Product Design

Techniques in Reverse Engineering and New Product Development

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Dedicated t
love.

To those tha
Laurie; my p
Bob, and Jud
first kindled

should not. Rather, one should identify competitors who are successful in the market, and then the benchmarking activity should focus on determining what it is the competitors do that makes them successful.

The second point one should realize about benchmarking is one that a student might think would go without saying, except that it is usually *the* key problem with benchmarking. Most often a company will complete or pay for an external benchmarking and then do absolutely nothing with the results. They may read the results, but often companies will "explain away" any shortcomings of their products or processes and not make fundamental change. This is especially true when it will involve a major restructuring of company processes. This *consistently* happens, because people are afraid of necessary change.

The point to take away is that benchmarking is one activity in a product development process, and as discussed in Chapter 1, different companies operate in different markets. As all decisions in product development, the decision over the level and frequency of benchmarking requires wisdom and judgment, and the actions that a benchmarking activity indicate are required should not be lightly ignored.

In any case, the establishment of opportunities and specifications for future products is required whether or not benchmarking is done. We next turn to discuss the activity of establishing product performance specifications.

V. SETTING PRODUCT SPECIFICATIONS

Having benchmarked competitive products on customer and technical criteria, one next step is to use this information to set targets for a new product development effort. Since new product specifications are the purpose behind and culmination of the benchmarking process, we discuss it next. The benchmarking process allows us to understand where there are potential openings in the market and so establish what it would take to take advantage of such opportunities. We now begin to establish these new required levels of performance.

We are therefore leaving behind the first phase of product development—*understand the opportunity*—and are moving on to initiate the second phase of product develop: *develop a concept* (Figure 1.6).

Specification Process

Specifications for a new product are quantitative, measurable criteria that the product should be designed to satisfy. They are the measurable goals for the design team. Specifications, like much design information, should be established early and revisited often.

There are two aspects to a specification that need to be clarified. First, the specification is on a dimension that can support units. That is, there are associated dimensions: meters, degrees Fahrenheit, lumens, horsepower, and so forth. A quantity that has units we will also call an *engineering requirement.* In addition to having units, though, a specification needs a target value. This is a number along the dimensional unit that establishes required performance. A target value can be a specific value or a range: 1, 30–42, ≥70, blue, and so on.

Product specifications can occur at many levels at different points in a development process: targets at the preconcept phase are different from refined targets at the embodiment phase. For example, with the coffee mill, knowing or not knowing that one will use a removable chopping chamber in the new concept will obviously make a difference in the appropriateness of a "chamber removal force" specification. Early concept-independent criteria (such as "Opening ease") get refined into performance specifications for a selected concept, which in term get refined into specifications for subsystems, assemblies, parts, features, and so on.

Each specification should be measurable—testable or verifiable—at each stage of the development process, not just at the end of the process when the product is designed and built. In the end, "if it isn't testable and quantifiable, it isn't a specification." The test(s), the means of measuring the performance of the product's system (and subsystems), should always be stated and agreed on up front.

We present here one important milestone of establishing specifications, one that occurs just after a benchmarking activity and just before new concept development. This stage is a point in the development process when overall product specifications should be well considered. Detailed specifications for individual parts and assemblies can wait, but high-level performance targets should be established.

We develop specifications using two approaches, the first from a checklist viewpoint and the second from a viewpoint of the translation of qualitative customer needs. Both are necessary. For the translation of customer needs, we present two methods, a basic approach using the House of Quality and an advanced approach using value analysis. First, however, we will present an important distinction among design specifications, that of functional performance requirements versus overall product constraints.

Functional Requirements Versus Constraints

When developing the engineering requirements for a product development project, the design team must collect enough information from the customers and other sources to produce a specific set of needs. Engineering requirements fall into two categories, *functional requirements* and *constraints*.

Functional requirements are statements of the specific performance of a design, that is, what the device should *do*. Functional requirements should be stated, initially, in the broadest (most generic) terms. They should focus on performance, be stated in terms of logical relationships, and be stated, initially, in "solution neutral" terms.

