Total Quality Management

Total Quality Management (TQM), a business process that became extremely popular in the mid to late 1980's, dates back several decades to the work of W. Edwards Demming, who, after World War II, went to Japan to teach quality. Demming insisted that employees could not produce products that on the average exceeded the quality of what the *process* was capable of producing. He emphasized the use of statistical techniques as the fundamental tool for improving the process. These techniques, known as statistical process control, differ somewhat from traditional statistics. Traditional statistics usually assume that there is a probability distribution for a population and is concerned with estimating the parameters of the distribution. Statistical process control, on the other hand, does not assume that there is a 'stable' probability distribution, but that, in fact, the mean and or variance of the distribution might be changing – that is, the process may be out of control. The first concern in statistical process control is to ascertain that the process is 'in control', and if not, determine what needs to be done to stabilize the system. Then, and only then, is attention turned to determining whether the system is 'process capable – capable of producing output that is within defined specification limits. Demming insisted that the use of intuition alone was not adequate to achieve quality. He gave examples to illustrate that without some theoretical basis, such as the use of statistics, the application of 'common sense' ways to improving quality often lead, surprisingly, to a reduction in quality. He was fond of saying that without a theory "Off you go to the Milky way".

Total quality management grew to encompass many other ideas and concepts. So many, in fact, that it is often difficult to say what TQM doesn't encompass. The historical shift in quality focus can be seen in Table 24. Another view of TQM is the categorization as three vertices of a triangle shown in Figure 3.

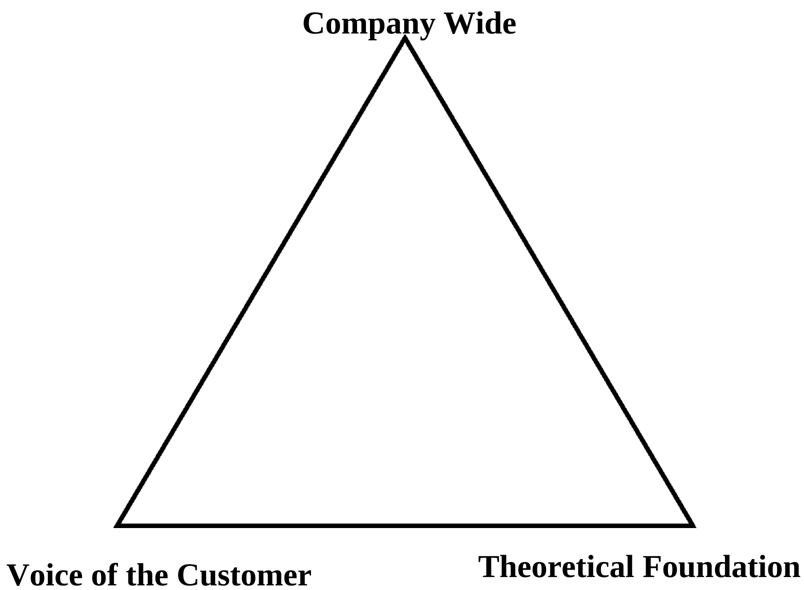
The meaning of the word 'total' is often misunderstood – it does not refer to total quality, but instead is a translation from the Japanese terminology for 'company -wide'. A consequence of organizational growth and compartmentalization has been the inability of any one 'department' to make an effective impact on quality improvement without cooperation and involvement of other departments. One vertex of the TQM triangle in Figure 3 is a concerted – company wide –effort to break down organizational barriers such as:

- poor communication or lack of communication
- lack of overall mission and goals
- competition between departments, shifts, areas, …
- too many levels of management that filter information
- decisions and resource allocation without regard to social memory

Table 24-- History of Quality

	Inspection	Quality Control	Quality Assurance	Strategic Quality Management
Primary Concern	detection of defectives	control of processes	coordination of entire production chain	strategic impact
View of quality	a problem to be solved	a problem to be solved	a problem to be solved, but one that is attacked proactively	a competitive opportunity
Emphasis	product uniformity	product uniformity with reduced inspection	the entire production chain, from design to market, and the contribution of all functional groups, especially designers, to preventing quality failures	the market and consumer needs
Methods	gauging and measurement	statistical tools and techniques	programs and systems	strategic planning, goal setting, and mobilizing the organization
Role of quality professionals	inspection, sorting, counting, and grading	troubleshooting and the application of statistical methods	quality measurement, quality planning, and program design	goal setting, eeucation and training, consultative work with other departments, and program design
Who Has Responsibility for Quality	the inspection department	the manufacturing and engineering departments	all departments, although top management is only peripherally involved in designing, planning, and exercising quality policies	everyone in the organization, with top management exercising strong leadership
Orientation and Approach	"inspects in" quality	"controls in" quality	"builds in" quality	"manages in" quality

Figure 3 -- TQM Vertices



The definition of quality is in the eyes of the beholder. Prior to many TQM efforts, the beholder was the person or persons responsible for quality. According to TQM, however, we should be looking through the customers' eyes, or, in TQM parlance, listening to their voices. The Voice of the Customer forms the second vertex of our TQM triangle. The decision of which what product (or service) characteristics are most relevant to the market segments that are most important to achieving the organizational objectives is addressed.

A strong theoretical foundation, as advocated by Demming, forms the third vertex of our TQM triangle. Specifically, the strong theoretical foundation of AHP is applicable to:

- Statistical Process Control
  - measurement of 'variables' and 'attributes'
- Quality Improvement
  - Pareto Analysis – is only a first step – too simplistic
  - cause and effect diagrams
    - Fishbone diagrams are AHP models in disguise
    - hierarchical structure allows many levels
    - can translate expert judgment into ratio scales
- Product and process design

- Pricing

The Analytic Hierarchy Process in TQM

Quality is multidimensional

The basic capabilities of AHP –structuring complexity, measurement, and synthesis over multiple dimensions – are applicable to numerous aspects of TQM. First of all, quality is multi-dimensional, as is illustrated by the Malcom Baldridge criteria shown in **Figure 4**[215].

[215] The Malcom Baldridge National Quality Award, United States Department of Commerce, Technology Administration, Gaithersberg, MD, 1996.

1996 AWARD CRITERIA - ITEM LISTING

1996 Categories/Items	Point Values	
1.0 Leadership		**90**
1.1 Senior Executive Leadership	45	
1.2 Leadership System and Organization	25	
1.3 Public Responsibility and Corporate Citizenship	20	
2.0 Information and Analysis		**75**
2.1 Management of Information and Data	20	
2.2 Competitive Comparisons and Benchmarking	15	
2.3 Analysis and Use of Company-Level Data	40	
3.0 Strategic Planning		**55**
3.1 Strategy Development. .	35	
3.2 Strategy Deployment	20	
4.0 Human Resource Development and Management		**140**
4.1 Human Resource Planning and Evaluation	20	
4.2 High Performance Work Systems	45	
4.3 Employee Education, Training, and Development	50	
4.4 Employee Well-Being and Satisfaction	25	
5.0 Process Management		**140**
5.1 Design and Introduction of Products and Services 40		
5.2 Process Management: Product and Service Production and Delivery	40	
5.3 Process Management: Support Services	30	
5.4 Management of Supplier Performance	30	
6.0 Business Results		**250**
6.1 Product and Service Quality Results	75	
6.2 Company Operational and Financial Results	110	
6.3 Human Resource Results	35	
6.4 Supplier Performance Results	30	
7.0 Customer Focus and Satisfaction		**250**
7.1 Customer and Market Knowledge	30	
7.2 Customer Relationship Management	30	
7.3 Customer Satisfaction Determination	30	
7.4 Customer Satisfaction Results 160		
TOTAL POINTS		**1000**

Figure 4 -- Baldridge Award Criteria

Some of these dimensions are quantitative and some are qualitative. Also notice the hierarchical structuring of the Baldridge criteria. The criteria have been clustered just as in an AHP model – with no more than seven, plus or minus two elements in any cluster. In the message to executives, the Baldridge guidelines state:

> "The Criteria's seven Categories and 24 Items focus on requirements that all business – especially those facing tough competitive challenges – need to thoroughly understand.

The Criteria address all aspects of competitive performance in an integrated and balanced way."

The 'integration' requires synthesis, the 'balance' is achieved through appropriate priorities for the seven categories and 24 items. The criteria and sub-criteria are, according to the Baldridge guidelines, 'not only to serve as a reliable basis for making Awards but also to permit a diagnosis of each applicant's overall performance management system." The weights 'assigned' by the Baldridge committee vary from year to year and are used to score the applicants for the award. How these weights are determined is not specified. For the purpose of a competition, establishing rules, including arbitrary weights as in this case, is adequate. However, these weights should *not* be used as a diagnosis of each applicant's overall performance – since the weights obviously should be tailored to the industry and company being assessed. A far more meaningful set of weights can be *derived* through pairwise comparisons as performed in AHP and discussed in Part I of this book.

