A MULTI-ATTRIBUTE APPROACH TO CONCEPTUAL SYSTEM DESIGN DECISIONS BASED ON QUALITY FUNCTION DEPLOYMENT (QFD) AND THE ANALYTIC HIERARCHY PROCESS (AHP)

by

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(ABSTRACT)

This research integrates a multi-attribute decision-support tool, the Analytic Hierarchy Process (AHP), with a customer-focused design methodology, Quality Function Deployment (QFD). The result is a hybrid methodology more complete than either of the two alone, involving synthesis, analysis, and evaluation activities necessary for completing conceptual system design.

An indicator was developed for the overall performance of an organization's product and its competitors' products using the information in a QFD matrix. In addition, a methodology was developed to determine if essential customer requirements and design dependent parameters (DDPs) have been adequately identified in the QFD matrix. A mathematical relationship was developed which relates technical and competitive assessments in the QFD matrix and helps test for inconsistencies. Finally, an indicator was developed to assess a new product concept for viability in the marketplace and to be used for accomplishing trade-off analyses. Examples are presented throughout this document to further illustrate the concepts.

This research is unique in its application. It adds to the body of knowledge for decision-making in the conceptual design phase of the systems engineering process.

ACKNOWLEDGMENTS

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Ideas for this thesis research originated through the implementation and completion of the Loral/Virginia Tech project. Accordingly, I would like to express my gratitude to the following members of the Loral team: Messrs. Alan Fitz, Ralph Giffin, David VanBuskirk, and Rowland Webb.

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I would like to express special thanks to my parents and my friends, Raj, Rich, and John for their support. Finally, I would like to thank my wonderful wife, Wendy, for being so patient, understanding, and supportive.

DEDICATED TO:

PHORN AND SAMANTHA POWERS
(My Parents)

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CHAPTER 1

INTRODUCTION

The purpose of Chapter 1 is to introduce this research. After summarizing the problem setting, the problem statement will be discussed along with the research objectives. Then, the research approach will be presented. Finally, the significance of this research is discussed, followed by a summary of the organization of this thesis.

1.1. PROBLEM SETTING

Facing increasing international competition, organizations today are constantly searching for a means of attaining a competitive advantage in the marketplace. One such means being used to realize economic competitiveness is the system life-cycle approach. That is, organizations can become more competitive by extending engineering through all phases of the life cycle of a system: design and development, production or construction, operational use and support, and phaseout and disposal [Blanchard & Fabrycky, 1990].

1.1.1. The Systems Engineering Process

The system life-cycle approach is an element of the systems engineering process. This approach not only includes the life-cycle consideration of the product itself, but also includes the life-cycle considerations for the manufacturing process and also support of the product as depicted in Figure 1.1 [Blanchard & Fabrycky, 1990].

The system life-cycle approach begins with the identification of a need for the product. This need for the product becomes the driving force during the conceptual and preliminary design phases to satisfy this need. At this point, consideration should be concurrently given to product production, initiating the beginning of the production life cycle. That is, design should include the manufacturability of the product in parallel. Also during conceptual design, a third life cycle is simultaneously initiated for the logistic support activities needed to service the product while it is being used [Blanchard & Fabrycky, 1990]. Thus, the concept of concurrent engineering (i.e., "*a viable approach in which the simultaneous design of a product and all of its related processes in a manufacturing system are taken into consideration, ensuring a required matching of a product's structural with functional requirements and the associated manufacturing implications*" [Parsaei & Sullivan, 1993]) is included within the system life-cycle approach.

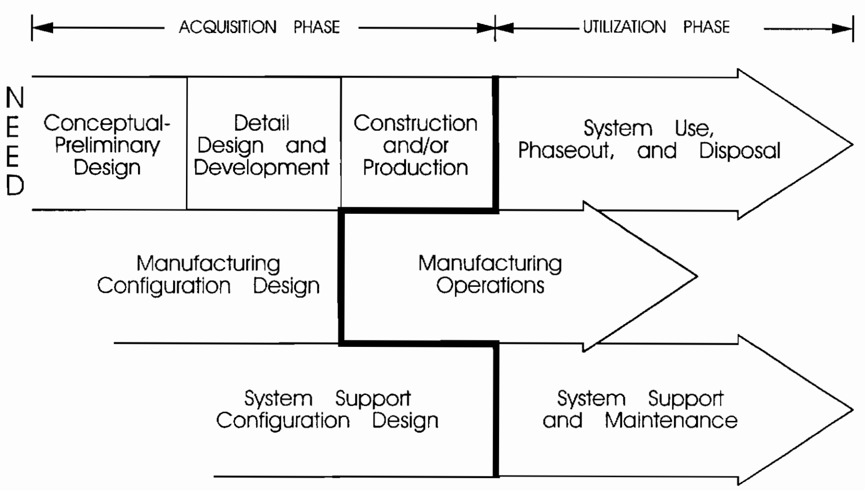

Figure 1.1. Product, process, and support life cycles [Blanchard & Fabrycky, 1990].

As shown in Figure 1.2, approximately two-thirds of the life-cycle cost is committed by the end of the conceptual and preliminary design phases, even though actual expenditures amount to much less [Fabrycky, 1992]. Thus, it is especially important to practice concurrent engineering during the conceptual and preliminary design phases of the system life cycle. For example, suppose a manufacturing organization did not practice concurrent engineering and decided during the conceptual and preliminary design phases that the best rod diameter for their product was 0.255 inches. The organization would have to pay much more to machine rods of diameter 0.255 inches than to purchase standard-sized rods of 0.250 inches. In addition, if the organization realized their mistake and decided to change the entire design around the standard rod, it could cost the organization much capital due to its commitment to the old design. Thus, if the manufacturing organization had practiced concurrent engineering in the beginning and designed manufacturability into the product, it would have designed the product around the standard part, possibly saving the organization capital over the system life cycle.

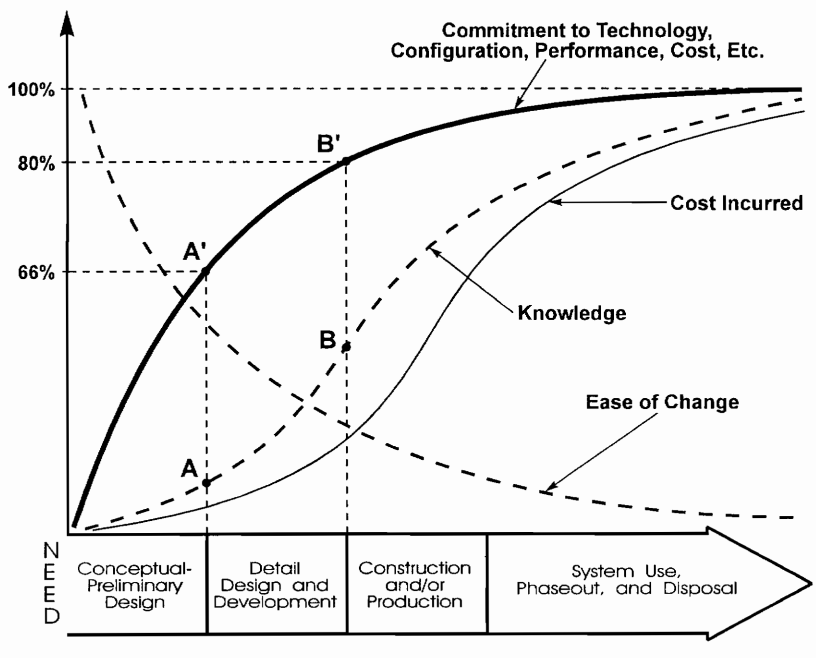

Figure 1.2. Commitment, cost incurred, knowledge, and ease of change [Fabrycky, 1992].

Also note in Figure 1.2 that during the earlier phases of design for a particular project there is a larger "gap" (i.e., design uncertainty) between commitment and knowledge than in the later phases of design, as shown by the distance between A and A' compared to B and B'. This design uncertainty or risk may be reduced by dedicating more design, testing, prototyping, etc. resources during the earlier phases of design [Fabrycky & Blanchard, 1991].

A structured and disciplined systems engineering process is key to the effective and efficient design and development of products and/or processes which are both competitive in the global economy and responsive to customer needs. Blanchard and Fabrycky [1990] have developed a structured systems engineering process, as depicted in Figure 1.3, in which systems engineering is defined as the application of efforts to:

1. *transform an operational need into description of system performance parameters and a preferred system configuration through the use of an iterative process of functional analysis, synthesis, optimization, definition, design, test, and evaluation;*

2. *incorporate related technical parameters and assure compatibility of all physical, functional, and program interfaces in a manner that optimizes the total system definition and design; and*

3. *integrate performance, producibility, reliability, maintainability, supportability, and other specialties into the overall engineering effort* [Blanchard and Fabrycky, 1990].

The systems engineering process (Figure 1.3) begins with the identification of a need or deficiency. This need is then translated into system-level requirements through the requirements definition activity (i.e., translating the need into a specific set of qualitative and quantitative customer and design requirements). Then, the requirements definition activity is followed by the conceptual design phase (involving the synthesis, analysis, and evaluation of system-level conceptual solutions) and the preliminary design phase

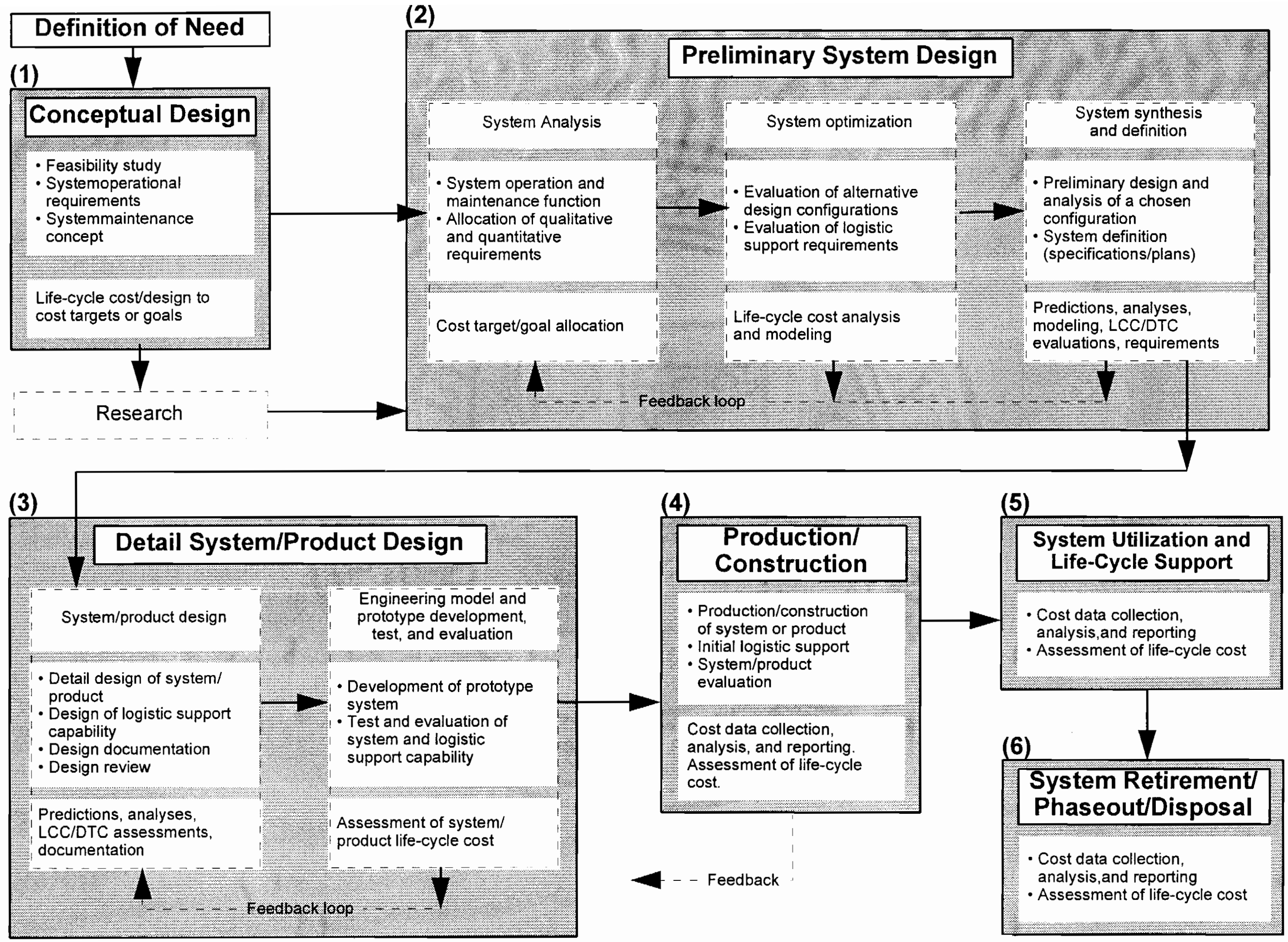

Figure 1.3. The systems engineering process [Blanchard and Fabrycky, 1990].

(involving the modeling of expected system behavior and the translation of system-level requirements into more detailed design specifications). The resulting detailed design specifications are then utilized during the detailed design and development phase, which leads to the production and/or construction of the product or structure. The manufactured or constructed product/structure is then deployed, installed, operated, and maintained. Finally, at the end of its economic life, the product or structure is either redesigned to satisfy an evolving need, or retired and recycled.

According to Verma [1994], "*any system design and development activity involves the three general tasks of synthesis, analysis, and evaluation.*" Figure 1.4 depicts the synthesis, analysis, and evaluation (SAE) cycle. Synthesis is the process of gathering a set of conceptual solutions which may potentially satisfy an identified need. Analysis is the process of reducing the conceptual solutions to a set of feasible solutions. Finally, evaluation is the process of selecting the "best" or preferred approach based on meeting the stated needs, objectives, and specifications. When the evaluation task is complete, the SAE cycle starts over to meet continuously evolving needs.