A clear definition(s) of the function(s) is essential in design. To solve any technical problem, we need to describe in a clear and reproducible way the relationship between each of the available (or specified) inputs and each of the desired (or required) outputs. These relationships between the inputs and the outputs establish the function of the system (Chapter 5). *In this sense, the function is an abstract formulation of the task that is to be accomplished and is independent of any particular solution (physical system) that is employed to achieve the desired result.* Functions are generally stated in terms of physically quantifiable (measurable) effects and in terms of mathematical relationships. Textual (or verbal) descriptions of functions usually consist of a verb and a noun; "increase pressure," "transfer torque," or "reduce speed." Functional requirements should be stated in these terms, followed by appropriate quantification to measure the specification.

Constraints are external factors that, in some way, limit the selection of system or subsystem characteristics. They are not directly related to the function (or functional objective) of the system, but apply across the set of functions for the system. They are generally imposed by factors outside the designers' control. Cost and schedule are constraints. Size, weight, materials properties, and safety issues such as nontoxic, nonflammable materials are constraints. Specifications relative to surface finish and tolerances may or may not be considered constraints (e.g., in the case of a mirror, a particular surface finish would be considered a functional requirement rather than a constraint).

Constraints can drive the solution of many products, especially large-scale systems. Because of this fact, the constraints should be added with particular care, and no constraint should be added frivolously, but only if it really exists. These guidelines lead to the following guideline:

Constraints should be established only after critical evaluation.

In addition to identifying functional requirements and constraints, it is useful to guide the specification generation process with a functional decomposition strategy, as in Chapter 5. That is, each specification can be consider as being met when several more-detailed specifications are simultaneously met. By taking this flow-down approach, specifications will be more directly relevant to particular subsystems and components and so have a greater likelihood of attainment. This will be further developed in Chapter 9 in discussions on product architecture and modularity.

Basic Method: Specification Sheets

Customer needs do not necessarily provide a complete picture for a design task. They provide the foundation to focus design efforts, but there also exist other criteria that are important to a design task that the customer may not even perceive, such as standards, ethics, and manufacturing. Therefore, it is important to supplement and complement consumer needs with engineering requirements. One method to supplement consumer needs is to consider a larger "customer" base, including stakeholders, such as the manufacturers, the assemblers, the marketers, and the distributors, and consider them design customers. This approach tends to obscure and diminish the point-of-view of the person who will be buying the product.

Alternatively, we may apply an approach known as *Specification List Generation* that uses decomposition to guide a search for relevant specifications. This approach focuses on specifications that are latent (the customers do need them, but they do not think to express them), such as safety, regulations, and environmental factors. Designating each specification as a required *demand* or a desirable *wish* will communicate its level of importance.

Consider the checklist in Table 7.2 that is quite useful in identifying specifications, (developed by Franke, 1975). Franke studied a number of specification processes in industry to develop this list. It provides a decomposition strategy for developing specifications, listing categories that aid a comprehensiveness and completeness.

Using the Franke breakdown, a convenient procedure for developing general specifications will now be outlined. This procedure represents a basic approach for specification generation, but it must be augmented with the necessary effort and "perspiration."

TABLE 7.2. CATEGORIES FOR SEARCHING AND DECOMPOSING SPECIFICATIONS (FRANKE, 1975).

Specification category	Description
Geometry	Dimensions, space requirements, . . .
Kinematics	Type and direction of motion, velocity, . . .
Forces	Direction and magnitude, frequency, load imposed by, energy type, efficiency, capacity, conversion, temperature
Material	Properties of final product, flow of materials, design for manufacturing (DFM)
Signals	Input and output, display
Safety	Protection issues
Ergonomics	Comfort issues, human interface issues
Production	Factory limitations, tolerances, wastage
Quality Control	Possibilities for testing
Assembly	Set by DFMA or special regulations or needs
Transport	Packaging needs
Operation	Environmental issues such as noise
Maintenance	Servicing intervals, repair
Costs	Manufacturing costs, materials costs
Schedules	Time constraints