Seven Stages of Quality

L.P. Sullivan identified seven stages of quality as follows[216]:

- Stage 1 – Product Oriented – Inspection after production, audits of finished products, and problem solving activities
- Stage 2 – Process Oriented – Quality assurance during production including SPC and foolproofing
- Stage 3 – Systems Oriented – Quality assurance involving all departments, i.e., design, manufacturing, sales and service
- Stage 4 – Humanistic – To change the thinking of all employees through education and training
- Stage 5 – Society Oriented – Product and process design optimization for more robust function at lower costs
- Stage 6 – Cost Oriented – Quality loss function
- Stage 7 – Consumer Oriented – Quality function deployment to define the 'voice of the customer' in operational terms

AHP has been useful or is applicable to several of these 'stages' as we will discuss next, starting from the most advanced stage and progressing backwards.

[216] L.P. Sullivan, "The Seven Stages in Company Wide Quality Control," *Quality Progress*, May 1986, p78.

Stage 7 – Consumer Oriented

Two aspects of the consumer oriented focus discussed below are The Voice of the Customer and Value Based Value Pricing

Assessing the Voice of the Customer

Quality, like beauty, is in the eyes of the beholder. But deciding who's eyes we look into and ascertaining what these eyes are looking at are not always easy to determine. We include here, a brief example developed by Zultner & Company, called "Before the House – The Voices of the Customers in QFD[217][218]" (The 'House' refers to the House of Quality in TQM parlance and is discussed in Stage 5 on page 315).

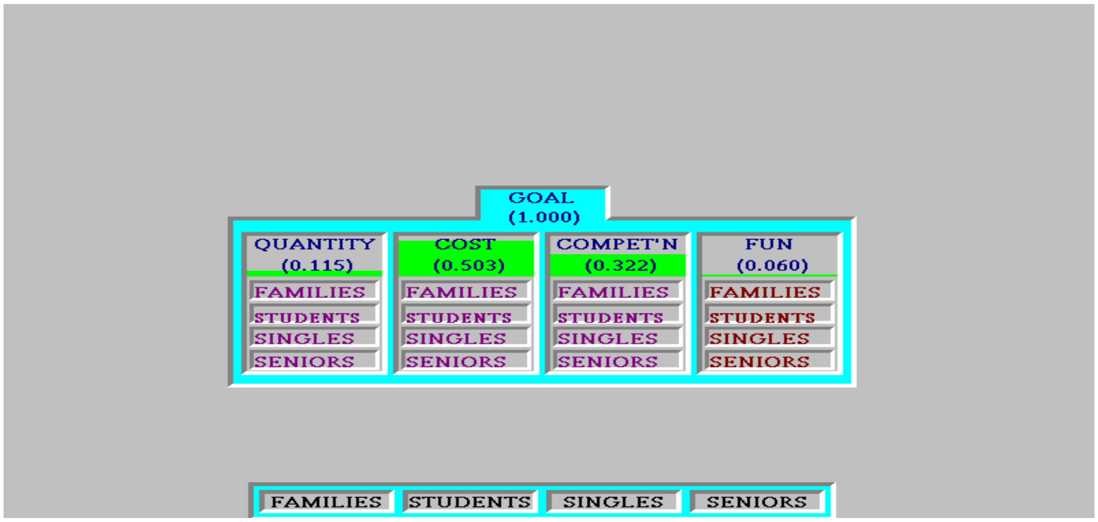
Consider a small 'Mom and Pop" restaurant. To be 'successful', should they focus on the tastiness of the food, serving large portions, providing comfortable surroundings, or making their restaurant a happening place? They want to 'listen' to the voice of the customer, but which customer? They service families, students, singles, and senior citizens. Furthermore, shouldn't *their* objectives influence how they operate their business? Making a profit is of course, a given, but having enjoyment from running the business, or 'fun', is one of the main reasons they decided to open a restaurant in the first place.

Zultner & Company developed two very simple, but powerful AHP models that together, are effective in assessing the voice of the customer. The first model(see Figure 5) to prioritize the market segments as a function of how well each serves their objectives, and the second model to prioritize the restaurant services as a function of how well they contribute to each of their market segments. Some of the priorities in Figure 5 were based on data, while others were based on verbal judgments.

[217] Richard Zultner, Software QFD, Princeton N.J., 1991.

[218] Quality function deployment (QFD) and the house of quality are discussed more fully in in Stage 5 below.

Which customers are more important to Restaurant Owner



Abbreviation	Definition
COMPET'N	lack of competition (judgment about)
COST	cost to service in thousands of dollars
FAMILIES	
FUN	fun in providing service to this type customer
QUANTITY	number of customrers in hundreds
SENIORS	Senior Citizens
SINGLES	
STUDENTS	

Figure 5 -- From Owner Objectives to Market Segment Priorities

The synthesis of this simple model produces priorities for the market segments as shown in Figure 6. These priorities are transferred to second model, shown in Figure 7, that leads to the derivation of service priorities shown in Figure 8.

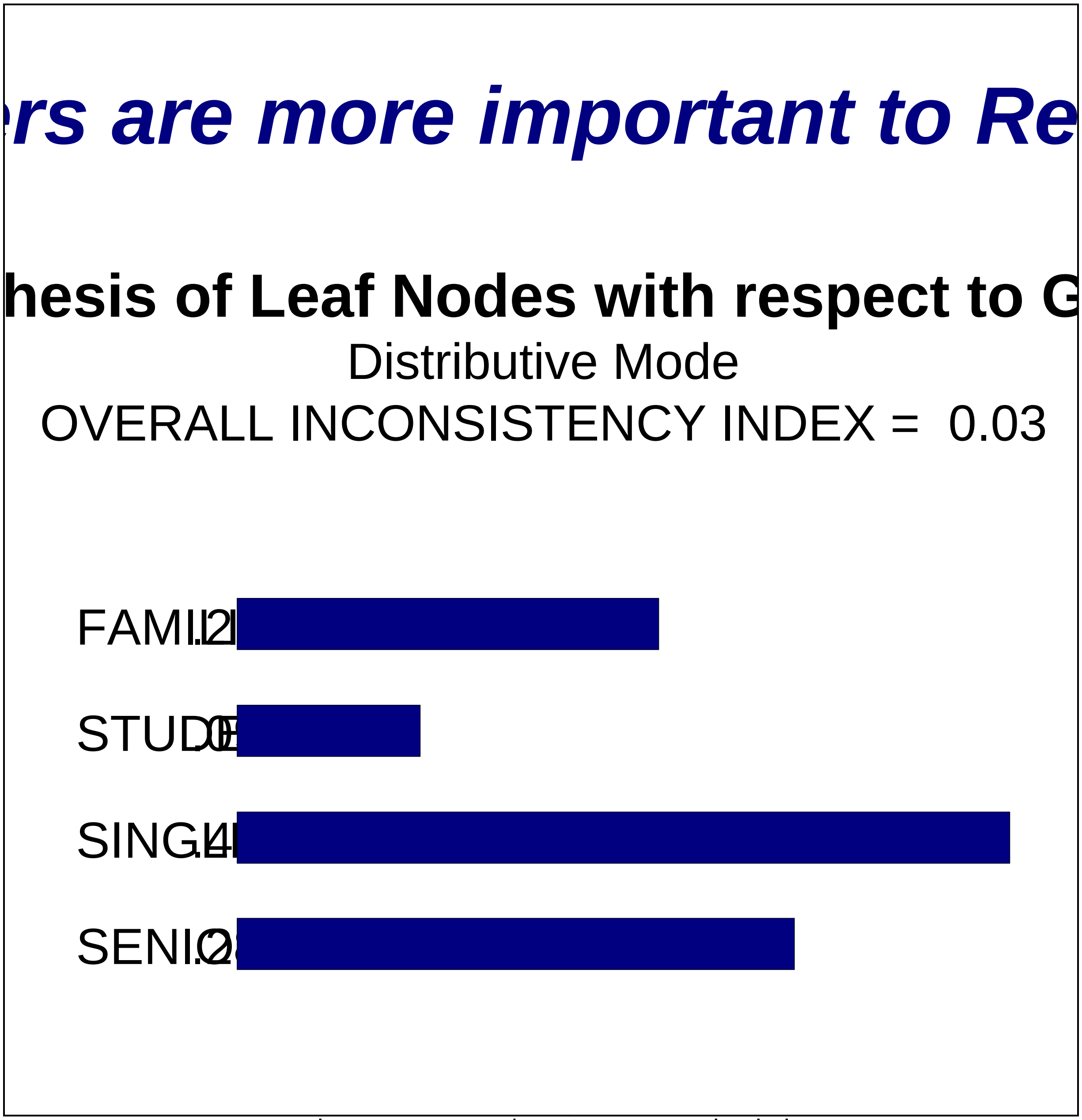
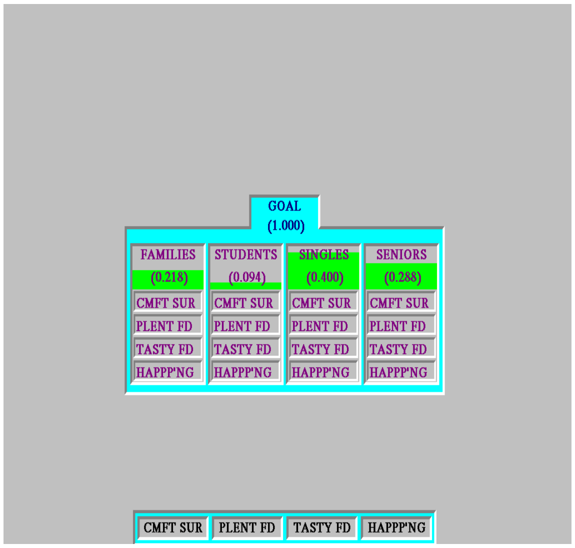