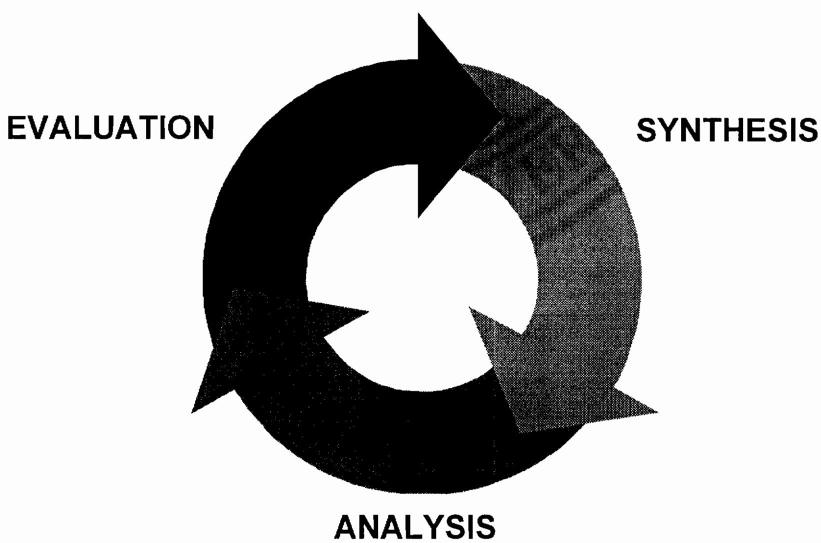

Figure 1.4. The synthesis, analysis, and evaluation (SAE) cycle.

1.1.2. Conceptual System Design

Conceptual system design, which is the first step in the systems engineering process, consists of several essential activities: needs analysis and requirements definition, synthesis of conceptual system designs, analysis of conceptual system designs, and evaluation of conceptual system designs [Verma, 1994]. Figure 1.5 depicts the conceptual system design process. Note that the SAE cycle is integrated into the conceptual system design process.

Conceptual system design begins with the identification of a need, based on a want or desire. After a need for a product is established, the need is translated into a set of customer and design requirements. Subsequent to the requirements definition activity, various conceptual design solutions are gathered that potentially satisfy the customer and design requirements (i.e., synthesis). Once the potential conceptual solutions have been gathered, they are analyzed for feasibility. Feasibility is analyzed in terms of physical realizability, functional compatibility, economic worthiness, and financial/budgetary constraints [Verma, 1994]. Then, the feasible conceptual solutions are evaluated to determine the most desirable concept(s) for further development. Upon completion of the evaluation activity, the system specifications are developed before entering the preliminary system design process [Blanchard & Fabrycky, 1990].

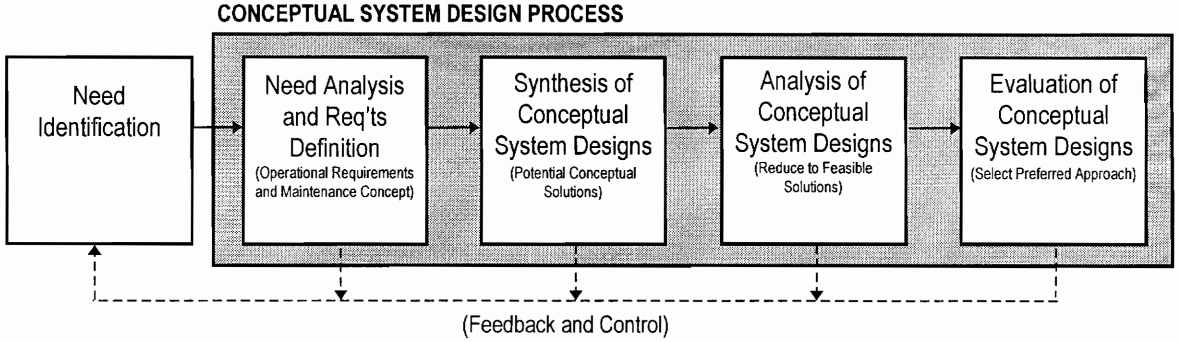

Figure 1.5. The conceptual system design process [Adapted from Verma, 1994].

As described in Section 1.1.1, activities in the conceptual system design phase are most critical because of their impact of downstream activities of the system life cycle. There are many tools that engineers can use to facilitate the conceptual design phase. For example, benchmarking, customer surveys, information from the sales force, customer complaints, questionnaires, and focus groups may be used to identify a need. Idea generation can be accomplished through brainstorming-like activities. Input-Output matrices, checklists, and Quality Function Deployment (QFD) can be used to perform feasibility studies and help translate needs into system-level requirements. Additionally, multi-attribute decision support tools such as utility theory and the Analytic Hierarchy Process (AHP) may be used to evaluate conceptual solutions. QFD and AHP will be discussed throughout the remainder of this thesis.

1.1.3. Introduction to Quality Function Deployment (QFD)

Quality Function Deployment (QFD) is a methodology which originated in Japan. It provides a means of translating customer requirements (expressed in their own terms) into technical requirements for each stage of product development and production. QFD is especially useful during the conceptual design phase since it accelerates the product development process and drives customer-focused products (i.e., facilitates bringing new products to the market faster than the competition with lower cost and improved quality). In addition to better customer satisfaction and increased design quality, QFD forces increased communication between functional areas within an organization, facilitates increased understanding of the customer, and provides corporate memory (i.e., one page of documentation that explains the project and the thinking that went into it) [Burrows, 1991; Lockamy & Khurana, 1995; Kinni, 1993; King, 1987].

To further illustrate the effectiveness of QFD, Figure 1.6 shows how a Japanese company that successfully implemented QFD made most of their design changes about a year and a half before production (i.e., focused their efforts during conceptual design), very few just before production, and none after the first production run. Conversely, the

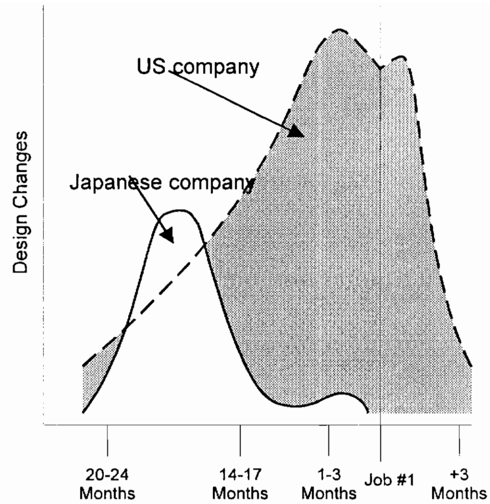

Figure 1.6. Comparison of a Japanese company with QFD and a US company without QFD [Sullivan, 1986].

US company that did not use QFD (and did not focus their efforts during conceptual design) made most of their changes 1 to 3 months before production and continued to make design changes after the first production run began. As illustrated in Figure 1.2 and explained in Section 1.1.1, the Japanese company cut costs over the system life cycle by using QFD and focusing their efforts during conceptual design. In addition, Toyota Auto Body reduced its start-up and pre-production costs by 61% over a seven year period by effectively implementing QFD, as shown in Figure 1.7. QFD has been so effective and provides such a competitive advantage that many companies refuse to discuss it [Rosenthal, 1992; Vasilash, 1989].

QFD can be used for both the design of static and dynamic products. Static products incorporate design improvements in which the basic concept remains unchanged. Conversely, dynamic products incorporate design changes in which radical changes are made in the basic concept [Hollins & Pugh, 1990]. This thesis specifically focuses on the use of the QFD methodology during the design of static products. The QFD methodology will be discussed in more detail in Chapters 2 and 3.

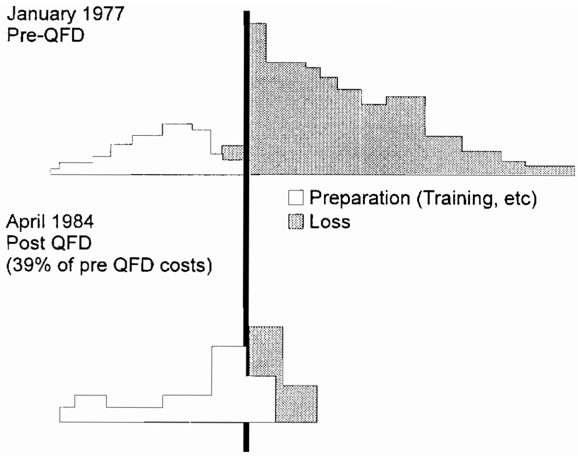

Figure 1.7. Startup and pre-production costs at Toyota Auto Body before and after QFD [Sullivan, 1986].

1.2. PROBLEM STATEMENT

Quality Function Deployment's success is highly dependent on identifying the customer's wants or needs, their importance ratings of the needs, and their competitive assessments (i.e., benchmarking) [Sullivan, 1986; Armacost et al, 1994]. Thus, it is vital that the customer's needs are well reflected in order to accurately translate customer specified requirements into design dependent parameters. Failure to properly identify customer needs while using QFD may allow differences between customer desires and engineering efforts to propagate throughout the system design and development process. This may result in the development of systems which fall short of satisfying the customer. Therefore, an indicator must be developed to assess whether or not the most important customer requirements have been adequately reflected [Nichols, 1994]. Once the most important customer requirements are identified, another indicator must be developed to assess that the design team has identified the best set of DDPs [Nichols, 1994; Sullivan, 1986].

While using QFD, the customer competitive assessment offers a way to indicate how well the organization's product compares with their competitor's products for each customer requirement. However, there is currently no means of using QFD to compare the organization's product with its competitor's products holistically (i.e., which product do the customers think is the best overall?).

Chilakapati [1995] discusses various means of addressing inconsistencies in the QFD matrix. In addition, Sullivan [1986] notes that the customer's competitive assessments may be compared with technical competitive assessments to determine areas of inconsistency between what the customers say and the technical evaluations. However, there is currently no mathematical relationship between the two types of assessments to help identify inconsistencies during the use of QFD.

Aswad [1989] found that inconsistency in quantifying the customer's judgment (i.e., the importance ratings of their needs) was a weakness in using QFD. The Analytic Hierarchy Process (AHP) has been successfully used to prioritize customer requirements in a consistent manor [Aswad, 1989; Armacost et al, 1994]. However, possible extensions still remain for interfacing AHP with QFD. For example, since QFD currently has a synthesis and an analysis component, but does not have an evaluation component, AHP may be utilized to mitigate this discrepancy.

Finally, the design community currently does not have indicators to predict how well a new product concept will do in the market, other than building a prototype and showing it to potential customers. This may be expensive and time consuming when evaluating several design concepts simultaneously.

1.3. RESEARCH GOAL AND OBJECTIVES

The main goal of this research is to make a contribution to the development of Quality Function Deployment (QFD) by interfacing it with a multi-attribute decision-support tool: the Analytic Hierarchy Process (AHP). Thus, the hybrid methodology would encompass the synthesis, analysis, and evaluation (SAE) components, which are necessary for completing conceptual system design. Specific objectives of this research include:

1. To develop a means to more precisely measure the overall performance of a organization's product and its competitors' products using QFD.
2. To develop a means to assess if the most important customer requirements have been adequately incorporated (i.e., how well does the QFD model represent the customer's true requirements?).
3. To develop a mathematical relationship between customer and technical competitive assessments through the relationship matrix and using this mathematical relationship to determine areas of inconsistency in the QFD matrix.
4. To develop an indicator to assess how well a new product would perform in the marketplace, thus facilitating trade-off analyses.
5. To establish a baseline for the future development of this avenue of study.

1.4. RESEARCH APPROACH

The research objectives stated in Section 1.3 will be achieved through interfacing the Analytic Hierarchy Process (AHP) with Quality Function Deployment (QFD). Specific activities which constitute the research approach are:

1. Apply the AHP to prioritize customer requirements in QFD.
2. Apply the AHP with the customer competitive assessments to indicate the overall performance of a product against its competitors.
3. Compare the AHP overall performance results with the customer's overall performance ratings and modify the customer requirements as necessary.
4. Use the relationship matrix to translate the prioritized customer requirements to prioritized design dependent parameters using the relationship matrix.
5. Apply the AHP with the technical competitive assessments to indicate the overall performance of a product against its competitors.

6. Compare the overall performance of the product from the technical competitive assessment with the overall performance of the product from the customer competitive assessment (using the AHP) and modify the relationship matrix and/or design dependent parameters as necessary.
7. Develop a mathematical relationship between the customer and technical competitive assessments through the relationship matrix using a weighted sum technique.
8. Compare the customer and technical competitive assessments using the mathematical relationship and modify the relationship matrix and/or design dependent parameters as necessary.
9. Use the mathematical relationship to translate the technical competitive assessments of a newly designed product to the customer competitive assessments and apply the AHP to assess overall performance.
10. Perform trade-off analyses as necessary to improve design of product.
11. Construct hypothetical example to demonstrate approach.
12. Discuss applicability of the approach and suggest enhancements.

1.5. RESEARCH SIGNIFICANCE

Although the AHP has been previously applied to QFD by prioritizing customer requirements, it has not been utilized as an integral part of the QFD process, (e.g., determining the overall performance of a product and its competitor's products using the customer competitive assessment, assessing the completeness of the customer requirements, determining the overall performance of a product and its competitors using the technical competitive assessment, assessing the completeness of the design dependent parameters and the relationship matrix, and developing an indicator to assess how well a newly designed product will perform in the marketplace).

By integrating AHP with QFD, the resulting hybrid should be more complete than either of the methodologies alone. Having a more complete QFD model ensures that the most important customer requirements are included in the model, that the design dependent parameters properly address these customer requirements, and that the relationship matrix is consistent. Thus, there should be more certainty that the resulting product will satisfy the customer's needs. Accordingly, this hybrid methodology can give an organization even more of a competitive advantage than they currently have with the traditional QFD process alone.