1. Compile specifications. Arrange the functional requirements (FR) and constraints (C) into a clear order. Table 7.3 shows an example specification-sheet template for compiling the specifications. A toy rocket product is shown in the template.
   When compiling the specifications, begin with the functional requirements and then list the constraints. Also, remember that at the preconcept stage, specifications must not be domain or form specific; for example, a specification on "Gear speed" would be inappropriate initially. This guideline on domain specifications only holds true before concepts are developed. Once a preferred concept is selected, the form-independent specifications are expanded into particular form-specific specifications.
2. Determine if each of the functional requirements and constraints is a demand or a wish.
3. Determine if the functional requirements and constraints are logically consistent. Check for obvious conflicts. It is important to make sure that the customer needs (and thus the specifications) can be met and that they are technically and economically feasible. If a system cannot be built to meet the stated specifications or within the stated constraints, the customer should be told immediately.

TABLE 7.3. SPECIFICATION SHEET TEMPLATE, EXAMPLE OF A TOY ROCKET PRODUCT (PARTIAL)

Date	Demand or wish	Project: Toy rocket design specification sheet functional requirements / constraints	Responsibility	Test/Verification
		Functional Requirements		
1/25	D	Provide thrust for maximum height (velocity > 20 m/s)	DT	Bernoulli and Conservation of Momentum Analysis
1/25	D	Maintain stable vertical flight path (less than than 0.25 m deviation from vertical profile)	JR	Flight tests with prototype, design of experiments
...	...	...	...	...
		Constraints		
		Geometric		
1/25	D	Rocket length ≤ 15 cm	WJ	Verify with engr. drawings during concept generation, embodiment, etc.
1/25	W	...	...	...
		Kinematic		
1/25	D	Safe operation ($\leq v_{max}$)	WJ	Verify fluids analysis and prototype testing with impact gauge
...	...	...	..	...
		Safety		
1/26	D	No detachable parts less than 5 cm in diameter (toilet paper roll tube test)	KW	Verify with dimensional check of engineering drawings
...	...	...	..	...

4. Quantify wherever possible. The team may begin with rather qualitative statements, but it is important, in the end, to develop a quantitative statement of the specification—no remaining statements such as "design ease of construction."
5. Determine detailed approaches for ultimately testing and verifying the specifications during the product development process. Examples of tests and verifications include engineering analyses; tests of scaled, full-size, partial, or complete prototypes; checks of engineering drawings; failure modes analyses; or user tests with an appropriate sample size.
6. Circulate specifications for comment and/or amendment. It is helpful to circulate the specifications for comment to all members of the design team, customers, interested colleagues, management, and others.
7. Evaluate comments and amendments. When comments are returned, examine objections and suggested amendments. Resolve the objections and, if necessary, incorporate the amendments in the specifications. It is critical that all specifications be clearly stated and fully justified. If specifications are too restrictive, we may

TABLE 7.4. EXAMPLE: LOUDSPEAKER DESIGN, QUALITATIVE SPECIFICATIONS VS. QUANTITATIVE

Specification type	Specifications	Quantification
Qualitative:		
	Functional:	
	Broad dynamic range	
	Broad frequency range	
	Very linear	
	Constraints:	
	Use standard box shape	
...	...	
Quantitative:		...
	Functional:	
	Dynamic range	0–100 dB at 1.75 m
	Frequency range	20–20,000 Hz within ± 1 dB
	THD (Total Harmonic Distortion)	less than 0.01%
...	...	...
	Constraints:	
	Geometry	no larger than $X \times Y \times Z$ (m)
...	...	...

miss a better solution. If specifications are not restrictive enough, the goals of a project may not be met. Table 7.4 depicts both quantitative and qualitative specifications for a loudspeaker design before different concepts are developed.

Basic Method: The House of Quality

At this point, from previous work, the design team should understand the customer needs, expressed in their voice. They should also understand the current product (if it exists) and how it satisfies these needs. We now need to determine the priorities for design to achieve the design goals and make the product better. To accomplish this task, we must

- find the weakly satisfied customer needs
- their dependencies or interrelationships
- determine what product changes we can effect to improve these weak points.

This process will define the level of modeling required, both in function and in product components.