Figure 6 -- Market Segment Priorities

Figure 7 -- Prioritizing Services

customer requirements (pariwise comparisons of requirements)

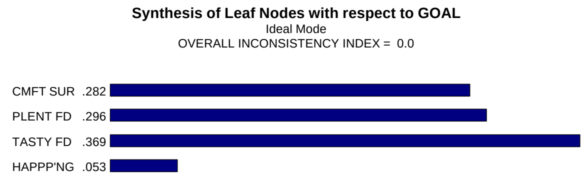


Abbreviation	Definition
CMFT SUR	comfortable surroundings
FAMILIES	
HAPPP'NG	happening palce
PLENT FD	plentiful food
SENIORS	senior citizens
SINGLES	
STUDENTS	
TASTY FD	tasty food

(Priorities shown are 'Local' -- relative to parent node.)

Figure 8 -- Resulting Service Priorities

customer requirements (pariwise comparisons of requirements)



Abbreviation	Definition
CMFT SUR	comfortable surroundings
PLENT FD	plentiful food
TASTY FD	tasty food
HAPPP'NG	happening palce

The application of AHP to derive priorities for a firm's products or services is both simple and sound. Simple because the purpose of each of the models is straightforward and easily understandable. Sound, because the priorities that are derived are ratio scale priorities and ratio scale priorities are required for the results to be mathematically meaningful!

Value Based Value Pricing

A second aspect of the consumer oriented focus stage of TQM developed by Knowledge Management Group[219] is called value based value pricing. Value Based Value Pricing is an analytical methodology developed to support pricing of products or services. The assumption is that the customer is the only judge that really matters in establishing the value of a product or service. The factors affecting buyers' decisions are better understood through a thorough and quantified analysis of customer needs and preferences. Value Based Value Pricing enables users

219 Strategus, Inc. 23, Hunters Lane, Nashua, NH.

to achieve this objective through an integration of behavioral analysis and value engineering, much more powerful and precise than cost justification or investment evaluation techniques.

Value Based Value Pricing is implemented in three steps. The first one (Customer Driven Value Analysis) analyzes what customers want and establishes values of these wants. The second step (Competitive Value Analysis) compares how well different companies satisfy customer requirements. The third step (Competitive Value Pricing) allows for the planning of pricing methodologies that take into account both competitive forces and also how well customers value the products or services offered.

Value Based Value Pricing offers additional collateral benefits. The information collected can be used to focus resources on the functionality of products and services that offer higher value to customers. Functionality that is not, or not often enough, appreciated by customers can be discarded. Marketing and sales strategies can be built around the elements that offer the best value to customers. Value Based Value Pricing can be used by buyers as well to analyze the relative value of multiple responses to a request for products or services.

Customer Driven Value Analysis

The method makes use of the Analytic Hierarchy Process, a tool developed for decision analysis in order to structure and quantify value to customers. It enables the user to structure the functionality of a product or service into mutually interacting elements and then to synthesize them by measuring the priority of the functional elements. The result is a list of functional attributes carrying weights established through a rigorous analysis with the user. For example, a company asked for a computerized order entry system. Small size, appealing design, and high reliability were among the specifications. When asked, the customer listed reliability as more important than size or appearance. A company called Systems Integration, needed a better understanding of the customers priorities in order to develop a pricing for its product proposal.

Order Entry System	Size	Design	Reliability	Priority
Size	1	7	1/7	0.1912
Design	1/7	1	1/9	0.0480
Reliability	7	9	1	0.7608

A Value Analysis workshop with the customer revealed that reliability was very strongly more important than size, and extremely more important than design. The AHP verbal scale and eigenvector priority computation method were used to derive the priorities of the customer wants.

Competitive Value Analysis

The priorities established through *Customer Driven Value Analysis* are used as input to the next tool, *Competitive Value Analysis.* The ability of different companies to satisfy requirements according to priority values established by the customer is compared through a simple process – rating the companies on a 1-10 scale for each of the functional attributes. In the example illustrated in the table, the System Integrator appeared at a disadvantage after a first analysis by being last in two of the three required characteristics. The relative importance of reliability to the customer and the competitive strength in this field showed that, in reality, the System Integrator was 23% better than Company B, and 36% better than Company A.

Order Entry System	Priority	Company A	Company B	Syst. Integr.
Size	.19	7	5	2
Design	.05	5	9	2
Reliability	.76	5	6	9
Competitive Value		5.38	5.96	7.32

An even more robust way to arrive at such results is to perform pairwise comparisons of the companies with respect to each of the functional characteristics and derive priorities using the AHP eigenvector technique. In fact, the first two steps, Customer Driven Value Analysis, and Competitive Value Analysis, can be combined into one simple AHP model to derive relative values for competing company products. This model is shown in Figure 9. The relative importance of what the customers want (size, design, reliability in this example) are derived with pairwise comparisons and the relative value of the competing companies with respect to each of the customer wants also derived with pairwise comparisons. A synthesis of the competing company values over the customer wants is shown in Figure 10.

Figure 9 – AHP Model to Derive Relative Value

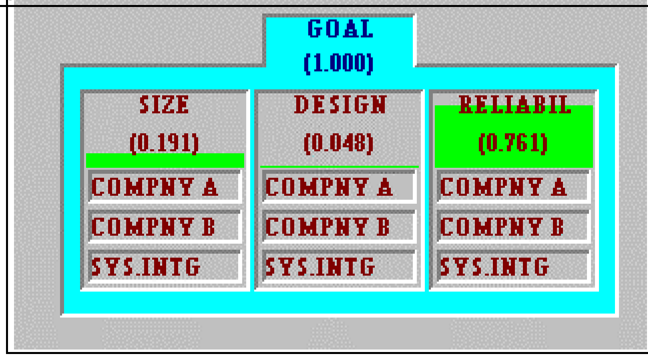
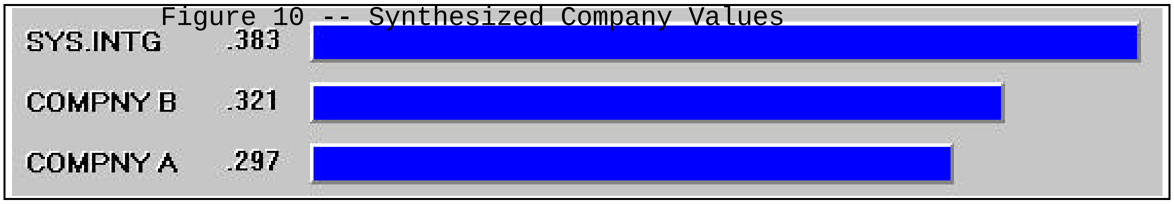