1.6. THESIS ORGANIZATION

This thesis is organized into five chapters with one supporting appendix. The general background for this research and problem domain is presented in Chapter 1, along with the research objectives, the significance of this research, and the research approach.

Given the research emphasis on Quality Function Deployment (QFD), Chapter 2 is devoted to explaining the fundamental steps of QFD, including its weaknesses and opportunities for enhancements. Thereafter, Chapter 3 will discuss the rationale for integrating AHP with QFD. In addition, Chapter 3 will discuss how to apply the AHP to determine the overall performance of a product against its competitors when using QFD and, in addition, how to use that information to ensure that the most important customer requirements have been gathered.

Chapter 4 will develop a mathematical relationship between the customer's competitive assessment and the technical competitive assessment. In addition, Chapter 4 will use the relationship as an indicator for the success of a new product concept in the marketplace. An illustration of the methodology will be integrated with the discussions in Chapters 3 and 4.

Finally, the results and conclusions of this research will be presented in Chapter 5, including potential extensions for future research. In addition, the overall thesis is supported by an appendix which presents a brief overview of the AHP.

CHAPTER 2

QUALITY FUNCTION DEPLOYMENT

Quality Function Deployment (QFD) is a total quality management methodology that provides a means of translating customer requirements into appropriate design requirements for each stage of product development, production, and support [Sullivan, 1986]. Thus, QFD ensures that the customer assumes a central role during the early phases of design.

QFD synthesizes diverse data from numerous sources. This synthesis promotes a logical and objective perspective through minimizing subjective judgment, leading to the identification of critical issues and effective design decision-making [Guinta & Praizler, 1993].

QFD originated in 1972 at Mitsubishi's Kobe shipyard site in Japan to help build supertankers and is currently still being developed, both in terms of methodology and in terms of application. Today, QFD has been successfully adopted by numerous manufacturing and service organizations.

Traditionally, QFD has been applied to support manufacturing within the automotive, construction, and electronics industries. As more organizations learn of QFD's success, additional advantages and applications of the QFD process are revealed. Organizations in the computer, chemical, pharmaceutical, personal care products, health care, consumer products, food and beverage, aerospace, defense, education, utility, telecommunications, and building industries have used QFD with success [Mazur, 1993].

Specifically, Hales [1993] has discussed application of QFD as part of the concurrent product and process development projects. In addition, AT&T has used QFD to check and refine translation of customer needs into system requirements while developing a software system for customers to reconfigure their own networks [Thompson & Fallah, 1989]. AT&T has also used QFD for specifying the characteristics of transmission systems and guiding the definition of batteries [Brown, 1991]. Conversely, Puritan-Bennett has used QFD to design medical equipment to regain their market share [Hauser, 1993; Kathawala & Motwani, 1994]. Several food manufacturers have used QFD to create new additive flavors for foods [Duxbury, 1991].

QFD has also been used for environmental decision making and environmental design [Berglund, 1993; Hochman & O'Connell, 1993]. In addition, QFD has been used to develop affordable industrialized housing [Armacost et al, 1994]. Burgar [1994] has applied QFD to course design in higher education using employers as potential customers and translating the required job skills into course topics and teaching techniques. In addition, QFD has been used to used to formulate long-range strategic marketing plans and evaluate strategic marketing policies [Lu, Madu, Kuei, & Winokur, 1994; Lu & Kuei, 1995]. QFD has also been applied to policy formulation and management procedures [Philips, Sander, & Govers, 1994].

An interesting application of QFD is in the design of market research questionnaires [Glushkovsky, 1995]. QFD is used to identify relationships between the questionnaire's stated objectives and the questions being asked. Once the relationships are complete, an analysis is performed to ensure the questions are consistent with and cover the objectives of the questionnaire. After the QFD process is finished, the questionnaire is pilot tested [Glushkovsky, 1995].

The matrices commonly used with the QFD process resemble houses, thus they are often referred to as "houses." As shown in Figure 2.1, there are four major phases (or houses) in the QFD process: product planning, parts deployment, process planning, and production planning. These four houses are linked together to convey the voice of the customer through to manufacturing. The first house, popularly known as the "House of Quality" (HOQ), translates customer requirements into measurable product characteristics, hereafter called design dependent parameters (DDPs). In the second house, during parts development, the DDPs are translated into parts characteristics. The parts characteristics are then translated into key process operations in the third house, which are later translated into production requirements in the fourth house [Houser & Clausing, 1988]. This document will focus primarily on the House of Quality within QFD, although many of the concepts are also applicable to the other houses, since the matrices are nearly identical.

The fundamental steps in the QFD process for the House of Quality are shown in Figure 2.2 and discussed in the remainder of this chapter. Upon determining the objective statement, QFD is implemented by filling in the "rooms" of the House of Quality. Although there are many different versions of the House of Quality (some with a "roof" and more rooms), the matrix in Figure 2.3, hereafter called the QFD matrix, will serve as this document's framework for the representation and analysis of information involved in the implementation of the QFD process.

2.1. DETERMINING AN OBJECTIVE STATEMENT

QFD begins with the objective statement, which is a description of the problem, goal, or objective of the team effort, usually in the form of a question. The purpose of the objective is to keep the design team focused on specific customer requirements.

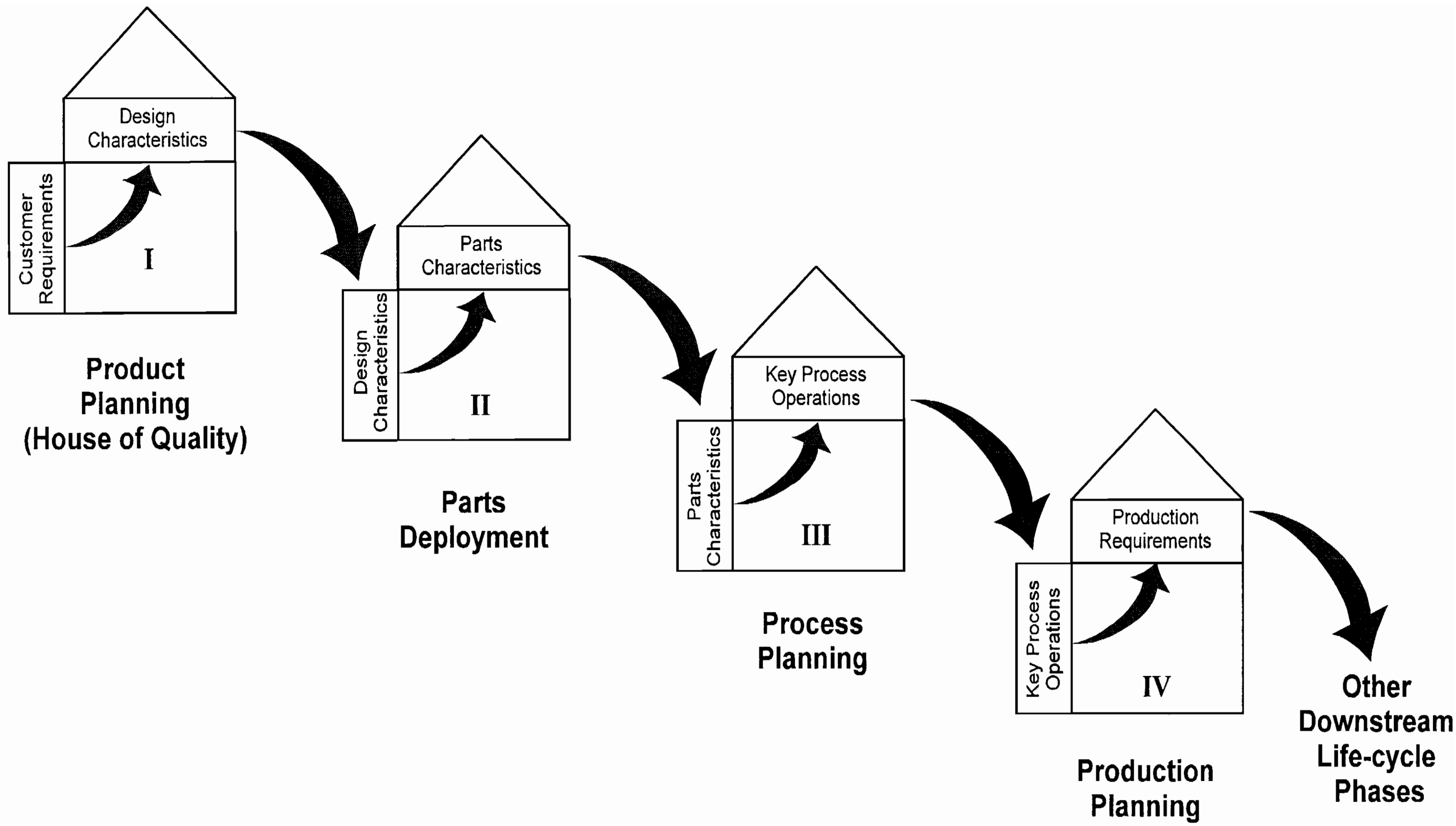

Figure 2.1. The Quality Function Deployment (QFD) process.

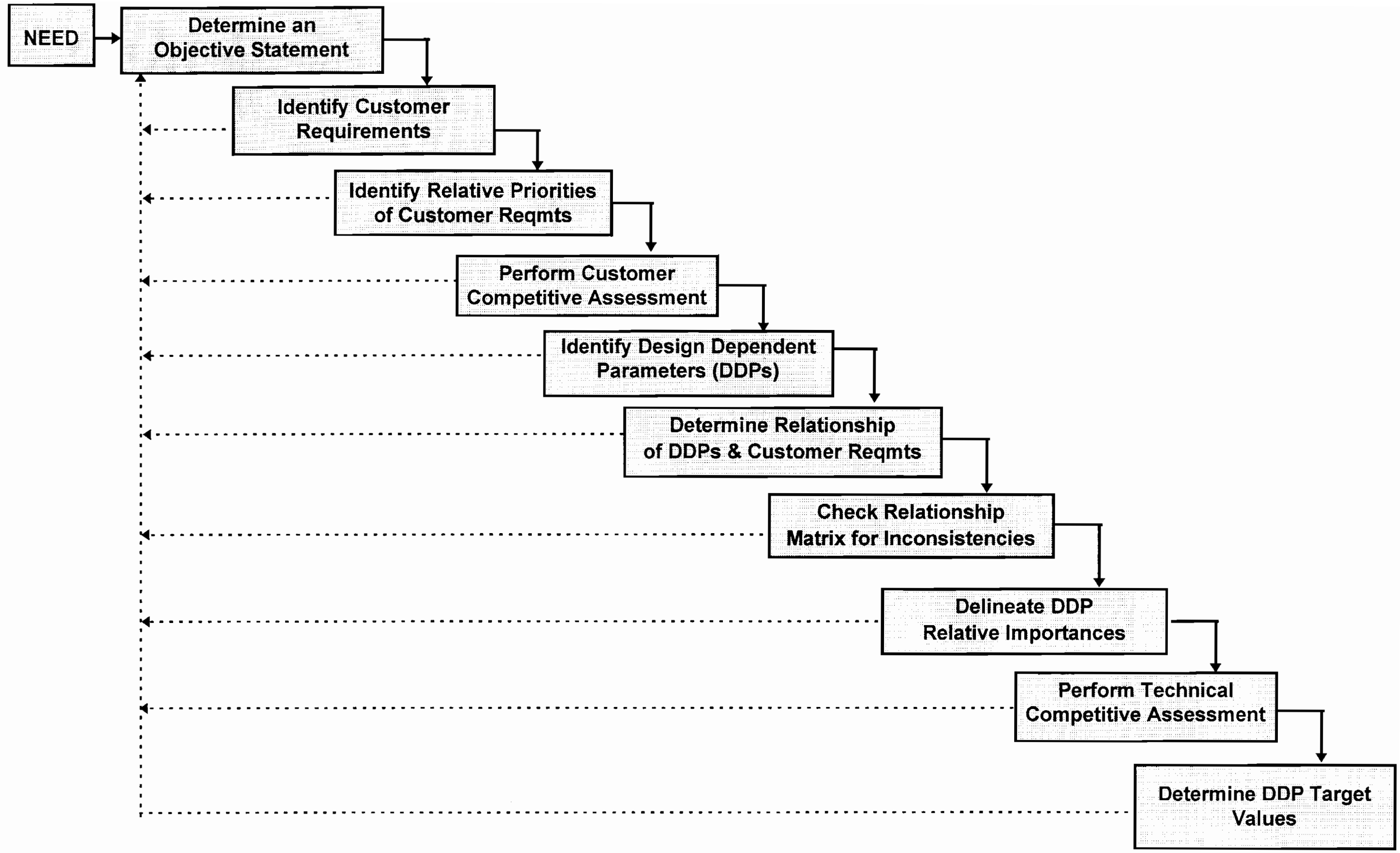

Figure 2.2. The fundamental steps for the house of quality.