Quality function deployment (QFD) is a methodology for defining the customer's desires in the customer's own voice, prioritizing these desires, translating them into engineering requirements (quantified specifications), and establishing targets for meeting the requirements. It also embodies a tool for defining the "right" problem to solve *(scoping)*, where a series of matrices are used to structure information acquisition and documentation. Each matrix is called a House of Quality (Hauser and Clausing, 1988).

QFD was developed in 1972 at Mitsubishi's Kobe shipyard and basically introduced into the United States by the Xerox Corporation after they had learned of it from their Japanese partner Fuji Xerox (Clausing, 1994). It has been adopted in a number of industries, including the automotive and electronics.

Overview

In product design, the ability to frame the problem is important to success, to ask the right question at the right time of the right person. QFD is a process intended to aid the design team in asking the right questions, at the right time, and of the right people. It is a development team consensus-building activity, to get agreement among the team on how the product should perform. It supports and documents the benchmarking and customer-need-analysis processes, and its intent is to improve the quality of products in the broadest sense. It means much more than avoiding repairs for consumers. It means learning from customer experience and reconciling what customers want with what engineers can reasonably build. It means aligning different disciplinary subsystem boundary specifications to establish a working whole product.

Before the industrial revolution, products were simple and the producers were close to their customers, they dealt with them and their needs on a one-on-one basis, and thus they had a better sense of their needs. With disciplinary specialization, there has been an increasing degree of separation between producers and consumers. Many of those most responsible for detailed disciplinary design decisions have "lost touch" with customer needs. QFD is a tool that can be used to reestablish this connection.

To establishing the link to the customer, QFD, and in particular the House of Quality, is used to first establish engineering requirements that can be used as measurable surrogates for the more-qualitative customer needs. QFD is also used to make clear the relationships between customer needs and engineering requirements, document benchmarking data (both quantitative and qualitative), form specifications by establishing target values on each engineering requirement, check for conflicts in engineering requirements, and finally record expected technical difficulty. These purposes establish our intended use for the House of Quality. The House of Quality forms a clear summary statement of

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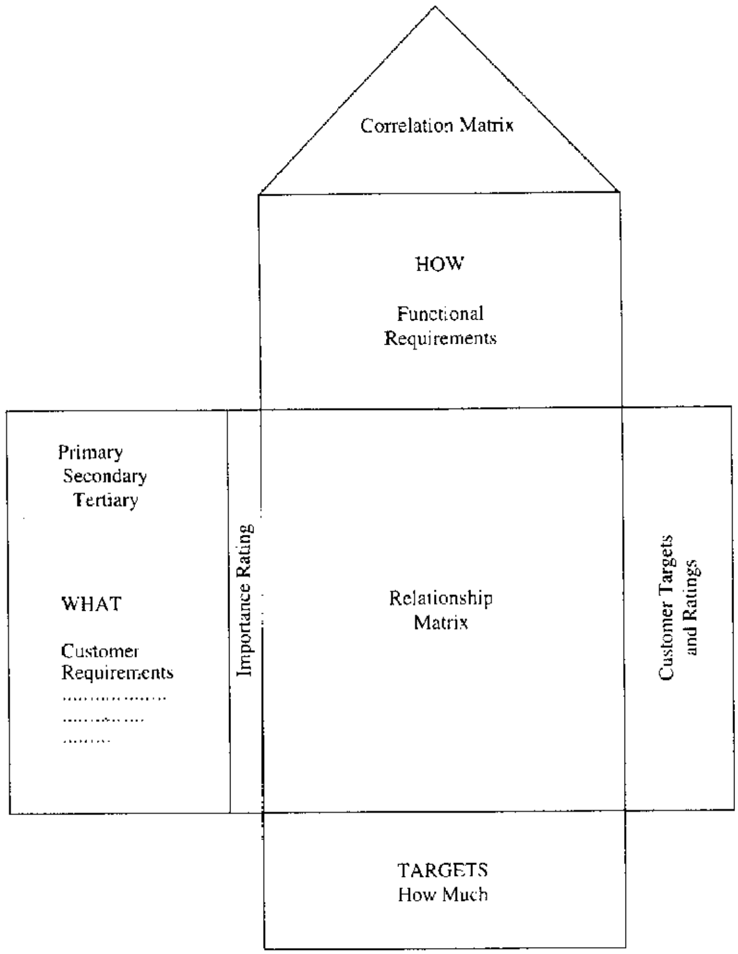
the product specifications and supporting data consisting of benchmarks, target values, and technical difficulty.