Figure 10 -- Synthesized Company Values

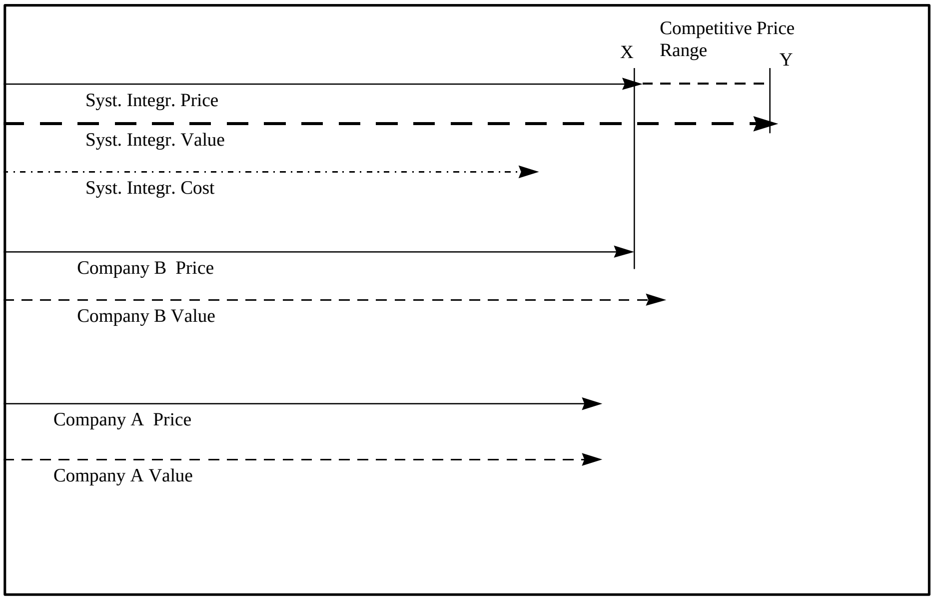


Competitive Value Pricing

Decisions about pricing depend upon a number of considerations. Questions must be answered about how aggressive a company wants to be in gaining market share or maximizing profit. The measurement of competitive value from step 2 allows for a better understanding of the price range available for a decision.

The first step is to assign an arbitrary number to the price of the company offering the lowest value. In our example, we assume that Company A has a basic ratio of value to price of 1 and indicate it by drawing two vectors of the same length in a diagram. Company B offered a price higher than Company A, but the higher price was more than offset by the higher value offered. When pricing for value, the issue is not to compete against the lowest price, but against the best value to price ratio. The System Integrator started by puffing on the diagram a vector indicating the relative value of its products, and a vector equal to its price. The decision about pricing lies between two points. Point X indicates the same price as Company B. This price is acceptable for a very aggressive competitive posture, because System Integrator would offer a much higher value for the same price. Price X would also offer the minimum profit for System Integrator. Price Y assumes that System Integrator will offer the same value/dollar as Company B. It maximizes profit, but it does not offer any specific competitive advantage to System Integrator. The final decision was made for a price at a point between X and Y.

Figure 11 -- Value Pricing



Another way to view the value pricing decision is to set lower and upper bounds as follows. The lower bound, or aggressive pricing is determined either by the cost to produce the product (break-even price), or even lower if the firm is willing to lose money in order to capture market share. The upper bound is found with the following relationship:

$$P \le \frac{V}{\max\left(V_i / P_i\right)}$$ where:

P is the maximum price such that the company's product value to price ratio is at least as large as any of the competitors,
V is the company's product value,
P_i is the price of competitor i's product,
V_i is the value of competitor i's product.

A two way data table and chart are shown below in Table 25 and Figure 12 respectivly.

Table 25 - -

	Syst. Intg.	Company B	Company A				
Value	7.32	5.96	5.38				
Price		120	100				
Value/Price		0.0496667	0.0538				
MaxCompPrice	136.0595						
		Company B's Price					
	136.0595	80	100	120	140	160	180
	80	98.255034	108.84758	108.8476	108.8476	108.8476	108.8476
Company A's	90	98.255034	122.45353	122.4535	122.4535	122.4535	122.4535
Price	100	98.255034	122.81879	136.0595	136.0595	136.0595	136.0595
	110	98.255034	122.81879	147.3826	149.6654	149.6654	149.6654
	120	98.255034	122.81879	147.3826	163.2714	163.2714	163.2714
	130	98.255034	122.81879	147.3826	171.9463	176.8773	176.8773
	140	98.255034	122.81879	147.3826	171.9463	190.4833	190.4833

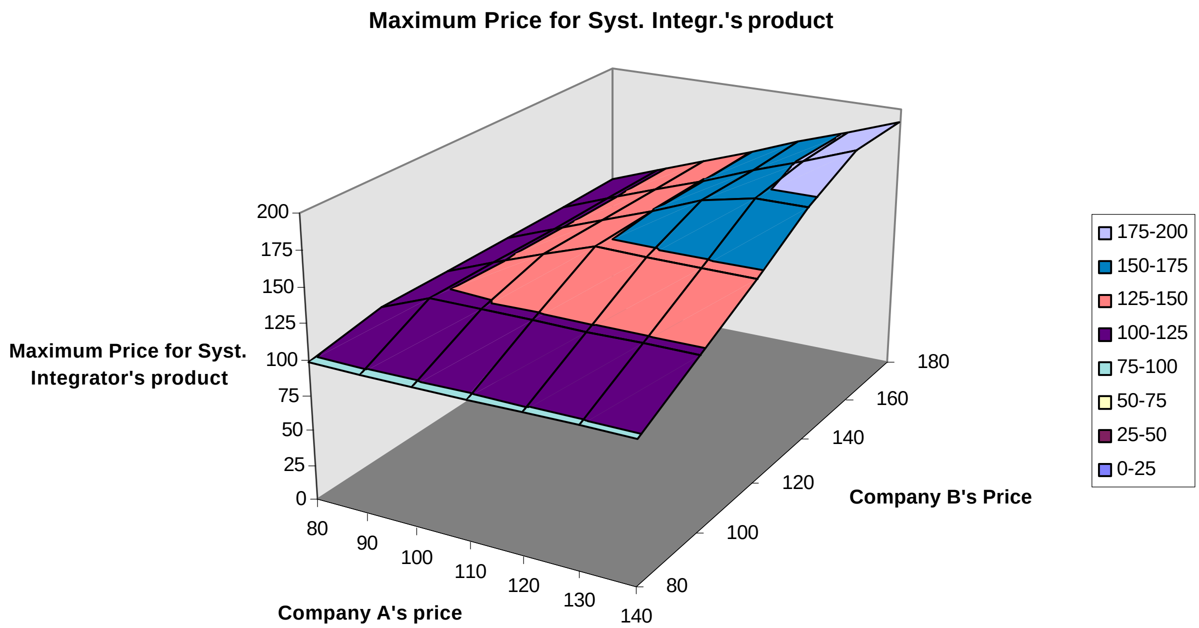


Figure 12- Maximum Product Price vs. Competitors' Prices

Planning for Value

The information obtained through a consistent use of the *Value Based Value Pricing* process can be used to learn which characteristics of products and services give the best value to customers and are more frequently requested. This knowledge can be used for a better allocation of resources and to establish value based cost and pricing strategies.

Stage 6 – Quality loss function: Zero Defects = Imperfect Products

No, the title to this section is not a misprint. But how could zero defects equate to imperfect products? With the traditional approach, specification limits are set and a defect is defined as being outside of the specification limits. By defining a defect as a 0 or a 1, instead of trying to get closer to a target, workers are content if they are within the arbitrarily chosen quality limit. Moreover, this leads to problems when you put several components together. Workers might think that they have zero defects when all parts are within the specification limits, and managers might think losses are low when the factory ships almost all that it builds, but customers are not interested in the factory's record of staying within specification. The customer is only concerned about how the product performs – and prefers a 'robust' product that functions well even when dropped or banged about. According to Taguchi and Clausing:

> From our experience, quality loss – the loss that comes after products are shipped – increases at a geometric rate. It can be roughly quantified as the Quality Loss Function (QLF), based on a simple quadratic formula. Loss increases by the square of the deviation from the target value, $L = D^2C$, where the constant is determined by the cost of the countermeasure that the factor might use to get on target[220].

Instead of striving for zero defects, Taguchi's quality methods strive to build robust products by setting ideal target values for components and then minimizing the average of the square of deviations for combined components. Taguchi and Clausing describe the zero defect problem and its ramifications:[221]

> The problem – and it is widespread – comes when managers of Zero Defects programs make a virtue of this necessity. They grow accustomed to thinking about product quality in terms of acceptable deviation from targets – instead of the consistent effort to hit them. Worse, managers may specify tolerances that are much too wide because they assume it would cost too much for the factory to narrow them. Consider the case of Ford vs. Mazda (then known as Toyo Koygo. … Ford owns about 25% of Mazda and asked the Japanese company to build transmissions for a car it was selling in the United States. Both Ford and Mazda were supposed to build to identical specifications; Ford adopted Zero Defects as its standard. Yet after the cars had been on the road for a while, it became clear that Ford's transmissions were generating far higher warranty costs and many more complaints about noise. Imagine that in some Ford transmissions, many components near the outer limits of specified tolerances – that is, fine by definitions of Zero Defects – were randomly assembled together. Then, many trivial deviations from the target tended to "stack up." An otherwise trivial variation in one part exacerbated a variation in another. Because of deviations, parts interacted with greater friction than they could withstand individually or with greater vibration than customers were prepared to endure. Mazda managers worked on the assumption that robustness begins from meeting exact targets *consistently* – not from always staying within tolerances.