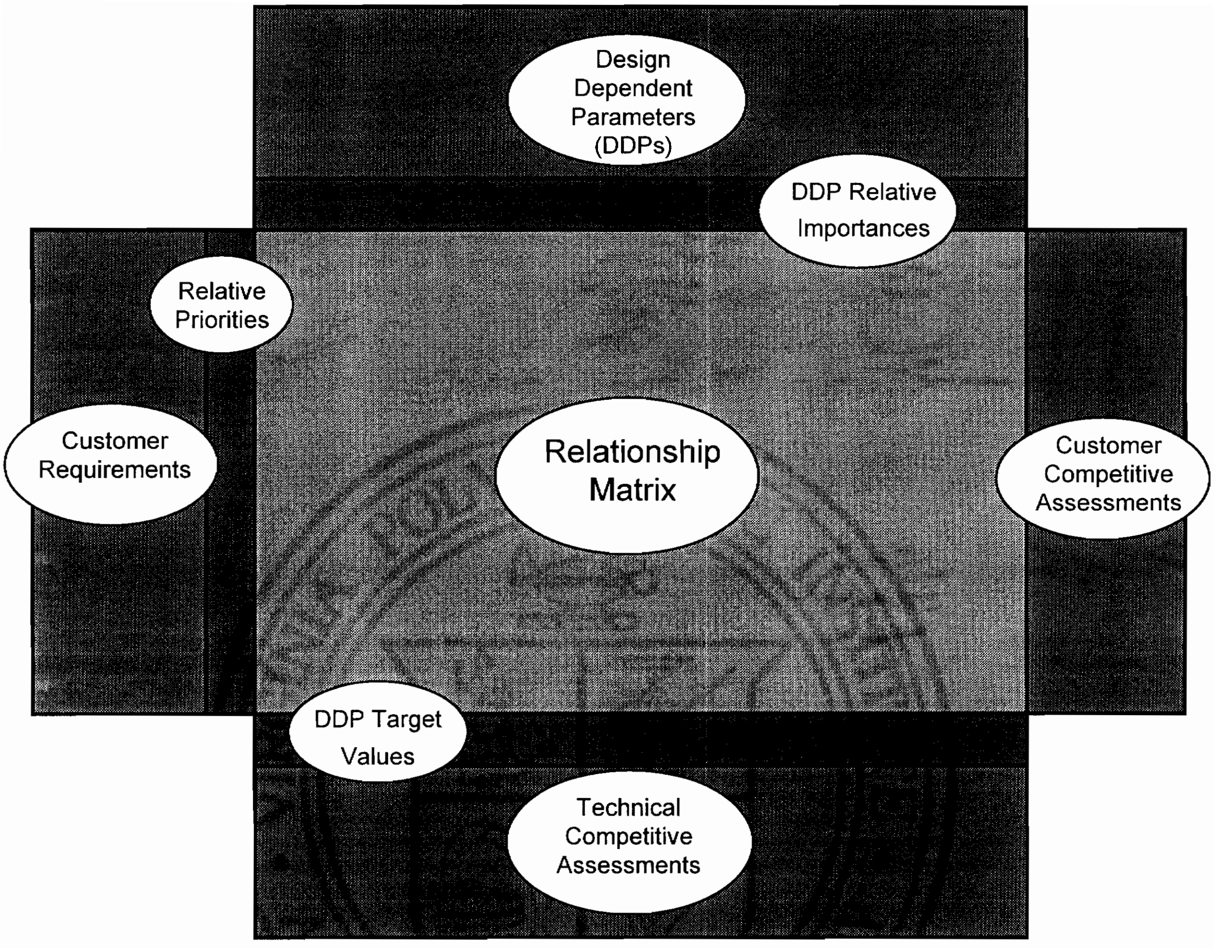

Figure 2.3. The QFD matrix or "house of quality".

It is important that the objective be derived from a need or deficiency and that it is specific to the qualities that need to be identified. For example, if an organization were to build a new line of off-road bicycles, a specific objective statement would be “What are the important qualities of a mountain bicycle?”

Once the objective statement is developed, the process of completing the QFD matrix begins. Figure 2.4 illustrates a completed QFD matrix. Although this matrix may appear complicated upon first glance, the remainder of this chapter will explain in detail what each aspect of the matrix represents and how the data is collected.

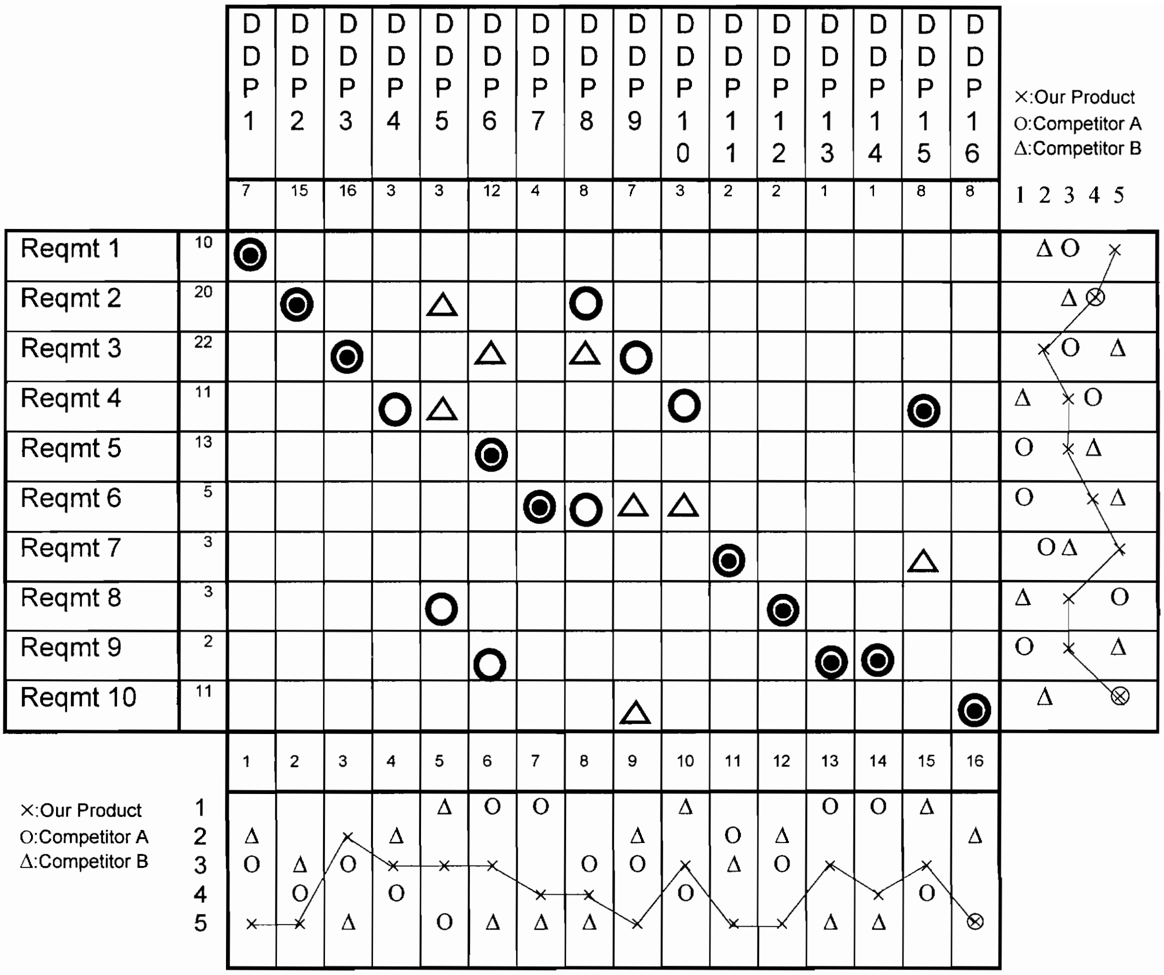

Figure 2.4. Completed QFD matrix.

2.2. IDENTIFYING CUSTOMER REQUIREMENTS

Identifying the customer requirements (also known as the "WHATs") is the most critical challenge in QFD [Sullivan, 1986]. These customer requirements, once identified, will later be translated into engineering design requirements, thus directly impacting the downstream life-cycle activities. Identifying customer requirements is especially difficult because it requires obtaining and expressing what the customers truly want, not what the designers think the customers want [Sullivan, 1986]. (Note: The term "customer" actually refers to stakeholders and includes not only the end-users, but also the applicable regulations and standards, the intermediate distributors, installers, retailers, and the maintainers). Refer to Figure 2.5 for placement of customer requirements in the QFD matrix.

According to Guinta & Praizler [1993], there are four levels of customer requirements: *expecters*, *spokens*, *unspokens*, and *exciters*. *Expecters* are the characteristics that customers assume are part of the product or service, but do not necessarily ask about. These are the most important requirements to address, because not satisfying them could result in a lost sale. For example, when a customer purchases a new house, it is expected that the house meets all of the local, city, and federal building codes. *Spokens* are specific features that customers say they want in a product or service. These are the second most important set of requirements to address, because they are the specific customer requirements beyond the basic requirements. For example, when purchasing a new house, a customer may specify the square footage requirements, the number of bedrooms or bathrooms, and color and fixture preferences. *Unspokens* are specific features that customers want, but do not ask about because they either did not remember to tell, did not want to tell, or were not aware of. For example, when purchasing a new house, a customer may notice a non-traditional layout for a house and realize that they want that type of layout. *Exciters* are unexpected features of a product or service that customers do not want, but are pleased to get. These features often distinguish a product or service from the competition. For example, in purchasing a house, the builder might offer a lifetime warranty on the roof. During the QFD process, firms that can adequately

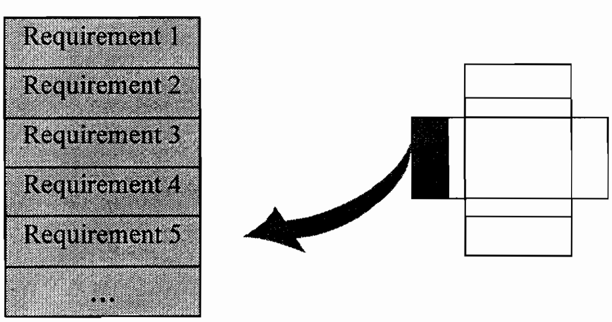

Figure 2.5. Customer requirements within the QFD matrix.

identify and exploit these types of customer requirements, especially the unapparent ones, may gain a competitive advantage in the marketplace [Guinta & Praizler, 1993].

Methods such as customer surveys, questionnaires, focus groups, brainstorming, customer interviews, market surveys, marketing research data, dealer input, trend analysis, complaints analysis, checklists, and competition analysis are often used to facilitate identification of the four levels of customer requirements. Competition analysis is useful in detecting the most popular product features, marketing research is useful in detecting the trends in consumer buying habits, and after-sales monitoring of products is useful in detecting faults or complaints [Mill, 1994]. In addition, questionnaires can reach a large sample population, but may receive a low response rate. Conversely, structured customer interviews or focus groups have a high response rate, but the time they demand will cover only a small sample population. Fortunately, convergence of customer requirements is often achieved after 20 to 30 interviews [Nichols, 1994].

When determining customer requirements, there is some doubt that all aspects of the customer's requirements are covered. Nichols [1994] questions how teams know when there is enough coverage of customer requirements to continue to the next step in the QFD process, given the criticality of this step. In Chapter 3, an indicator will be developed to assess if the most important customer requirements have been adequately incorporated.

When the customer requirements are identified, they are listed in the QFD matrix exactly as they are described by the customers. This ensures that the "Voice of the Customer" is captured. For example, a customer requirement might be that the door in a car is "easy to close". Although using the exact customer's words may raise a problem of interpretation, designer's words may correspond even less to customer's actual views [Hauser & Clausing, 1988].

Often, customer requirements with similar characteristics are classified into groups and/or sub-group(s) as shown in Figure 2.6 for a car [Hauser & Clausing, 1988]. This leads to the development of a hierarchy of customer requirements going from the most general to the most specific. The number of levels depends upon the complexity of the product or process being designed.

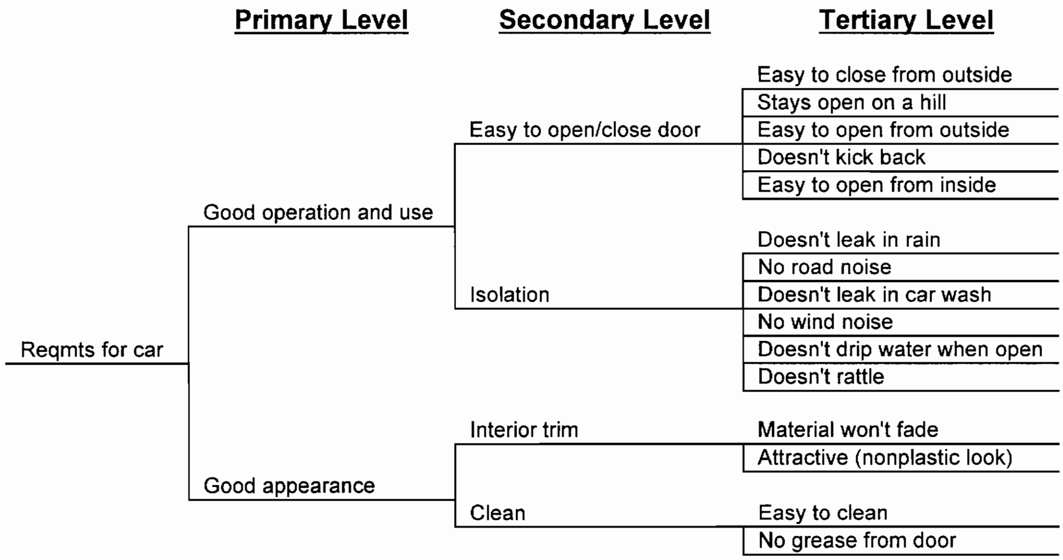

Figure 2.6. Customer requirements classified into groups and sub-groups.

2.3. IDENTIFYING RELATIVE PRIORITIES OF CUSTOMER REQUIREMENTS

Although all customer requirements identified in the QFD matrix are important, some are more important than others. After having the customers rate the importance of the previously identified customer requirements, the QFD matrix can then be used to prioritize them. Often, the customer requirements are rated on a scale from 1 to 5 (or 1 to 10), with 1 being least important and 5 (or 10) being the most important. In general, the customer requirements with a rating of 4 or 5 (on a 1 to 5 scale) are the *expecters* and *spokens*, which are requirements that should be incorporated in the design first [Guinta & Praizler, 1993]. Upon completion of the customer ratings, the values are normalized to 100% to establish relative priorities of the customer requirements [Hauser & Clausing, 1988]. In addition to numeric scales, linguistic scales (utilizing concepts from fuzzy set theory) have also been used to establish relative priorities [Masud and Dean, 1993; Verma, 1994; Wasserman and Mohanty, 1993]. Refer to Figure 2.7 for placement of customer relative priorities in the QFD matrix.