Filling in the Matrix

Figure 7.12 illustrates a template for a House of Quality. The procedure for documenting information in this template is as follows:

1. Identify the customer(s) (both internal and external).
   - Consumers, production (manufacturing), regulators, marketing/distribution/sales



▼ ***Figure 7.12.***
Template for the House of Quality.

2. Determine the customer needs (or WHATs). Customer requirements are the "WHAT IS TO BE DONE" definition of a project. These customer needs may be documented based on the results of Chapter 4.
   - The "what's" can be listed in primary, secondary, and tertiary sequence.
   - List needs in the customer's own voice ("easy," "fast," "lightweight," . . .)
3. Determine the relative importance or priority of the customer needs (scale of 1–5 or 1–10). Importance levels should be determined following the methods in Chapter 4.
4. Translate customer needs into measurable engineering requirements (or HOWs). Determine how the product can be changed in performance to better meet customer needs. The customer domain tells us *what* to do, the engineering domain tells us *how* to do it, at least in terms of measurements. For any customer need, there may be multiple engineering requirements that can be expressed in quantifiable terms. One should document:
   - each *how* in terms of a label and specification value
   - the direction for improvement for each *how*, using a + or − or arrows
5. Determine relationship of engineering design requirements to customer needs. Indicate the relationship and the strength of the relationship between the engineering requirements and the customer needs.

Indicator	Meaning	Strength
⊙	Indicates a strong relationship or much importance	9
○	Indicates some relationship or some importance	5
△	Indicates a small relationship or importance	3
Blank	Indicates no relationship	0

   If there are no strong engineering requirements for a given customer need, there is a problem. Possible engineering requirement responses for the customer need should be reconsidered.

6. Perform or execute competitive benchmarking. Here the objective is to determine how the customer perceives the competition's ability to meet each of their needs. Use a simple device to capture customer input, such as a compressed scale such as 1–5, with 1 representing not satisfied and 5 fully satisfied, comparing the benchmark's design attributes with the list of customer needs. This step represents a qualitative benchmarking exercise, capturing the "feelings" of the customer.

7. Rank the technical difficulty of each engineering requirement. Again a pair-wise comparison can be used to determine ranking. The technical difficulty of achieving each customer need in terms of the changes defined by the engineering requirement should also be defined, again using a scale of 1–5 or 1–10.

8. Correlate technical relationships to determine interrelationships of design requirements. This step entails completing the "roof" of the House of Quality. Technical characteristics may be competing rather than complementary. These relationships must be defined and resolved.

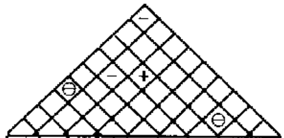
Indicator	Meaning
⊕	Indicates high positive correlation
+	Indicates positive correlation
–	Indicates negative correlation
	Indicates high negative correlation

9. Set engineering requirement targets (specifications) for the product design. One can do this by comparing the requirement measurements of each of the benchmarking products and positioning the new product among these specifications.
   Fundamentally, one must consider two factors when setting a target: the cost and the benefit of achieving a value. One might gain some from a very low coffee mill noise specification, but it may be prohibitively costly. One must weigh these qualitatively in the basic House of Quality approach. More quantitative means are discussed in the next section of value analysis.
   Setting targets early in the design process is advantageous. Specific values work best for targets. Relatively narrow ranges of values are next best, but if a range is used, be wary of allowing the least satisfactory end of the range to be adopted as a *de facto* target, especially when such an approach is adopted for every range.

10. Select areas for improvement. Similar in spirit to the proposal for redesign above, here we can use analysis of the QFD matrix to define final design targets and to identify areas that need further concentrated effort. To make these decisions, the importance rating of the customer needs must be considered in conjunction with the qualitative benchmarking. This analysis leads to the choice of the most critical engineering requirements through the relationship matrix. The HOWs, technical difficulty, correlation matrix, target values, and quantitative benchmarks should be used to guide further development and product improvements.