Of course, the Mazda managers' assumptions of meeting exact targets consistently is hardly ever possible in the strict sense of its meaning. However, it is almost always possible to come 'closer' to a target by applying additional resources. Rather than saying how close is close enough, the Taguchi approach centers around a Quality Loss Function that measures the 'loss' due to poor quality is a function of the *distance* from the target. A *distance* measure of closeness is a ratio scale measure – in contrast to the traditional good-defect measure or 0,1 which is an ordinal measure.

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[220] Robust Quality", G. Taguchi and D. Clausing, *Harvard Business Review*, January-February 1990, p65.

[221] Ibid., p 67.

The Quality Loss Function, seen at the top of Figure 13 takes the general form of a quadratic formula – loss increasing as the square of the deviation from the target value – and includes customer dissatisfaction, warranty and service costs; internal inspection, repair, scrap costs, as well as costs to society[222]. Notice the difference between quality measured with the quality loss function (top of Figure 13) compared to traditional conformance-oriented quality measures (bottom of Figure 13).

Figure 13- Quality Loss Function

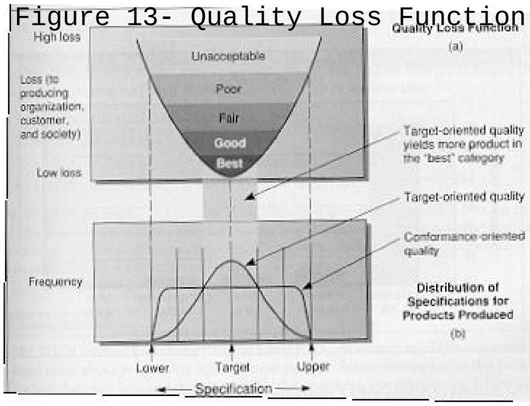

Figure 14 -- Specification limits and 'defects'

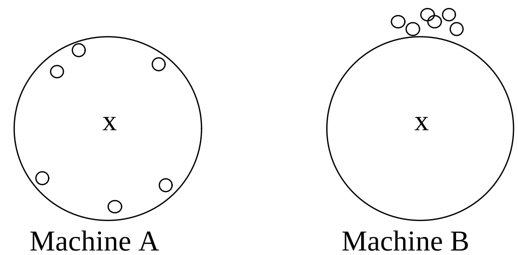

Figure 14 contains another illustration of how setting specification limits[223] can lead to inferior performance. Suppose 'x' marks the target and the circle represents the 'specification limit', outside of which a part is considered to be a 'defect'. We would conclude that there are no defects for machine A, but numerous defects for machine B. Even if no corrective action were taken for parts produced with Machine B (there would be no reason to consider corrective action for Machine A because all parts are with the specification limits), products built with parts from Machine B would function no worse than those produced by Machine A since the distances from the target are about the same.

Even though Machine B is producing all defects while machine A is producing no defects, the Machine B situation is actually preferable to the Machine A situation for two reasons. The first is that by considering only whether or not parts are within specification limits, there is a clear indication for Machine B that corrective action may be warranted, an indication that cannot help but improve the product. The second reason is that there may be a simple x, y corrective action that will move most parts produced with Machine B very close to the target, while such a simple corrective action would not be available for Machine A.

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[222] Jay Heizer and Barry Render, *Production and Opertions Management – Strategic and Tactical Decisions*, 4th Edition, Prentice Hall, p. 89.

[223] Or using aspiration levels or musts in decision problems

If the specification limit had been set a bit further out there would be no corrective action indicated for either Machine B or Machine A. A question that should come to mind is how can we avoid being subjected to the vagaries of an arbitrarily set specification limit? Instead of using specification limits and the (ordinal) defect/no defect approach, we can look at the (ratio scale) distances from the target. The need for corrective action would be evident for both Machines. Furthermore, this need would not be subject to producing different results for slight changes in an arbitrarily set specification limit.

Taguchi's quality loss function approach relies on such 'ratio scale' measures of distance from target. However, 'distance' measures are not always easy to acquire because (1) there are typically a number of factors (or different dimensions) that need to be combined, and (2) some of the factors might be quantitative while others might be qualitative. The Analytic Hierarchy Process provides a way to derive and synthesize ratio scale measures of distance from the target on each of the applicable dimensions of product or service quality– leading to a practice of "continuous improvement." AHP hierarchies can be used to evaluate alternative approaches to producing a product or service during design or re-engineering phases, or to measure the relative outputs of the process during system operation. An outline of the use of AHP in deciding how best to move toward ones' targets is presented next.

Prioritizing Defects and Evaluating Solutions with AHP

Suppose an organization has a mission with several (numerous) specified objectives, some of which were more important than others. Also suppose the organization identifies a set of 'defects' in its processes, defects that hamper the achievement of the mission objectives. (The defects can be thought of as deviations from 'targets' discussed above). Further suppose the organization has identified a set of 'solutions' that can be applied to mitigate defects. How can the organization decide which solutions to implement subject to budgetary constraints?

A rational approach to such a problem requires ratio scale measure of the relative importance of the mission objectives; ratio scale measures of the impacts of the defects on the mission objectives, and ratio scale measures of the mitigating effects of the solutions on each of the defects. AHP can be applied to derive such ratio scale measures, which can then be used in a resource allocation optimization. The process is described next.

A hierarchy of mission objectives, sub-objectives, sub-sub-objectives, is established. Since the defects, d_i i= 1, 2, … n will typically be too large in number to compare in a pairwise fashion, rating intensities can be defined for the lowest level of the hierarchy. The intensities will be used to rate the impact that each defect has on each of the lowest level sub-objectives.

After pairwise comparisons are made to derive ratio scale priorities for the factors in the hierarchy, ratio scale priorities are derived for the defects by rating each defect against the lowest level sub-objectives in the hierarchy. We will refer to the priority of the i^{th} defect as d_i below.

We turn now to the set of possible solutions, s_1, s_2, … s_m each with a cost c_1, c_2, … c_m. Considering each defect in turn, we must determine the fraction of the defect that each applicable solution can mitigate. If 'engineering' judgment is not adequate to estimate this factor, an AHP hierarchy can be constructed to derive ratio scale measures for the importance of the factors that contribute to the defect, as well as ratio scale measures for the relative effectiveness of the solutions in addressing each factor. If a many solutions are applicable, the ratings approach can be used. An 'ideal' solution, one that would mitigate each factor entirely, is included in the set of solutions being evaluated so that the resulting priorities can be normalized – dividing by the priority of the ideal solution – in order to translate the priorities of the solutions to percent mitigating measures. We refer to the mitigating effect of solution j on defect i as $m_{j,i}$ below.

Resource Allocation:

minimize $\sum_{i=1}^{n} d_i * \left(1 - \sum_{j=1}^{m} s_j * m_{j,i}\right)$

subject to:

$$\sum_{j=1}^{m} c_j * s_j \le F$$

$s_j = 0,1$

where:

d_i is the priority of the i^{th} defect

$m_{i,j}$ is the mitigating effect of solution j on defect i

c_j is the cost of solution j

F is the available funds.

When two or more solutions are dependent, they are evaluated as combinations. For example, if there are three solutions available to address a particular deficiency, we can define and evaluate the mitigating effect of each of the 2^3-1 combinations in the set of possible combinations. The combinations, rather than the individual solutions, are considered for implementation in the resource allocation, and a constraint is added to permit no more than one of these combinations to be implemented. There can be many such combination sets.

If *all* solutions were dependent and applicable to every deficiency, a limiting case, there would be 2^n-1 combinations to consider for each deficiency, a daunting task. The optimization would be trivial, as only one of the combinations can be included.

Finally, in the spirit of Taguchi's quality loss function described above, the objective function can be modified to consider the square of the remaining deficiencies, resulting in a non-linear optimization problem.