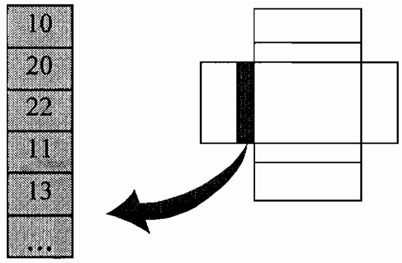

Figure 2.7. Customer relative priorities within the QFD matrix.

To ensure that the customers have properly assigned ratings, a technique called *multiple passes* can be utilized [Guinta & Praizler, 1993]. In this technique, the QFD facilitator takes the participants through the customer requirements list several times before accepting the final values. In addition, a technique utilizing the Analytic Hierarchy Process (AHP) can generate consistent relative priorities of customer requirements [Wasserman, 1993, Armacost et al, 1994; Akao, 1990; Aswad, 1989]. Potential customers are asked to complete a questionnaire to assess the relative importance of the customer requirements on a pairwise basis. The resulting relative importances are aggregated to determine the priorities of the requirements. This technique will be further developed in Chapter 3. A supporting discussion regarding AHP is included in the Appendix.

2.4. PERFORMING CUSTOMER COMPETITIVE ASSESSMENTS

Organizations want to match or exceed their competition; but to do so, they must first know how well their product measures up to their competitors. Thus, on the right side of the QFD matrix, as shown in Figure 2.8, the customers' assessments of their product and their competitors' products are listed for each customer requirement. Comparisons with the competition can help identify strategic opportunities for improvement [Sullivan, 1986]. For example, if a very important customer requirement is rated weak for the organization's product and its competitor's products, a competitive advantage could be gained by improving the product with respect to this requirement. In addition, if the

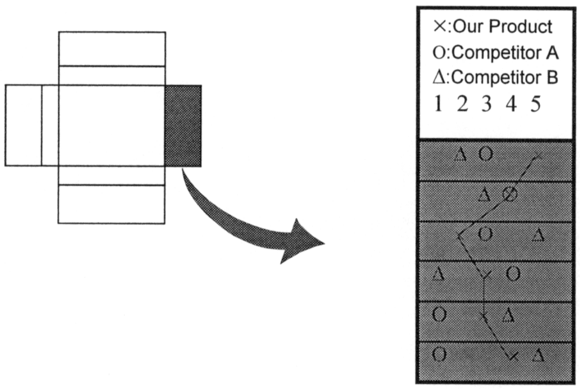

Figure 2.8. Customer competitive assessments within the QFD matrix.

organization's product is better than its competitors' products for an important customer requirement, it must maintain its advantage. Conversely, if the organization's product is worse than its competitors' products for an important customer requirement, it must improve its product with respect to this requirement. Essentially, the customer assessments help identify absolute strengths and weaknesses of the product, while helping to identify areas that require improvement.

Often, the scale used to rate the performance of the customer requirements is the same as the scale used to determine prioritized customer requirements (e.g., 1 to 5, with 5 being the best rating and 1 being the worst rating). In addition, to aid in viewing the comparisons, lines are drawn to connect the customer assessments of the organization's product. It is important that potential customers rate the requirements through focus groups, interviews, surveys, etc., since the members of the design and development team are likely to bias the results [Slabey, 1993]. By performing the competitive assessment, it helps to verify that the customer requirements previously identified are the ones that are important to the customers. Also, it is possible to identify additional requirements (i.e., *unspokens* and *exciters*) [Guinta & Praizler, 1993].

Currently, the customer competitive assessment offers a way to indicate how well the organization's product compares with their competitor's products for each specific customer requirement. However, there is currently no means of using QFD to compare the organization's product with its competitors' products holistically. Since the best product overall is likely to be the one that most customers purchase, Chapter 3 will develop an overall indicator of the products by aggregating the individual competitive assessments and using the priority of the customer requirements.

2.5. IDENTIFYING RELEVANT DESIGN DEPENDENT PARAMETERS (DDPS)

Design dependent parameters (DDPs, also known as the "HOWs") are engineering design characteristics under the designers' control, which are how the customers' requirements are to be achieved. For example, one DDP for the customer requirement "opens door easily" would be "number of foot-lbs to open door." Usually, a team consisting of members from representative functions throughout the organization holds a brainstorming session for ideas of achieving the customer requirements. Of the abundant list of potential DDPs, the ones with the greatest impact need to be identified.

Again, determining the proper list of DDPs is a vital step in the QFD process. Sullivan [1986] and Nichols [1994] question how a team knows when they have the right set of DDPs in order to continue to the next step in the QFD process. In Chapter 3, an indicator will be developed to assess if the identified DDPs have properly addressed the customer requirements.

In general, the DDPs must be quantifiable or measurable [Hauser & Clausing, 1988]. Once the DDPs are identified, they must be deployed throughout design, production, and support in order to manifest customer satisfaction [Sullivan, 1986]. Refer to Figure 2.9 for placement of DDPs in the QFD matrix.

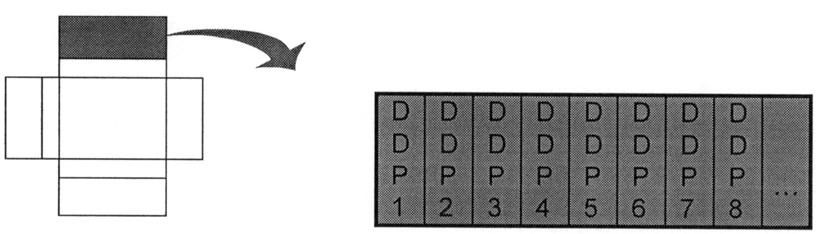

Figure 2.9. Design Dependent Parameters (DDPs) within the QFD matrix.

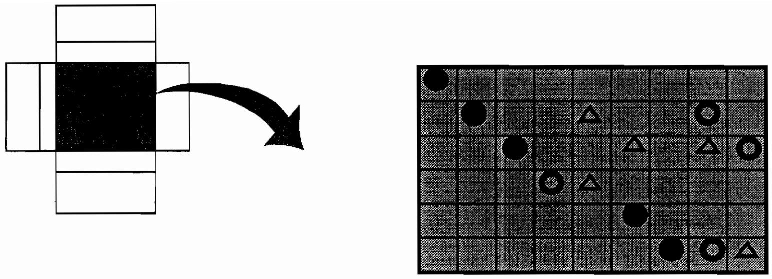

Figure 2.10. The relationship matrix within the QFD matrix.

2.6. DETERMINING THE RELATIONSHIP BETWEEN DDPS AND CUSTOMER REQUIREMENTS

This step of the QFD process involves identifying the relationship of the DDPs and the customer requirements in the relationship matrix. It is a means of analyzing which DDPs can indeed fulfill which customer requirements. The relationship matrix is located in the center of the QFD matrix, as shown in Figure 2.10, where each DDP is analyzed by the organization's cross-functional team in terms of the extent of its influence on achieving each customer requirement. The relationship between DDPs and customer requirements is represented through the use of symbols or numbers such as those shown in Table 2.1.

Table 2.1. Relationship between customer requirements and DDPs.

Relationship	Corresponding Symbol	Corresponding Values
None	(blank)	0 or (blank)
Weak	△	1
Moderate	○	3
Strong	◉	9

2.7. CHECKING THE RELATIONSHIP MATRIX FOR INCONSISTENCIES

Upon completion of the relationship matrix, it is necessary to examine it for inconsistencies. For example, if there is an open column it may indicate that the DDP does not adequately support the customer requirements. At this point, the team should reconsider the DDP and decide if it should remain in the matrix or if an unidentified customer requirement has been found. Similarly, if there is an open row, it indicates that a customer requirement has not been addressed. The team should reexamine the set of DDPs and identify additional ones, if necessary.

Chilakapati [1995] identified numerous types of inconsistencies throughout the QFD matrix and developed a structured process as well as a computer-based expert system for identifying them. In addition, this document will address some new means of identifying inconsistencies.

2.8. DELINEATING DDP RELATIVE IMPORTANCES

To facilitate design analysis and evaluation activities it is necessary to delineate the relative importances (or priorities) of the DDPs. By comparing relative importances to actual component costs, design teams can set priorities for improving components. This is particularly important when cost cutting is a goal [Hauser & Clausing, 1988]. Refer to Figure 2.11 for placement of DDP relative importances in the QFD matrix.

In order to preserve traceability to the customer requirements, DDP relative importances are computed as a function of the relative priorities of the customer requirements and their relationship with the DDPs. The absolute DDP importance weighting, w_j', as described by equation 2.1, is formed by the sum of the products of the degree of importance of customer requirement i and the quantified relationship values of customer i and DDP j for the entire column. For the quantified relationship values, 9

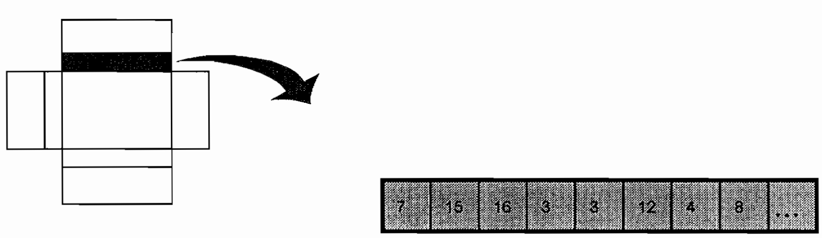

Figure 2.11. DDP relative importances within the QFD matrix.

'points' is used for strongly related requirements, 3 'points' for moderately related requirements, 1 'point' for weakly related requirements and 0 'points' for unrelated requirements, as described in Table 2.1. To get the relative importances, w_j, as described by equation 2.2, normalize the absolute weights, w_j', by dividing by the sum of the absolute weights, w_k' [Wasserman, 1993].

$$w_j' = \sum_{i=1}^{m} d_i \cdot R_{i,j} \tag{2.1}$$

where

w_j': absolute importance rating for DDP j; $j = 1, 2, ..., n$.

d_i: degree of importance of customer requirement i; $i = 1, 2, ..., m$.

$R_{i,j}$: quantified relationship between customer requirement i and DDP j; $i = 1, 2, ..., m$; $j = 1, 2, ..., n$.

$$w_j = w_j' / \sum_{k=1}^{n} w_k' \tag{2.2}$$

where

w_j: relative importance rating for DDP j; $j = 1, 2, ..., n$.

w_j': absolute importance rating for DDP j; $j = 1, 2, ..., n$.

w_k': absolute importance rating for DDP k; $k = 1, 2, ..., n$.

2.9. PERFORMING TECHNICAL COMPETITIVE ASSESSMENTS

Similar to the customer competitive assessment of customer requirements, the technical competitive assessment of DDPs is an activity that is used to identify where the organization's product stands against its competitors in technical measures (i.e., from an engineering perspective). As in the case for the customer competitive assessment, technical comparisons with the competition can help identify strategic opportunities for improvement. Refer to Figure 2.12 for placement of DDP competitive assessment in the QFD matrix.

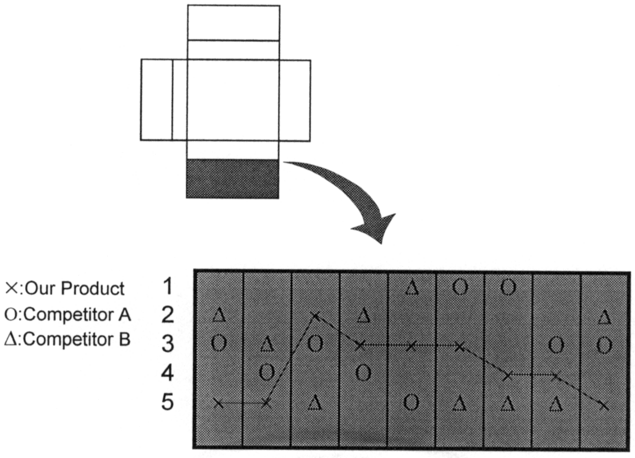

Figure 2.12. The technical competitive assessments within the QFD matrix.

The measures of the DDPs (such as how many foot-lbs it takes to close a door) are usually obtained from tests or evaluations performed within the organization. These measures can then be translated into a numerical performance rating (e.g., 1 to 5 scale) based on group consensus [Sullivan, 1986]. As in the case for customer competitive assessments, lines are connected for the organization's product.

When completed, the technical competitive assessments can be compared with the customer competitive assessments to determine areas of inconsistency between what the customers say and the technical evaluations [Sullivan, 1986; Hauser & Clausing, 1988; Chilakapati, 1995]. These types of inconsistencies may signal faulty measures or misinterpretation of customer perception [Hauser & Clausing, 1988]. Chilakapati [1995] has developed a structured process as well as a computer-based expert system for identifying the inconsistencies between the customer competitive assessments and the technical competitive assessments. However, there is currently no mathematical relationship between the two types of assessments to help identify inconsistencies during QFD use. This research will develop such a mathematical relationship.

2.10. DETERMINING DDP TARGET VALUES

The target values (also known as the "HOW MUCHES") are how engineers summarize the QFD matrix in a usable form. They represent the customer's voice and can be used to discover strategic opportunities [Hauser & Clausing, 1988]. Hence, this is a critical step in the system design and development process. During all phases of design, these target values impact all subsequent design decisions. For example, in conceptual system design, these target values specify the requirements for preliminary system design.