Product Example: Automatic Iced Tea Brewer

Figure 7.13 shows a partial House of Quality for an automatic iced tea brewer product. The primary customer needs are listed as the rows of the matrix, ranging from "stronger tea" to "adequately contain steam." These customer needs are converted to measurable engineering spec-



	Relative Importance	Temperature of water in steeping basket	Time water is in contact with tea	Volume of water in tank	Temperature of exiting hot tea	Time needed to add tea	Time to clean product	Total Volume	Largest size of brew	Hottest temperature outside container	Mr. Coffee Iced Tea Maker	West Bend Coffee Maker	Old Fashion Way	Powdered Tea	West Bend Iced Tea Maker
		↑	↑	↓	↓	↓	↓	↓	↑	↓					
Stronger tea	9	●	●								4	1	5	5	1
Easy to add ice	5			●	●						3	2	2	2	3
Easy to add tea	5					●					3	3	2	2	3
Easy to clean	3						●	○			3	3	2	4	3
Easy to store	3							●	○		4	3	5	5	3
Brew larger amount	2			●					●		3	2	4	4	3
Contain steam	2	△								●	4	4	2	5	[illegible]
Technical Difficulty		3	4	1	3	3	2	3	3	2					
Measurement Units		C	m-m	cup	C	sec	sec	ft^3	qt	C					
Object target values		98	8.0	3	44	0	30	0.2	3	?					
Objective Measures: West Bend		98	<<	4.75	88	5	20	0.4	2	100					
Objective Measures: Mr. Coffee		?	8	4.75	?	1	20	0.2	2	?					
Objective Measures: WB Coffee Maker		98	na	0	?	5	20	0.4	1.5	?					
Objective Measures: Old Fashion Way		99	5	na	hot	5	240	na	na	100					
Objective Measures: Powdered Tea		na	na	na	25	5	60	na	na	25					
Technical Importance: Absolute		83	81	63	45	45	27	36	27	18					
Technical Importance: Relative		1	2	3	4	4	6	5	6	8					

▼ ***Figure 7.13.***
Automatic iced tea maker House of Quality (partial).

ifications in the columns of the matrix. In this case, the metrics for stronger tea (not a 1:1 mapping of a customer need to a metric) are temperature of the water and the time that tea is in contact with the water. The metric for easy-to-add ice is the volume of the water in the tank, since this volume, at a high temperature, will define the quantity of ice needed. The greater the volume, the more ice that will be needed. Metrics are listed for the remaining customer needs.

For each of the metrics, units are listed below the customer needs as a row. Arrows are included above the metrics to show the goal of the metric, minimize, maximize, or a target value. In the case of volume of water in the brewer tank, we wish to minimize it, because more hot water will require more ice to cool it. As long as the requisite tea flavor is infused, additional cooler water may be added to the brewed tea to obtain the desired quantity of iced tea.

The matrix cells correlate the customer needs (rows) to the metrics (columns). This correlation is not necessarily 1:1, but is typically 1:many, that is, there will exist more than one metric, on average, for each customer need. The correlation cells are filled with a strong, weak, or no relationship. In the case of the tea brewer, stronger tea, for example, is related strongly to its two metrics, with no (or minimal) correlation to the other metrics.

The roof of the House of Quality, located above the metrics, shows the relationships between the performance metrics. A strong positive relationship indicates that as one metric is significantly improved, the other improves significantly as well (and vice versa). A negative relationship, on the other hand, represents a conflict. If one metric improves, the other will deteriorate. Such conflicts must always be carefully analyzed and monitored. In the case of the tea brewer, the total volume has a strong negative relationship to the largest amount to brew. A large storage container is desired to brew large quantities of tea; however, a small total volume of the brewer is also desired for stowage purposes. These metrics strongly conflict; yet, by separating the storage container from the brewer (separation in time and space), stowage problems are reduced, decreasing the importance of "easy to store." Overall, both of these metrics must be analyzed together to understand the tradeoffs in the conflict.