Stage 5 – Society Oriented – Product and process design optimization for more robust function at lower costs

Quality Function Deployment and The House of Quality

In their article *The House of Quality*[224], John Hauser and Don Clausing describe how marketing and engineers can better talk to each other and, in the process, improve product and process design. The 'house of quality' (see Figure 15) is but one 'house' in a chain of houses that make up Quality Function Deployment (QFD), a management approach that originated in 1972 at Mitsubishi's Kobe shipyard site. QFD consists of planning and communication routines to design, manufacture, and market those goods and services that customers will want to purchase – those they judge to be high *quality*. But what can a large organization actually *do* to manufacture high quality products or services? The doing will involve people from throughout the organization, each performing specific *functions*. Putting these functions into action is called *deployment*. QFD addressed the *deployment* of organizational *functions* in order to produce *quality* products or services[225] The deployment requires communication between people having different functional responsibilities. There can be several transformations of 'inputs' to 'outputs', each performed in a 'house'[226] as depicted in Figure 16 and Table 26.

(HBR May-June 88 pg 72) figure goes here.

Figure 15 -- House of Quality

[224] Hausing, John R., and Clausing, Don, "The House of Quality", *Harvard Business Review*, May-June 1988, p 63-73.

[225] We can add – and that best meets organizational objectives.

[226] The word house is used because the transformation from inputs to outputs can be viewed as a matrix with a 'roof' representing interactions among outputs – the whole of which looks like a house.

Figure 16 -- Linked Houses Convey the Customer's Voice Through to Manufacturing

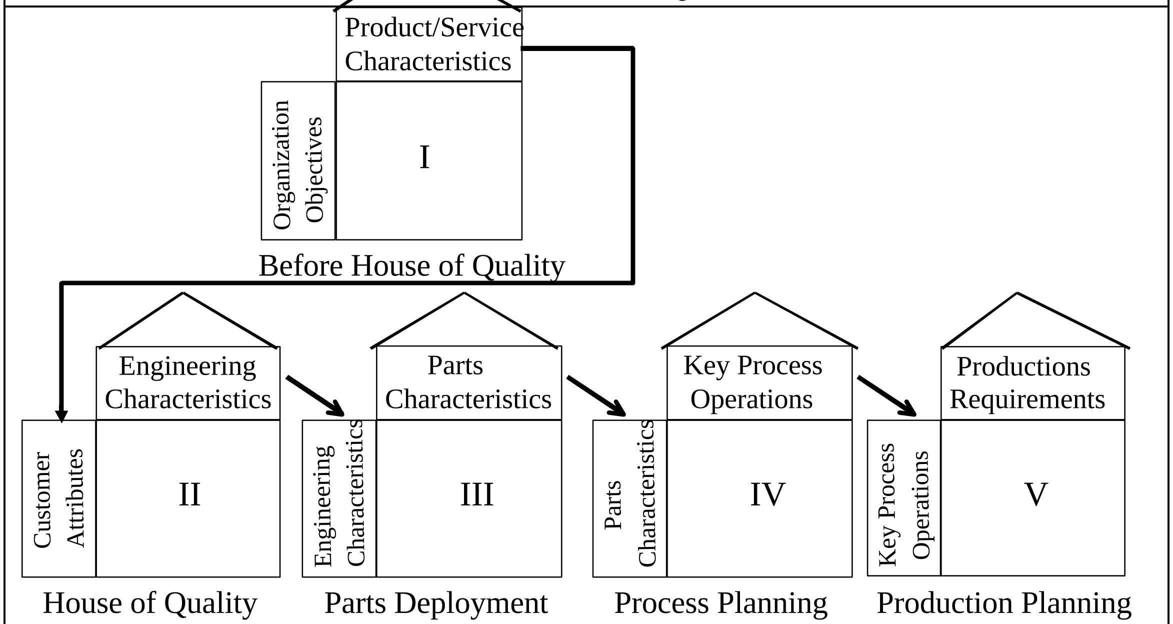


Table 26 -- Linked Houses

Input	**'House'**	**Output**
Organization objectives	Before the house of quality	Product / service characteristics referred to as 'customer attributes'
Customer Attributes	House of quality	Engineering characteristics
Engineering characteristics	Parts deployment	Parts characteristics
Parts characteristics	Process planning	Key process operations
Key process operations	Production planning	Production requirements

An example of the transformation of organization objectives to customer attributes is given on page 301, in a house referred to as 'Before the House of Quality". Corporate objectives are prioritized to determine the relative importance of market segments. These market segment priorities are then used to synthesize the product / service characteristics (referred to as 'customer attributes') of the market segments. The resulting customer attributes are the inputs to the next house, the House of Quality.

David Garvin noted that there are many dimensions to what a consumer means by quality and that it is a major challenge to design products that satisfy all of those at once.[227] Hauser and Clausing wrote:

> "Before the industrial revolution, producers were close to their customers. Marketing, engineering and manufacturing were integrated – in the same individual. Today's fifedoms are mainly inside corporations. Marketing people have their domain, engineers theirs." Usually, managerial functions remain disconnected, producing a costly and demoralizing environment in which product quality and the quality of the production process itself suffer."… "Top executives are learning that the use of interfunctional teams benefits design. But if top management *could* get marketing, designing, and manufacturing executives to sit down together, what should these people talk about? How could they get their meeting off the ground?"[228]

The house of quality is a communication vehicle for marketing and design personnel that translates customer attributes or CA's (what customers say in describing desirable product characteristics) into engineering characteristics (EC's) that specify how the product (or service) can be designed to best meet what the customer means by quality. In other words, the marketing domain tells us what to do, the engineering domain tells us how to do it and the house of quality helps translate from the language of marketing to the language of the engineer.

Customer attributes appearing in the left part of the house of quality, can be grouped into bundles (and sub-bundles) of attributes, not all of which are equally important. Measures of the relative importance of the customer attributes must be obtained. Traditionally, this has been done by assigning values to the customer attributes from some arbitrary scale.. Difficulties in deriving accurate measures with such traditional approaches, particularly when more than just a few factors are involved, were discussed on page 4 and 31. Measures derived with an AHP model will more accurately reflect the judgments of the participants, and will produce ratio measures as well. The AHP model alternatives are the individual customer attributes, clustered into groups and subgroups as necessary. The relative importance of the clusters can be determined by pairwise comparisons with respect to customers in general, or, if desired, with respect to prioritized market segments. (The priorities of the market segments being determined through pairwise comparisons

[227] David A. Gavin, "Competing on the Eight Dimensions of Quality," HBR November-December 1987, p. 101.

[228] Hausing, John R., and Clausing, Don, "The House of Quality", *Harvard Business Review*, May-June 1988, p 64.

with respect to organizational objectives in what Zultner calls before the house of quality (see Table 26, Figure 16, and 'Before the House', on page 301).

Along the top of the house of quality (see also column 1 of Table 26), the interfunctional team lists those engineering characteristics (see also column 3 of Table 26) that affect one or more customer attributes. Designers often have to trade off one benefit against another. This tradeoff involves deriving priorities for the engineering characteristics with respect to the each of the customer attributes. This process, performed by an interfunctional team of marketing and engineering personnel –traditionally involves putting check marks or scores in the body of the house, but can be readily improved with an AHP model. The overall priorities of the engineering characteristics are determined by multiplying priorities of the engineering characteristics by the respective priorities of the customer attributes and then summing over the customer attributes – again part of the AHP process. This transformation of input measures into output measures in the house of quality, as well as in the other 'linked houses' depicted in Table 26 and Figure xx, require that the input measures and measures derived within each 'house' be ratio level measures. Otherwise, the results are mathematical meaningless and may distort the data and judgments used in the process (see discussion beginning on page xxx.) While we can be confident that priorities derived with AHP models are ratio level measures, we have no such confidence with the traditional approaches such as ordinal scales, check marks, or symbols to which arbitrary numbers are assigned[229]. Since there is no reason to believe that these numbers or symbols possess interval or ratio scale properties, the multiplication of these numbers can produce mathematically meaningless results.

The 'roof' matrix of the house of quality helps engineers specify some of the inter-relationships between the engineering features. In general there can be numerous interactions between customer attributes and engineering characteristics. For example, an engineer's change of the gear ratio on a car window may make the window motor smaller, the door lighter, but the window will go up and down more slowly. The Analytic Network Process (ANP) is a powerful tool that has potential in modeling such interactions.

A series of linked 'houses', shown in Figure 16, can convey the customer's voice through to manufacturing. Each house having the 'whats' in the rows and the 'hows' in the columns can be implemented with an AHP model. For example, customer attributes, the rows of the house of quality are used to prioritize engineering attributes, or the columns of the house of quality. Subsequently, the 'hows' from our house of quality become the 'whats' of another house, one mainly concerned with detailed product design. Engineering characteristics like foot-pounds of

[229] Traditional quality function deployment uses numbers such as 1,3, and 9, or symbols to fill in the matrix

closing energy can become the rows in a parts deployment house, while parts characteristics – like hinge properties or the thickness of the weather stripping – become the columns" or the 'hows'. The process can continue to a third and fourth phase as the 'hows' of one stage become the 'whats' of the next. Weather-stripping thickness – a 'how' in the parts house- becomes a 'what' in a process planning house. Important process operations, like 'rpm of the extruder producing the weather stripping' become the 'hows.' In the las phase, production planning, the key process operations, like 'rpm of the extruder," become the 'whats,' and production requirements – knob controls, operating training, maintenance – become the 'hows.' The linked houses implicitly convey the voice of the customer through to manufacturing[230].

