_2 \cdot x_2 + \ldots + w_m \cdot x_m\right\} \tag{5.14}$$

In this formulation there is an implicit assumption that the level of customer satisfaction will be modified for those technical characteristics whose fulfillment will produce a high marginal increase in the overall *CS*.

The objective function is seen to be a simple, linear weighting of the technical importance measures w_j for the normalized relationship matrix, and the decision variables x_j. Generally, this assumption must be verified according to the particular product under examination, and the capability to render quantifiable in terms of costs all the contributions of the single technical characteristics.

5.5.2 Interpreting the Model

The suggested costing model — Equations (5.13) and (5.14) — takes us back to the classic *knapsack problem* 0-1. Given a series of different-sized items, each one having a specific value, we endeavor to maximize the value of the contents in the knapsack, without overstepping its overall capacity bound B.

It can be shown that an upper bound to the value of contents of the knapsack is obtained by prioritizing the articles, assigning the unit value for each item in decreasing order. If the integer restrictions in the knapsack problem are relaxed, then it can be shown that the optimal packing of the knapsack is obtained by following this ranking exactly.

Although as formerly said, x_j = 100% represents the level of optimal quality status, c_j represents the cost required to reach the target for the j-th characteristic. To neutralize the effects of antagonism among the negatively correlated planning specifications, we assume that the scale on the planning specifications varies in the continuous interval between [–100% and +100%]. In other words, we can allow negative variations in the values of the characteristics starting from their basic values.

Thus, the allocation of resources according to the strategy best suited to solving the knapsack problem should be strictly based on the value of a simple index formed by the (w_j/c_j) ratios, $j = 1, \ldots, m$. This is coherent with the opinions expressed by Hales, Lyman, and Norman [1990], who suggest indicating in QFD matrices the *importance of the effort required*. In effect the *effort required* might be considered, as a first approximation, as a cost proportional to the resources allocated and the organizational efforts required.

5.5.3 Illustrative Example

Returning to the example of the pencil design, let us suppose that the marginal costs connected to reaching an optimal level of performance for the various characteristics are those defined in the column "cost c_j" in Table 5.2. As we can observe, due to the restriction of 2 cents it is impossible to reach an optimal level in all the characteristics, because the necessary expenditure would be of $2.90.

The relative weights w_j (shown in the first column on Table 5.2) tell us that as far as the satisfaction of customer requirements is concerned, the most important characteristics are, in order, 3 and 5 (which are the redundant characteristics), followed by 4, 2, and 1. If we consider the costs, however, characteristic 4 is shown to be the most economical to improve, followed by characteristics 3 and 5, then by 2 and 1 (Table 5.3).

According to the model described in Section 5.5.1 of Chapter 5, to maximize global customer satisfaction while keeping in mind the budgetary restrictions, it is necessary to rank the characteristics on the basis of a weight and cost quotient rating. Successively, the available economic resources will be allocated starting from the technical characteristics having the highest value according to this quotient rating.

Table 5.2 shows the optimal allocation of economic resources resulting in an improvement of the product pencil, keeping to the available budget of 2 cents.

5.6 CONCLUSIONS

In this chapter we have focused our attention on the problems associated with gathering and processing the data essential for working on a product when using

TABLE 5.2
Recommended Allocation of Incremental Design Resources

Technical Characteristic	Technical Importance (%)	Cost c_j (c$)	w_j/c_j (%/c$)	% Allocation	Resources Allocated (c$)
Length of pencil	7	1.00	7	10	0.10
Time between sharpening	12	0.60	20	100	0.60
Lead dust generated	26.5	0.50	53	100	0.50
Hexagonality	28	0.30	93	100	0.30
Minimal erasure residue	26.5	0.50	53	100	0.50
Total	100	2.90			2.00

From Wasserman, G.S. [1993], *IIE Trans.*, 25(3), 59–65. With permission.

TABLE 5.3
Prioritization of Technical Characteristics with Respect to Importance, Cost, and Importance/Cost Index

Technical Characteristic	Prioritization According to Technical Importance	Prioritization According to Cost	Prioritization According to Importance/Cost Index
Length of pencil	5	5	5
Time between sharpening	4	4	4
Lead dust generated	1	2	2
Hexagonality	3	1	1
Minimal erasure residue	1	2	2

From Wasserman, G.S. [1993], *IIE Trans.*, 25(3), 59–65. With permission.

QFD. We have seen that QFD, to be applied, must undergo an attentive phase of design analysis and must include a multitude of carefully gathered information concerning the customer.

Therefore, as we shall notice in Chapter 7, a preeminent role in this direction is played by the use of quantitative and nonquantitative scales, used to gather various responses. Choosing the most suitable scales, how to formulate the questions, and how to gather information* are therefore not problems of secondary importance when using QFD. The choice of one scale instead of another could direct the planning process toward entirely different design solutions.

* According to Urban and Hauser [1993], the design of questionnaires is to be considered an art.

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