Before target values are determined, the QFD matrix should first be checked for inconsistencies [Chilakapati, 1995]. Upon completion of the inconsistency checking, target values are determined by giving consideration to the priority of customer requirements, their correlation with design dependent parameters, the customers' perception with regard to existing products and systems, and the technical competitive assessment data [Verma, 1994].

Verma [1994] has developed two indices to facilitate defining target values: the *IPN* (Improvement Potential and Necessity) index and the *TOF* (Tolerance Of Fuzziness) index. The *IPN* index, which helps to exploit the most prominent opportunities, was generated by developing a matrix linking customer satisfaction levels to the correlation between customer requirements and DDPs. The *TOF* index, which defines tolerance levels for targets, are generated from the *IPN* index and the relative priorities of the customer requirements. In determining the final target values for the QFD matrix, however, the team should emphasize a single value versus tolerances, because when tolerances are given, the final design tends to drift toward the least costly end of the tolerance [Hauser & Clausing]. Refer to Figure 2.13 for placement of DDP target values in the QFD matrix.

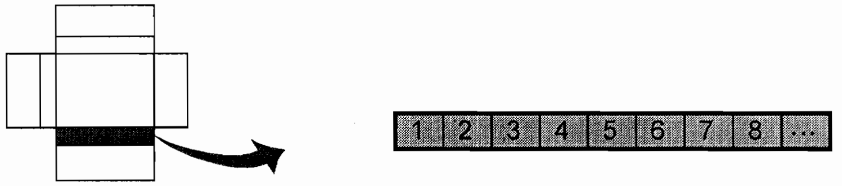

Figure 2.13. DDP target values within the QFD matrix.

CHAPTER 3

INTEGRATING THE ANALYTIC HIERARCHY PROCESS (AHP) WITH QFD

This chapter will present the motivation for integrating a multi-attribute decision support methodology called the Analytic Hierarchy Process (AHP) with QFD. In addition, this chapter presents how the AHP is currently being used within the QFD process. Thereafter, a new application for the AHP within the QFD process will be presented. Finally, this chapter will present a modified AHP adaptation for use in the traditional QFD matrix. Examples will be integrated into the discussion to further illustrate the concepts. The basic AHP methodology is discussed in the Appendix as a supporting document.

3.1. MOTIVATION FOR INTEGRATION

There are three types of data commonly used to determine the importances of customer requirements in the QFD matrix: absolute importance, ordinal importance, and relative importance [Cohen, 1995]. Absolute importance is typically determined by a five-point scale as described in Chapter 2. Data from a group of customers can be obtained by gaining group consensus. However, the main problem with using absolute importance ratings is that customers tend to rate almost everything as important, thus making it more difficult for the design team to prioritize DDPs [Cohen, 1995]. It is necessary for the design team to prioritize the DDPs, since they may need to make trade-offs due to constrained resources.

Ordinal importance is determined by asking several customers to rank-order the requirements, with the least preferred requirement assigned a 1 and so on (i.e., rank from least preferred to most preferred). The scores assigned by the customers are totaled and the requirement with the highest value is the most important, and so on. The ordinal importance method gives a reasonable estimate of the way the customers feel about the requirements; however, it strongly over-emphasizes the most important requirements and is considered invalid for mathematical use [Cohen, 1995].

The relative importance method reflects that if one requirement is twice as important as another to the customer, then the score associated with the more important requirement would be twice the score of the less important requirement. The Analytic Hierarchy Process (AHP) is one of the most common techniques for determining relative importances. The AHP begins by performing paired comparisons on all of the requirements. For example, if there were three requirements A, B, and C; then A would be compared with B, then A with C, and then B with C. As with the absolute importance method, group judgments can be obtained by group consensus. In addition, the individual judgments can be aggregated using the geometric means [Armacost et al, 1994]. The comparisons are stored in a matrix and then processed into weights for each customer requirement, indicating the relative importances of the requirements (refer to the Appendix as to how the matrix is processed into weights).

Another benefit of using the AHP in generating relative importances is that it can ensure a certain minimum consistency of judgment. That is, if A is twice as important as B, and B is twice as important as C, then a cardinal consistent judgment would be that A is four times as important as C. Although cardinal consistency is difficult to achieve, the AHP allows a certain threshold of inconsistency before the judgments must be re-examined (refer to the Appendix for more information regarding inconsistency of judgments).

Cohen [1995] finds relative importance to be the most useful measure of importance for QFD. The drawback for using relative importance models, such as the AHP, is that they are generally complex enough to require the use of professional market researchers [Cohen, 1995]. However, considering the cost of a product that does not meet the customer's requirements, the use of professional market researchers should be well worth the investment.

In addition to using the AHP to develop relative importances of customer requirements, it can also provide a means for evaluating a company's product against its competitors' products overall. With the traditional use of QFD, the competitive assessments offer a way to indicate how well the organization's product compares with their competitors' products for each customer requirement or DDP. The AHP can then be used to aggregate these assessments into an overall indicator. This will be discussed in more detail in Sections 3.3 and 3.4.

In summary, the integration of the AHP with QFD has many advantages. The AHP can ensure consistency of judgment when determining relative importances and can also be used to effectively evaluate a product against its competitors.

3.2. PRIORITIZING CUSTOMER REQUIREMENTS USING THE AHP

As discussed in Section 3.1, the AHP can be used to develop relative importances for customer requirements in the QFD matrix. To do so, the AHP utilizes the paired (also called pairwise) comparison process. In the paired comparison process, customer requirements are compared with one another in relative terms as to their importance/contribution with respect to the overall goal of customer satisfaction. For example, a customer responds to a question that compares two customer requirements *a*

Table 3.1. Suggested degrees of preference.

If answer is	then the numerical preference is $a \geq b$	$a \leq b$
equally important/preferred,	1	1
weakly (less) more important/preferred,	3	(1/3)
strongly more (less) important/preferred,	5	(1/5)
very strongly more (less) important/preferred,	7	(1/7)
absolutely more (less) important/preferred,	9	(1/9)

Even numbers (2, 4, 6, 8) are used to represent compromises between the above preferences. If *a* has been compared to *b*, then the comparison of *b* to *a* is merely the reciprocal; also the comparison of *a* to *a* is always 1.

and *b* in terms of importance or preference: "With respect to customer satisfaction, how much more important/preferred is [customer requirement *a*] than [customer requirement *b*]." The answer choices commonly used in the AHP are listed in Table 3.1. In addition, the answers are "converted" into a numerical equivalent ranging from 1 to 9. However, if customer requirement *a* is <u>less</u> important/preferred than customer requirement *b*, then the numerical numbers would be the reciprocals, e.g., *x* would be *1/x*.

When the paired comparison process is complete, the result is a matrix of paired comparisons. Table 3.2 illustrates an example matrix of paired comparisons using five customer requirements: A, B, C, D, and E. Notice that the paired comparison process needed to be performed by the customers only for the shaded area because of the symmetry of the matrix. For example, in Table 3.2, requirement A is weakly <u>more</u> important (denoted by '3') than requirements C and E, and strongly <u>more</u> important (denoted by '5') than requirement D; therefore requirements C and E must both be weakly <u>less</u> important (denoted by '1/3') than requirement A, and requirement D must be strongly <u>less</u> important (denoted by '1/5') than requirement A. In addition, requirements compared to themselves are always equally important (denoted by '1') as shown by the diagonal of the matrix.

Table 3.2. Example matrix of paired comparisons for five customer requirements.

	A	B	C	D	E
A	1	1	3	5	3
B	1	1	3	5	3
C	1/3	1/3	1	3	1
D	1/5	1/5	1/3	1	1/3
E	1/3	1/3	1	3	1

One valuable step in the AHP is to perform a consistency check on the paired comparison matrix to ensure validity for the suggested degrees of preference of the customer requirements. The consistency ratio (CR) is an approximate indicator of the inconsistency of the paired comparisons. It is based on the deviation of the paired comparisons from perfect cardinal consistency. Saaty [1990] suggests that if the CR is less than or equal to 0.10, then the consistency is generally acceptable. However, if the CR is greater than 0.10, the paired comparisons should be rechecked. All matrices in this document have been checked for consistency, although the actual CRs will not be given.

Subsequent to the paired comparisons (i.e., after the matrix is filled), the relative importances can be calculated using the principal right eigenvector method [Saaty, 1990]. The eigenvector of the matrix can be calculated by most matrix/math computer programs such as MatLab®, which raise the matrix to a large power until the numbers converge [Saaty, 1990]. After the eigenvectors are determined, they are normalized to 1 by dividing each value by the total sum. Saaty [1990] has developed a good approximation method for calculating the eigenvectors of a matrix, but with the aid of computers, this is unnecessary. The resulting normalized eigenvectors (i.e., relative importances) of the matrix from Table 3.2 are listed in Figure 3.1 and are directly inputted into the QFD matrix (after the consistency check has been performed). The higher the value, the more important the requirement is to the customer.

Customer Requirement	Relative Importance
Requirement A	0.343
Requirement B	0.343
Requirement C	0.129
Requirement D	0.055
Requirement E	0.129

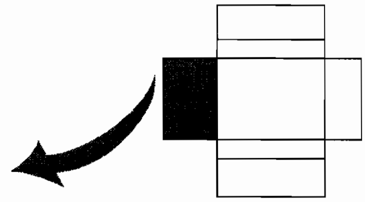

Figure 3.1. Resulting relative importances from paired comparison matrix.

In the event that more than nine requirements are identified, the requirements are classified into groups and subgroups as discussed in Chapter 2. Figure 3.2 illustrates an example hierarchy of 3 groups (i.e., primary requirements) consisting of requirements A, B, and C, and 3 subgroups (i.e., secondary requirements) under each group consisting of A1, A2, A3, etc. The paired comparison process is first performed for the primary level of requirements (i.e., between A, B, and C) and then at the secondary level of requirements (i.e., between A1, A2, and A3, then between B1, B2, and B3, etc.) as illustrated in Figure 3.3. Again, it is important to calculate the CRs to ensure consistency in judgments after the matrices have been completed.

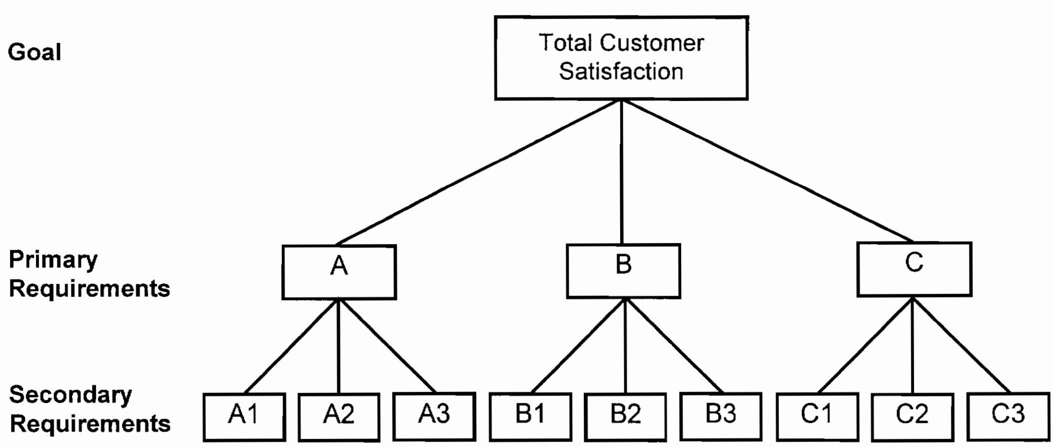

Figure 3.2. Example hierarchy of groups and subgroups of requirements.

	A	B	C
A	1	1	3
B	1	1	3
C	1/3	1/3	1

A

	A1	A2	A3
A1	1	3	1/3
A2	1/3	1	1/9
A3	3	9	1

B

	B1	B2	B3
B1	1	1/7	1/3
B2	7	1	5
B3	3	1/5	1

C

	C1	C1	C3
C1	1	1	1
C2	1	1	1
C3	1	1	1

Figure 3.3. Example matrices of paired comparisons for levels of requirements.

Table 3.3 summarizes the resulting relative importances calculated for each level using the principle eigenvector method. In Table 3.3, since the relative importance for the secondary level requirement is relative to the primary level (e.g., A1 is currently 0.231 of A, which is 0.637 of the total), it must be "converted" into a relative importance of the overall goal of total customer satisfaction before being inputted into the QFD matrix. To calculate the overall relative importance for a secondary level requirement, multiply its relative importance by the relative importance of its primary level parent as shown below for requirement A1:

Overall relative importance of A1 = (relative importance of A1) x (relative importance of A)

Overall relative importance of A1 = (0.231)x(0.637)

Overall relative importance of A1 = 0.147

Table 3.3. Summary of relative importances for each level.

Primary Requirements	*A*			*B*			*C*		
Primary Level Importances	**0.637**			**0.105**			**0.258**		
Secondary Requirements	*A1*	*A2*	*A3*	*B1*	*B2*	*B3*	*C1*	*C2*	*C3*
Secondary Level Importances	0.231	0.077	0.692	0.081	0.731	0.188	0.333	0.333	0.333

Primary Requirements	Secondary Requirements	Relative Importances
A	A1	0.147
	A2	0.049
	A3	0.441
B	B1	0.009
	B2	0.077
	B3	0.020
C	C1	0.086
	C2	0.086
	C3	0.086

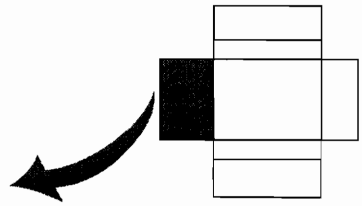

Figure 3.4. Overall relative importances in the QFD matrix .

Figure 3.4 summarizes the overall customer relative importances as they would appear in the QFD matrix. Once determined, these relative importances can easily be translated into DDP relative importances as described in Chapter 2.