Benchmarking

One aspect of a TQM effort that is instrumental in gaining or maintaining a competitive advantage is the comparison or benchmarking of *key business processes* with other best-of-breed companies and organizations[231]. Processes can be defined as key business activities that are needed to run an enterprise. Processes are activities that convert inputs, such as materials, resources, information, etc., into outputs (products and services) for the customer. In order to evaluate and assure that one has the best processes (and decide what improvements are needed), it is necessary to make comparisons with other best-of-breed companies and organizations. Comparisons should be made with the best regardless of industry membership or geography. Finding out what other companies are doing to operate their key business processes, setting the right goals, and achieving these goals, is a key strategy that will help put an enterprise on the road to being *best*.

It is important to thoroughly understand processes that are to be benchmarked before contacting companies with which to make comparisons. Without proper preparation, each member of a benchmarking team would have their own list of priorities to focus on and the utility of the results would be minimal. In order to maximize the return on benchmarking resources and achieve significant results, a consensus has to be developed as to what it means to be "best". This involves the evaluation and synthesis of many factors, both quantitative and qualitative. The AHP methodology was used by the IBM Rochester Minnesota's computer integrated manufacturing (CIM) process team to articulate what needed to be accomplished to be the best. The approach consisted of the following steps:

[230] Hausing, John R., and Clausing, Don, "The House of Quality", *Harvard Business Review*, May-June 1988, p73.
[231] Eyrich, H.G., "Benchmarking to Become the Best of Breed," Manufacturing Systems magazine, April 1991.

1. Develop a hierarchical structure or model of the CIM processes and define relationships.
2. Compare the relative importance of hierarchical factors.
3. Synthesize the comparisons to arrive at overall weights for deciding what requirements are the most important for success.

The CIM hierarchy (see Figure 17) was developed by a team of leading experts at IBM Rochester. The expertise of the team members contributed significantly to the validity of the model. The goal of the hierarchical model (level 0), decided through consensus is *to be the best computer integrated manufacturer--globally*.

The level below the goal (level 1) contains four sub-goals that add substance to the main goal: quality (total quality control), responsiveness (timely customer solutions), flexible (adapting to changing business needs) and cost (product cost). The next level (level 2) contains the critical success factors for achieving the sub-goals: process (business activities needed to run an enterprise), methodology (key manufacturing techniques), integration (system solution for total enterprise), management systems (plans, controls, measurements, resources, support, etc), and technology (CIM architecture & technology). Because more granularity of the critical success factors was needed, the hierarchy was further decomposed by identifying requirements (level 3 of the hierarchy). This gave greater definition of what had to be done to achieve the sub-goals and main goal.

After the hierarchy was established, a team of 10 people were hand selected for their expertise to perform the comparisons. Several people who designed the hierarchy were included on this comparison team in order to insure continuity. Interactive sessions were held in which both subjective and objective information were used to make the comparative judgments. The knowledge and experience of the participants were leveraged through consensus which resulted in the best possible judgments.

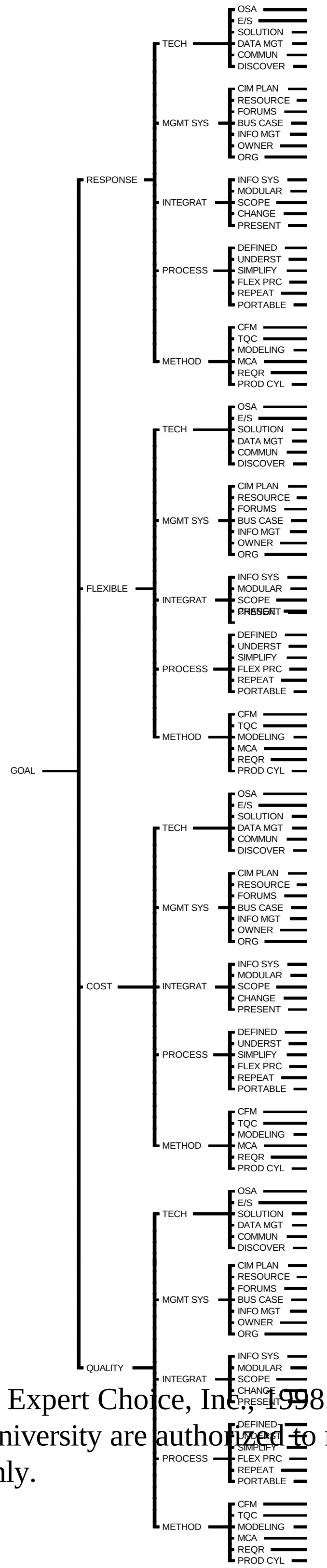
Finally, the relative importance of the *requirements* was evaluated for each critical success factor. Informative discussions took place among the CIM experts in reaching consensus on each of 350 pairwise comparisons. A synthesis of the priorities produced global priorities (priorities with respect to the goal) and is shown in Figure 18. Not only did these results tell us the rank order of requirements, but more significantly, we knew *how much* each would contribute to the goal. For example, the heavily weighted requirement *define*, which means to define business processes and identify owners, has a global priority of 0.099 or approximately 10% of the goal. As a result of structuring, we not only identified requirements, but we decided on what the priorities should be (on a ratio scale) for achieving the goal.

BENCHMARKING EFFORT RESULTS

AHP helped provide structure to the benchmarking effort. It not only helped identify what had to be done to be best, but also helped prioritize (on a ratio scale) the importance of each critical success factor and requirement. Lacking this structure, each benchmarking member would have had their own list of priorities, or no list at all, making the teams much less effective. The AHP hierarchical model articulated what was required to become best. In addition to giving the benchmarking teams focus, AHP also assisted with identifying the best companies to benchmark and with setting benchmarking agendas. Finally the AHP results provided a framework to summarize the benchmarking teams' findings. A maturity index (not discussed here) facilitated comparison with other companies, making gaps clearly visible. Without a maturity index, it would have been difficult to make these comparisons from team notes, especially when comparing multiple companies. The maturity index also helped identify what companies to approach for follow-up visits. The structuring methodology described in this paper complemented the overall benchmarking developed at IBM Rochester, Minnesota. Once these processes were structured, the IBM Rochester model was used in making comparisons with leading companies around the world. The goals set and achieved from the benchmarking process enhanced IBM's ability to be the *best* in mid-range computers and played a significant role in IBM's winning the Malcolm Baldrige National Quality Award in 1990.

Figure 17 -- CIM Hierarchy

To become the best of breed CIM site (globally)



Distributive Mode

Abbreviation	Definition
GOAL	
BUS CASE	Strategic/financial business justification prior to implement
CFM	Continuous Flow Manufacturing & also Short Cycle Mfg techniques
CHANGE	
CIM PLAN	
COMMUN	
COST	
DATA MGT	
DEFINED	
DISCOVER	
E/S	
FLEX PRC	
FLEXIBLE	
FORUMS	
INFO MGT	Is the management of information as an ASSET
INFO SYS	Integrated Info Sys incl data mgmt, common sol's & communication
INTEGRAT	Integration is the sys solution for the total business enterprise
MCA	Manufacturing Competitive Analysis to understand competition
METHOD	Methodologies are key manufacturing techniques
MGMT SYS	Plans, controls, measurements, resources & support
MODELING	Process & data modeling techniques
MODULAR	Pluggable s/w & hdwe components used to build the CIM system
ORG	Organize around processes and a site CIM organization
OSA	Open Systems Architecture or CIM architecture
OWNER	Line management become owners of CIM solutions (vs CIM orgs)
PORTABLE	Processes must be portable to various parts of the enterprise
PRESENT	Presentation is a consistent end user interface
PROCESS	Processes are business activities needed to run an enterprise
PROD CYL	Shorter product cycles impacting manufacturing (eg EMI)
QUALITY	BOB Quality includes QBP, repeatable processes, 0 defects & etc
REPEAT	Repeatable processes are necessary to be BOB in quality
REQR	Requirement gathering process
RESOURCE	Resource utilization is people (skills), capital equip & facility
RESPONSE	Offer customers the solutions they need on a timely basis
SCOPE	Scope is the total enterprise vs just manufacturing
SIMPLIFY	Once a process is understood it is simplified via modeling