Qualitative and quantitative benchmark values are also shown on the House of Quality. These values help to understand the market position of a product. They also provide a logical means of setting target values for product evolution. In the case of the tea brewer, ideal goals are given by the benchmark comparisons to the powered tea brewing and old-fashioned method of tea brewing. These goals provide a normalization when comparing products. The tea brewer QFD also shows a comparison of two tea brewers currently on the market. If our product is the West Bend brewer, we need to set aggressive goals in stronger tea containing steam and stowage space to compete in the equivalent value market. Target values of the West Bend show goals for meeting or surpassing the competition.

Finally, the House of Quality shows the relative and absolute ranking of the product metrics, as listed at the bottom of the figure. For the tea brewer, product development should focus on the first three or five metrics to satisfy the voice of the customer. These choices depend on the resources (time and money) available and the technical difficulty expected for improving a metric (as shown in the matrix). The tea brewer shows that the volume of water in the tank is relatively easier to address technically compared to the other high-ranked metrics. This metric should thus be addressed first, in conjunction with temperature of the water due to the strong negative relationship.

In sum, the House of Quality provides a large quantity of information in a very concise and well-organized form. A logical progression through this information leads to the setting of priorities, allocation of resources, and the development of real engineering specifications (metrics) for a product. It also establishes, at a basic level, the current market status of a product and the desired target values for surpassing the competition.

Comments on House of Quality

A number of hints exist for effectively using the House of Quality. For example, one should not let the matrix grow too large; one should keep it under 50 rows and columns. If it gets too large, it becomes unwieldy. To keep it simple, one should operate at different levels in the product.

For example, considering the benchmarking of automobile product, one can develop vehicle-wide specifications with a vehicle-wide House of Quality. Entries might include overall dimensions and weight (measurable) and "ease of unlocking" (not measurable). These specifications can then be flowed down to door-level specifications and a separate House of Quality completed at the door level. Here the "ease of unlocking" specification might flow into a measurable key-turning torque specification. Similarly, the "ease of unlocking" might flow down differently into a different measurable specification on the electronics subsystems House of Quality, where a keyless remote specification might be established for distance that the remote operates. Putting both of these and their counterparts in one large detailed vehicle House of Quality is unreasonable. Separate House of Quality's can be developed along the functional decomposition of the product. This approach will be further developed in Chapter 9 in discussions on product architecture and modularity.

Another hint is to use the function structure to help establish the specifications. Every subfunction has flows in and out. Differences between these flows are readily measurable and so are candidates for specifications. Chapter 6 details an approach for relating product functions to engineering requirements (metrics).

Finally, it should be kept in mind that the intent of the House of Quality is consensus building. It is a tool to ensure that the variety of specifications, typically representing a variety of different disciplines and development subgroups, all converge to a successful product. The matrix does not generate specifications; it documents them.

Advanced Method: Value Analysis

In the approaches discussed so far, target values are established by design team judgement. Basically, for any engineering requirement, a target value is determined by simultaneously judging the cost of attaining that target and the customer desire in delivering that target.

A more quantitative approach is to create models of these two factors. For each specification value, one might create a model of customer preference over the possible target. This model can be developed by using customer questionnaires ("How much more would you pay for twice as much performance") or through conjoint analysis studies, both discussed in Chapter 4.

Similarly, one could estimate the cost of delivering different levels of performance, based on estimation of components required and their cost of manufacture. With these two models of customer desire D and cost to produce C, both measured in dollars, one can determine the foremost target value to use.

We can define *value* or *worth* as the difference in the desire of the customer from the cost of producing it:

$$V = D - C, \tag{7.1}$$

and then we can pick a target value that maximizes this quantity. Other forms include

$$V = \frac{D}{C}, \tag{7.2}$$

a normalized form that can be less sensitive to model errors, such as if all of the cost estimates are made using the same cost analysis tool and are off by the same factor. A normalized form also need not have the desire and the costs expressed in identical units.

This analysis can be completed in detail. For example, the cost function can be expressed over the subassemblies and down to the components of a product. The desired function can be expressed as an overall func-