3.3. MEASURING THE OVERALL PERFORMANCE OF A PRODUCT USING THE COMPETITIVE ASSESSMENTS

As stated earlier in Section 3.1, the competitive assessments offer a way of measuring how well the organization's product compares with their competitors' products for each customer requirement or DDP, but there is currently no means of using QFD to compare the organization's product with its competitors' products overall (i.e., whose product is the best overall using the customer inputs). This section will develop a means of using the AHP within the QFD process to obtain an overall indicator of effectiveness for a product against its competitors in the marketplace.

Suppose a company wants to perform a customer competitive assessment using its product and two benchmark competitors. Using the example given in Section 3.2, the resulting hierarchy would be given by Figure 3.5. In this hierarchy, the paired comparison process is first performed for the primary and secondary levels of customer requirements as illustrated in Section 3.2. In addition, another group of paired

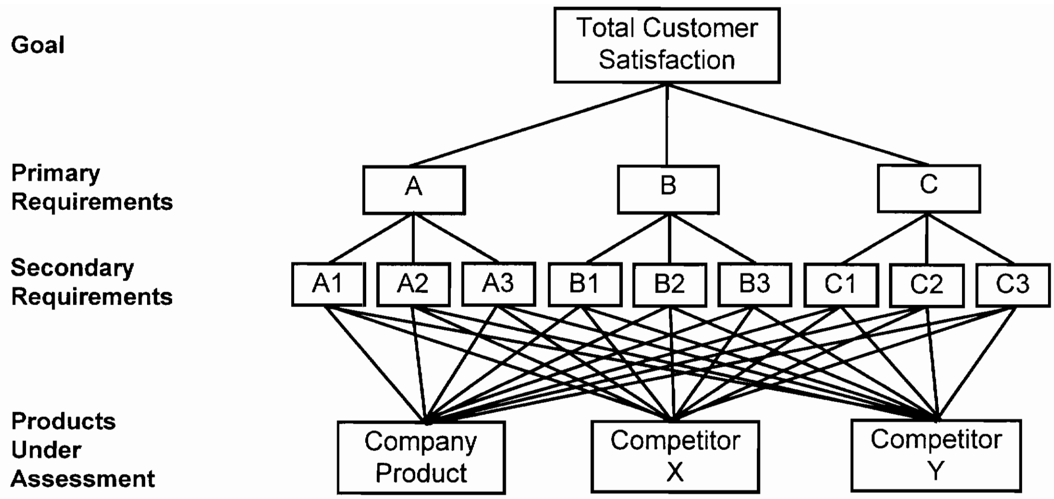

Figure 3.5. Example hierarchy of customer requirements and product assessments.

comparisons is performed by the customer on the company's product and its competitors' products for each secondary level of customer requirements as illustrated in Figure 3.6. For example, with respect to customer requirement A1, the paired comparison process is performed on the company's product ("co."), competitor "X", and competitor "Y". This process is repeated for customer requirements A2, A3, B1, B2, etc. Again, the CRs are calculated to ensure consistency after the matrices have been completed. Table 3.4 summarizes the calculated relative importances (using the principle eigenvector method) for the two levels of customer requirements as well as for the three products in the competitive assessment.

Once all of the relative importances have been obtained, the customer global priority weights (GPWs) can be calculated. The GPWs are the overall relative importances of the products, which are normalized to 1. To determine the customer GPWs of the products, compute the sum of the product of importances for all levels (i.e., primary level, secondary level, and the product under assessment) that include the

	A	B	C
A	1	1	3
B	1	1	3
C	1/3	1/3	1

A

	A1	A2	A3
A1	1	3	1/3
A2	1/3	1	1/9
A3	3	9	1

B

	B1	B2	B3
B1	1	1/7	1/3
B2	7	1	5
B3	3	1/5	1

C

	C1	C1	C3
C1	1	1	1
C2	1	1	1
C3	1	1	1

A1

	Co.	X	Y
Co.	1	7	3
X	1/7	1	1/3
Y	1/3	3	1

B1

	Co.	X	Y
Co.	1	5	9
X	1/5	1	3
Y	1/9	1/3	1

C1

	Co.	X	Y
Co.	1	9	9
X	1/9	1	1
Y	1/9	1	1

A2

	Co.	X	Y
Co.	1	3	1/3
X	1/3	1	1/9
Y	3	9	1

B2

	Co.	X	Y
Co.	1	7	3
X	1/7	1	1/3
Y	1/3	3	1

C2

	Co.	X	Y
Co.	1	1/5	1/7
X	5	1	1/3
Y	7	3	1

A3

	Co.	X	Y
Co.	1	1/3	1/3
X	3	1	1
Y	3	1	1

B3

	Co.	X	Y
Co.	1	1/5	1
X	5	1	5
Y	1	1/5	1

C3

	Co.	X	Y
Co.	1	1	1/7
X	1	1	1/7
Y	7	7	1

Figure 3.6. Example matrices of paired comparisons for customer requirements and product assessments.

Table 3.4. Summary of all customer relative importances.

Primary Requirements	*A*			*B*			*C*			**GPW**
Primary Level Importances	**0.637**			**0.105**			**0.258**			N/A
Secondary Requirements	*A1*	*A2*	*A3*	*B1*	*B2*	*B3*	*C1*	*C2*	*C3*	N/A
Secondary Level Importances	0.231	0.077	0.692	0.081	0.731	0.188	0.333	0.333	0.333	N/A
Company Product	0.669	0.231	0.143	0.751	0.669	0.143	0.818	0.072	0.111	**0.320**
Competitor X	0.088	0.077	0.429	0.178	0.088	0.714	0.091	0.279	0.111	**0.270**
Competitor Y	0.243	0.692	0.429	0.070	0.243	0.143	0.091	0.649	0.778	**0.412**

product being evaluated. For example, using Table 3.4, the customer GPW for competitor X is shown below:

$$\begin{aligned} GPW(X) = {} & (0.637)[(0.231)(0.088) + (0.077)(0.077) + (0.692)(0.429)] + \\ & (0.105)[(0.081)(0.178) + (0.731)(0.088) + (0.188)(0.714)] + \\ & (0.258)[(0.333)(0.091) + (0.333)(0.279) + (0.333)(0.111)] = 0.270 \end{aligned}$$

Similarly, the GPW for the company's product and competitor Y are 0.320 and 0.412, respectively (Note: the numbers add up to 1.002 vice 1.000 due to round-off errors). Since the GPW for competitor Y is the highest, it is the best product overall of the three, according to the QFD matrix. In addition, Expert Choice™, which is a computer-based application of the AHP, has several sensitivity analysis tools available for further analysis of the results if desired.

3.3.1. Determining That Sufficient Customer Inputs Have Been Collected

As discussed in Chapter 2, QFD's success is highly dependent on identifying the customer's wants or needs (i.e., requirements), their importance ratings of the needs, and their competitive assessments. In Section 3.3, the overall relative importance of the products was developed in the form of the GPW by aggregating the customer's requirements, the relative importances of the requirements, and the customer competitive assessments (in the form of paired comparisons). Thus, by asking the customer to answer another set of questions to determine which product is best overall, second best, etc., the GPWs can be compared with the overall values to indicate that the customer inputs have been sufficiently reflected to continue the QFD process.

There are several methods that can be used to determine the overall values of the company's product and its competitors' products. Customer(s) can rank order the products according to preference, rate each product on a five point scale, and/or perform paired comparisons on the products using the AHP. As stated earlier in this chapter, the paired comparison method is the most preferred method of determining relative ratings. In addition, the AHP calculates the CR, which identifies if the comparisons are inconsistent. If several customers are evaluating the products, the evaluations can be performed through group consensus or the individual evaluations can be aggregated by using the geometric means of each paired comparison.

As an example, Figure 3.7 illustrates the overall evaluations of three different customers using the paired comparison process on the company's product, competitor X, and competitor Y. A final matrix is aggregated using the geometric means of the

Individual 1

	Co.	X	Y
Co.	1	3	1/3
X	1/3	1	1/5
Y	3	5	1

Individual 2

	Co.	X	Y
Co.	1	3	1
X	1/3	1	1/5
Y	1	5	1

Individual 3

	Co.	X	Y
Co.	1	1	1/3
X	1	1	1/3
Y	3	3	1

Final Matrix

	Co.	X	Y
Co.	1	2.1	.48
X	.48	1	.24
Y	2.1	4.2	1

Figure 3.7. Paired comparisons for evaluating products overall.

individual matrices (e.g., for the company vs. competitor X comparison, the aggregated value is $[3 \times 3 \times 1]^{1/3} = 2.1$). Table 3.5 lists the relative ratings (i.e., importances) of the products, which are calculated by applying the principle eigenvector method on the final matrix.

When comparing the customer's evaluations with the GPW, the most important criterion is that the product rankings are consistent with one another (i.e., both methods have matched product rankings). For example, in Table 3.5 using the customer's overall relative rating, the best product overall was competitor Y, followed by the company product, followed by competitor X. Similarly, using the customer GPW calculations, the best product overall was competitor Y, followed by the company product, followed by competitor X. Thus, both are consistent with one another.

In addition, the values associated with the rankings should be reviewed. If the ranking of products is inconsistent, but the values of the inconsistently ranked products are relatively close, then the customer inputs may still be valid. This is possible when two or more products are rated about the same in terms of preference, but the rankings are inconsistent when comparing the customer GPW and the overall relative ratings as shown in Table 3.6. The company product is ranked higher than competitor X using the customer's overall relative rating, but competitor X is ranked higher than the company product for the customer GPW. However, looking at the values reveals that both the company product and competitor X are rated about the same in terms of preference for both the overall rating and the GPW. In addition, they are both ranked less than the product from competitor X. Thus, the overall relative ratings and the customer GPWs are consistent.

Table 3.5. Resulting relative ratings of the products under assessment.

Product	Overall Relative Rating	Customer GPW
Company Product	0.282	0.320
Competitor X	0.137	0.270
Competitor Y	0.581	0.412

Table 3.6. Inconsistent rankings in similarly rated products.

Product	Overall Relative Rating	Customer GPW
Company Product	0.207	0.298
Competitor X	0.212	0.290
Competitor Y	0.581	0.412

However, if the rankings between the customer overall ratings and the GPW are inconsistent and the values do not reveal any reasons for the inconsistency as shown in Table 3.7, then the list of customer requirements should be checked for essential requirements that may be missing. In addition, the relative importances and customer competitive assessments should be checked as well. Finally, the customer's overall assessments should be checked as needed. It is important that these two measures of product viability in the marketplace closely match to ensure that customer inputs have been sufficiently reflected in the QFD matrix.

Table 3.7. Inconsistency in ratings between the customer's overall relative rating and the customer GPW.

Product	Overall Relative Rating	Customer GPW
Company Product	0.207	0.320
Competitor X	0.469	0.270
Competitor Y	0.324	0.412

3.3.2. Determining That Customer Inputs Have Been Adequately Translated Into Technical Parameters

After the customer inputs have been sufficiently reflected, the same process should be performed using the DDPs, the relative importances of the DDPs, and the technical competitive assessments to determine the technical GPW. The technical GPWs can be calculated using the same process as the customer GPWs with minor differences.

For instance, there is no paired comparison process for determining DDP relative importances since they are derived from the customer requirement relative importances and the relationship matrix. However, paired comparisons are still performed for the technical assessments. Since the DDPs are generally not grouped, there is only one level of DDPs, making the technical GPW computations much easier. Table 3.8 summarizes the resulting derived DDP relative importances as well as the relative ratings calculated from the technical competitive assessment paired comparison matrices using the eigenvector method.

To calculate the technical GPWs, compute the sum of the product of DDP relative importances and the rating of the product being evaluated for each DDP. For example, using the example data in Table 3.8, the technical GPW of competitor X is shown below:

$$
\begin{aligned}
GPW(X) = \; & (0.147)(0.088) + (0.049)(0.077) + (0.441)(0.429) + \\
& (0.009)(0.178) + (0.077)(0.088) + (0.020)(0.714) + \\
& (0.086)(0.091) + (0.086)(0.279) + (0.086)(0.111) = 0.270
\end{aligned}
$$

As in the case of customer GPWs, the product with the highest value is the best, etc. Once determined, the technical GPWs can be compared to the customer's overall assessments as well as the customer GPWs in the same manner as described in Section 3.3.1. Rankings should be consistent with one another and the values associated with the rankings should be reviewed as well. If inconsistencies are present, the DDPs should be checked for essential DDPs that may be missing. In addition, the relationship matrix and technical competitive assessments should be checked. It is important that these three

Table 3.8. Summary of all technical relative importances.

DDPs	*DDP1*	*DDP2*	*DDP3*	*DDP4*	*DDP5*	*DDP6*	*DDP7*	*DDP8*	*DDP9*	**GPW**
DDP Importances	0.147	0.049	0.441	0.009	0.077	0.020	0.086	0.086	0.086	N/A
Company Product	0.669	0.231	0.143	0.751	0.669	0.143	0.818	0.072	0.111	**0.320**
Competitor X	0.088	0.077	0.429	0.178	0.088	0.714	0.091	0.279	0.111	**0.270**
Competitor Y	0.243	0.692	0.429	0.070	0.243	0.143	0.091	0.649	0.778	**0.412**

indicators of product viability in the marketplace closely match to ensure that customer inputs have been sufficiently translated into technical parameters in the QFD matrix.

3.4. A MODIFIED AHP ADAPTATION FOR USE IN THE TRADITIONAL QFD MATRIX

When performing the customer and technical competitive assessments using the QFD matrix, the products are traditionally assessed by a five point absolute scale for each customer requirement or DDP as discussed in Chapter 2. The absolute scale is desirable because it allows the data to be graphically displayed and it can be performed quickly by the customers or design team (i.e., 1 decision for each product for each customer requirement or DDP).