To become the best of breed CIM site (globally)

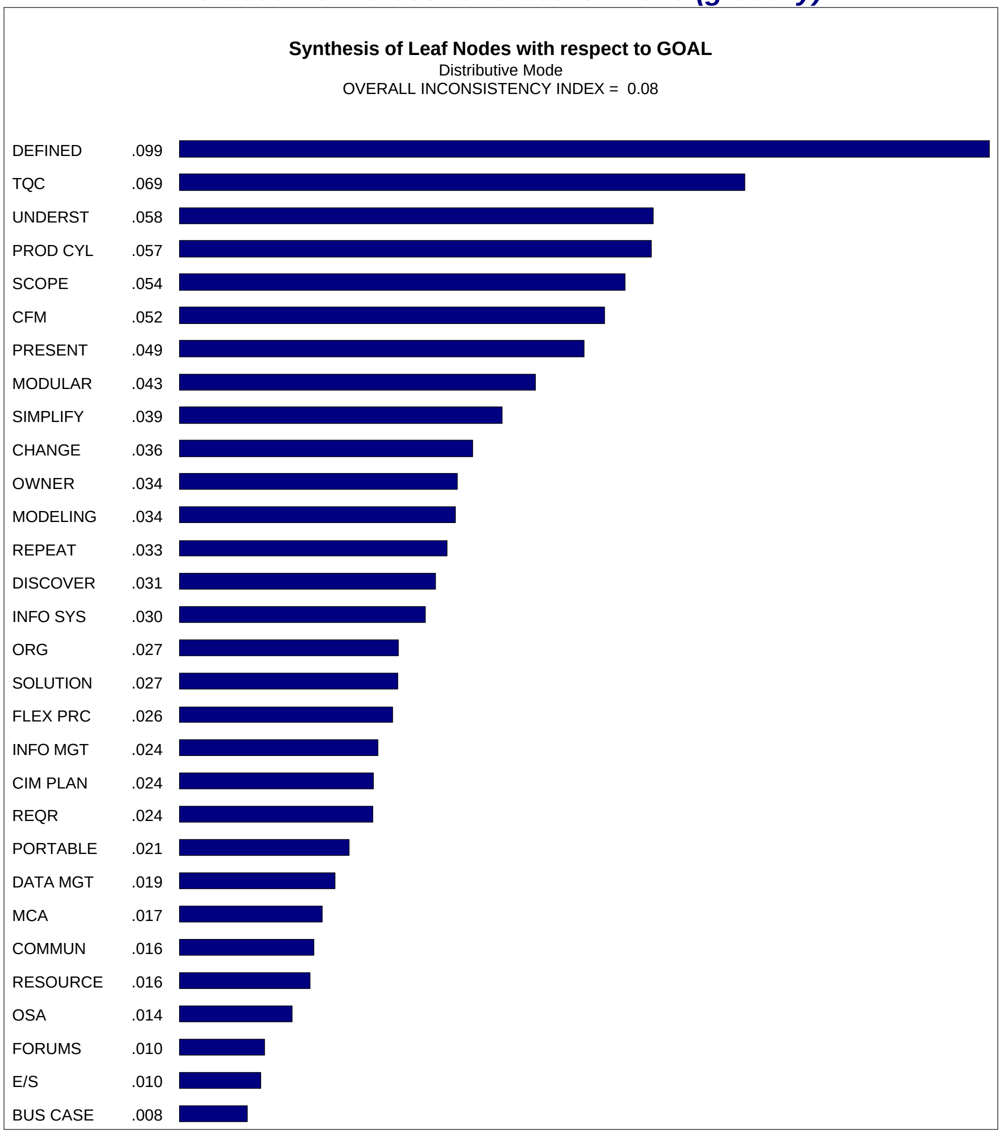


Figure 18 -- Overall Priorities

Stages 4 and 3 Changing the thinking of all employees through education and training

An AHP model of a decision or process must, by its very nature, entail all relevant parts of an organization. Thus, AHP necessitates that employees think about synthesizing what they must do *in conjunction with* what others in the organization must do to produce quality products and services. Just forming quality teams, or quality circles is not enough. The synthesis of data, knowledge, and experience from all parts of an organization is extremely difficult because of the various, often conflicting objectives of different parts of the organization. AHP provides a way to achieve a systems orientation through its structuring, measurement and synthesizing capabilities.

Stage 2 Quality assurance during production

Latrobe Steel Company

Latrobe Steel Company, a subsidiary of The Timken Company, developed a quality system incorporating Expert Choice with a goal of increasing yields during the ingot-to-ground billet stages of processing. The system creates a knowledge tree containing the opinions of the plant's experts regarding what the variables in the process are and how each one affects yields. The most significant variables were then analyzed using regression analysis to determine their effect on yields. The system identified statistically significant variables in the process, their effect on yield, and resulted in spin-off projects that directly affected yield improvement. In addition, the system served as a learning tool, emphasized team effort concepts, provided structure to group discussion, and provided a means for summarizing/storing the information gained from group discussion. The system was credited with saving more than three million dollars.

Cause and Effect or Fishbone diagrams

A cause-and-effect diagram (also known as an Ishikawa diagram or Fishbone chart) is a tool for identifying possible causes of quality problems. In a sense, the Latrobe Steel Company system discussed above is very similar but serves to identified variables to improve yield rather than variables that are causing quality problems. Figure 19 is a fishbone chart for problems in airline customer service. When drawn with the lines on an angle, the shape of the diagram resembles the bones of a fish, hence the name fishbone chart. Each 'bone' represents a possible source of error. Certain 'bones' can have sub-bones. In essence, this is just an AHP diagram. The fishbone diagram in Figure 19 has four main categories applicable to many problems – these four 'M's are: material, machinery/equipment, manpower, and methods. Whereas fishbone diagrams like this are often used only as check lists, an AHP model of a fishbone diagram can be used to elicit expert judgment in order to derive priorities for the possible causes or to allocate resources if there are several causes, each requiring some intervention. Figure 20 is a portion of a fishbone diagram for causes of Midway Airlines flight departure delay. This diagram is more specific than that in Figure 19 and contains an additional level of factors.

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[232] Evans, J. R., *Statistical Process Control for Quality Improvement*, Prentice Hall, Englewood Cliffs, N.J., 1991, p4.

Figure 19 -- Fishbone chart for problems in airline customer service

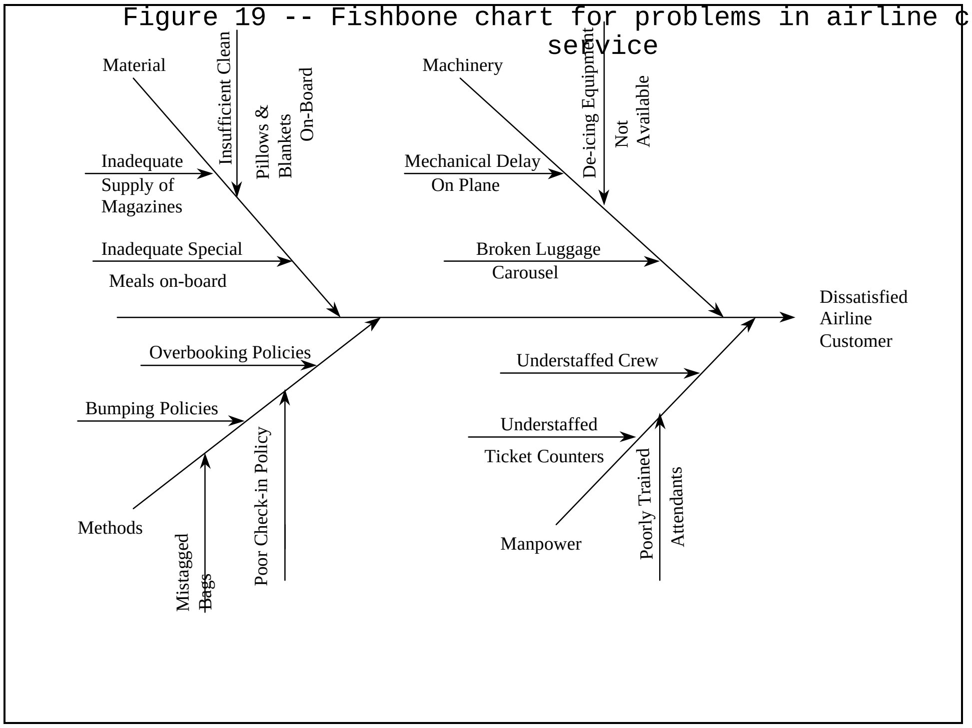

Figure 20 -- Fishbone diagram