When using the paired comparison process for the competitive assessments, the relative ratings can easily be converted to a ten point absolute scale by multiplying the ratings by 10. Using the data in Table 3.4, Figure 3.8 illustrates the overall customer relative importances and customer competitive assessments (converted to the ten point scale) as they would appear in the QFD matrix.

Primary Requirements	Secondary Requirements	Relative Importances	
A	A1	0.147	Relationship Matrix
	A2	0.049	
	A3	0.441	
B	B1	0.009	
	B2	0.077	
	B3	0.020	
C	C1	0.086	
	C2	0.086	
	C3	0.086	

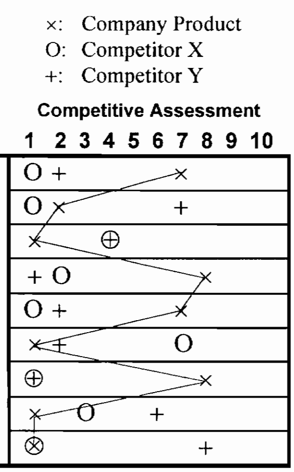

Figure 3.8. Overall customer relative importances and competitive assessments in the QFD matrix.

One disadvantage of using paired comparisons for the competitive assessments is that the ratings of products are relative to one another, and not necessarily to what absolutely satisfies the customer. For example, suppose in the paired comparison process that product X is absolutely better than product Y. This could mean that the customer is extremely satisfied with product X and indifferent with product Y or it could also mean that the customer is moderately satisfied with product X and absolutely dissatisfied with product Y. Therefore, although relative importances are better than the absolute importances for calculating relative ratings in the competitive assessments, the design team may still choose to use the five point absolute scale in order to know how well the products satisfy the customers for each customer requirement. This information is especially helpful when determining new target values. Ideally, the design team should obtain both absolute and relative ratings, but this may be infeasible.

In addition, it may be more desirable for the design team to use absolute ratings since the paired comparison process is more complex than the five point scale. Further, because the traditional method does not require breaking the customer requirements into hierarchies of levels, the use of absolute ratings may be much quicker. Finally, a design team that has used the traditional five point scale method may want to apply the methods developed in this research to their previously completed matrices. Thus, a modified adaptation of the integrated AHP methodology is developed in this section for use with absolute ratings.

To begin, instead of performing the paired comparison process, the five point absolute scale can be used for the competitive assessments and then converted to relative ratings by normalizing the values to 1 (i.e., divide each by the total sum). For example, suppose the customer requirement A1 was used to evaluate the company's product against the products from competitors X and Y; and that the customer evaluated the company's product as a '4', competitor A's product as a '3', and competitor B's product as a '5'. Then, the relative importances for the products are normalized to 1 as follows:

Company product	$4/(4+3+5)$	=	*0.333*
Competitor X	$3/(4+3+5)$	=	*0.250*
Competitor Y	$5/(4+3+5)$	=	*0.417*
	Σ	=	*1.000*

Once determined, the relative importances can be used to calculate the GPW in a similar manner as described in Section 3.3.2.

Table 3.9. Example paired comparison process for comparing the company product with competitors A and B.

	Co.	X	Y
Co.	1	3	1/3
X	1/3	1	1/5
Y	3	5	1

Although this process is valid within the AHP methodology (using the five point scale as performance data), absolute ratings are used instead of relative ratings. As discussed earlier in this chapter, the problem with using absolute importance ratings is that customers tend to rate almost everything as important, thus making it more difficult for the design team to prioritize DDPs. For example, the same products are compared using the paired comparison process as shown in Table 3.9. Table 3.10 lists the calculated relative ratings compared to the normalized ratings from the five point scale. Clearly, the ratings derived from the paired comparison process are more spread out. In addition, using the normalized five point scale method loses the advantage of the consistency checking mechanism within the paired comparison process. However, because of its simplicity, this method should not be ignored.

Table 3.10. Comparison of ratings calculated from the normalized five point scale and ratings calculated from paired comparisons.

Product	Ratings calculated from paired comparisons	Ratings calculated from five point scale
Company Product	0.258	0.333
Competitor X	0.105	0.250
Competitor Y	0.637	0.417

CHAPTER 4

QUALITY FUNCTION DEPLOYMENT AS AN EVALUATION TOOL

This chapter begins by developing a relationship between the technical and competitive assessments. Thereafter, this relationship will be used to test for inconsistencies in the competitive assessments and/or the relationship matrix. Upon correcting any inconsistencies, the QFD matrix combined with the AHP is used to indicate a new product concept's viability in the marketplace as well as to help perform trade-off analyses.

4.1. THE RELATIONSHIP BETWEEN THE TECHNICAL AND CUSTOMER COMPETITIVE ASSESSMENTS

Chilakapati [1995] discusses various means of addressing inconsistencies in the QFD matrix. In addition, Sullivan [1986] notes that the customer's competitive assessments may be compared with technical competitive assessments to determine areas of inconsistency between what the customers say and the technical evaluations. However, there is currently no mathematical relationship between the two types of assessments to help identify inconsistencies during the use of QFD. This section will develop such a relationship.

The relationship between the technical and competitive assessments can be adapted from an equation using weighted averages, such as the one used to determine the center of mass (or center of gravity) of an object. The center of mass of an object is the point in an object which its weight is evenly distributed or balanced. The calculation of the center of mass (CM) coordinate is the weighted sum of the distances to the center of mass of subobjects, d_i, divided by the total weights (i.e., mass) as shown by Equation 4.1.

$$CM = \frac{\Sigma(d_i \cdot m_i)}{\Sigma m_i} \tag{4.1}$$

where

CM: center of mass coordinate.

d_i: distance to center of mass of subobject i; $i = 1, 2, ..., n$.

m_i: mass of subobject i; $i = 1, 2, ..., n$.

The calculation of the center mass is performed for each axis. The resulting values represent the coordinates of the center of mass for the object. For example, using the object in Figure 4.1 and the data in Table 4.1, the center of mass for the object in the x-direction (from the left) is calculated as follows:

$$CM = [1.25(10) + 4(5) + 7.5(10)] / (10 + 5 + 10) = 4.3 \text{ centimeters}$$

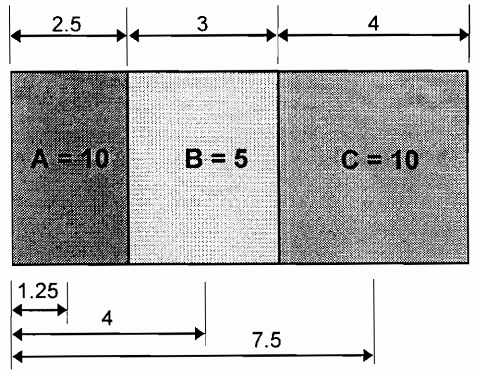

Figure 4.1. Sample object to calculate center of mass.

Table 4.1. Sample data to calculate center of mass (CM).

Subobject	Mass	Distance to CM
A	10 g	1.25 cm
B	5 g	4.00 cm
C	10 g	7.50 cm

The relationship between the technical and customer competitive assessments is a function of the technical competitive assessment values, the customer competitive assessment values, and the correlation between the two competitive assessments. However, since some technical competitive assessment values are more strongly related to some customer competitive assessment values than others (via the relationship matrix), the relationship is calculated using the strength of the correlation (i.e., the stronger the correlation, the more weight should be given to the assessment value used). Accordingly, the customer competitive assessment values for a requirement can be estimated by the weighted average of the technical competitive assessment values that are related (i.e., weakly, moderately, or strongly related) to the requirement. This weighted average relationship assumes that the essential customer requirements and DDPs have been identified, the relationship matrix is consistent, and the judgment scale of the design team and the customer is the same. In Section 4.2, this relationship is utilized to test for inconsistencies in the QFD matrix (i.e., if the QFD matrix is inconsistent, then one or more of the assumptions has not been satisfied and therefore must be rechecked).

The center of mass equation can be adapted for the relationship between technical and customer competitive assessments as given by Equation 4.2. The customer competitive assessment value of product k for customer requirement j, $CCA_{k,j}$, is formed by the sum of the products of the technical competitive assessment values of product k for DDP i, $TCA_{k,i}$, and the quantified relationship values of customer requirement j and DDP i, $R_{i,j}$, divided by the sum of the quantified relationship values of customer requirement j and DDP i, $R_{i,j}$, for the entire row. For the quantified relationship values, 9 'points' is used for strongly related requirements, 3 'points' for moderately related requirements, 1 'point' for weakly related requirements and 0 'points' for unrelated requirements.

$$CCA_{k,j} = \frac{\sum_{i=1}^{m} (TCA_{k,i} \cdot R_{i,j})}{\sum_{i=1}^{m} R_{i,j}} \qquad (4.2)$$

where

$CCA_{k,j}$: customer competitive assessment value of product k for requirement j; $k = 1, 2, ..., p$; $j = 1, 2, ..., n$.

$TCA_{k,i}$: technical competitive assessment value of product k for DDP i, $k = 1, 2, ..., p$; $i = 1, 2, ..., m$.

$R_{i,j}$: quantified relationship between customer requirement j, and DDP i; $j = 1, 2, ..., n$; $i = 1, 2, ..., m$.

Equation 4.2 can be used for absolute ratings (either five point scale or normalized) or relative ratings derived from paired comparisons. In order to illustrate the calculation, the absolute rating scales will first be used since it requires less computations, thus easier to delineate. In Section 4.3, an example calculation will be performed using the relative rating scale derived from paired comparisons.

Using the QFD matrix in Figure 4.2 as an illustration, the estimate of the customer competitive assessment value of competitor A for requirement 3, $CCA_{A,3}$, is calculated below using Equation 4.2. The CCA values in this instance are based on the five point absolute rating scale.

$$CCA_{A,3} = \frac{[3(0) + 4(0) + 3(9) + 4(0) + 5(0) + 1(1) + 1(1) + 3(1) + 3(3)]}{(0 + 0 + 9 + 0 + 0 + 1 + 1 + 1 + 3)} = 2.7$$

The estimates of the customer competitive assessment values are summarized in Table 4.2. Discrepancies between the actual and estimated values can be caused by many different reasons, including inconsistencies. This will be discussed further in Section 4.2.

Similarly, the technical competitive assessments can be estimated using the relationship matrix and the customer competitive assessments as shown in Equation 4.3. The technical competitive assessment of product k for DDP i, $TCA_{k,i}$, is formed by the

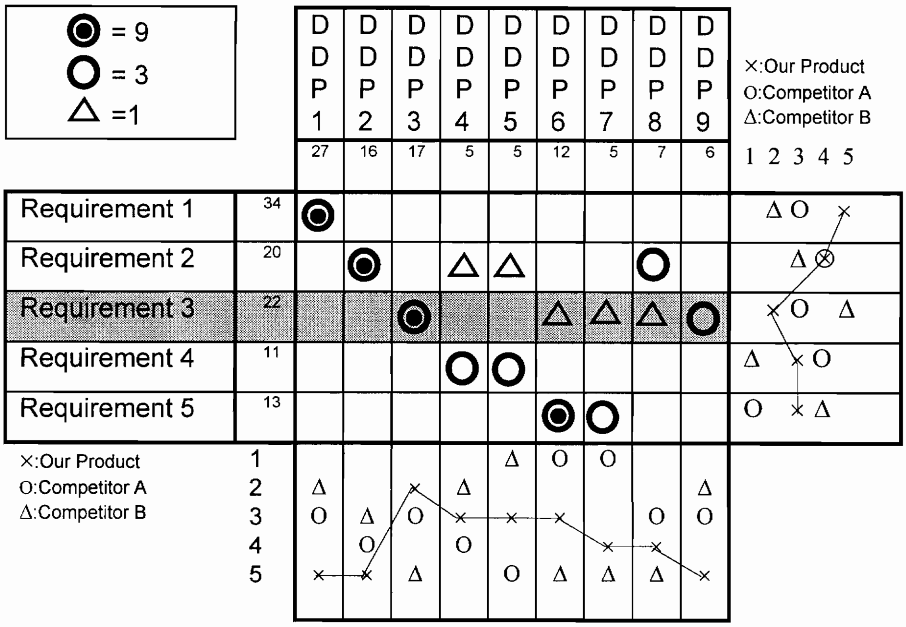

Figure 4.2. Example QFD matrix for use with Equation 4.2.

sum of the products of the customer competitive assessments of product k for customer requirement j, $CCA_{k,j}$, and the quantified relationship values of customer requirement j and DDP i, $R_{i,j}$, divided by the sum of the quantified relationship values of customer requirement j and DDP i, $R_{i,j}$, for the entire column. The same assumptions for Equation 4.2 still apply for Equation 4.3.

Table 4.2. Customer competitive assessment value estimates for absolute ratings.

Customer Requirement	Company Product (×)		Competitor A (O)		Competitor B (Δ)	
	Estimated CCA	Actual CCA	Estimated CCA	Actual CCA	Estimated CCA	Actual CCA
1	5	5	3	3	2	2
2	4.5	4	3.9	4	3.2	3
3	2.9	2	2.7	3	4.4	5
4	3	3	4.5	4	1.5	1
5	3.3	3	1	1	5	4

$$TCA_{k,i} = \frac{\sum_{j=1}^{n} (CCA_{k,j} \cdot R_{i,j})}{\sum_{j=1}^{n} R_{i,j}} \tag{4.3}$$

where

$TCA_{k,i}$: technical competitive assessment value of product k for DDP i, $k = 1, 2, ..., p$; $i = 1, 2, ..., m$.

$CCA_{k,j}$: customer competitive assessment value of product k for requirement j; $k = 1, 2, ..., p; j = 1, 2, ..., n$.

$R_{i,j}$: quantified relationship between customer requirement j, and DDP i; $j = 1, 2, ..., n$; $i = 1, 2, ..., m$.

Using the QFD matrix from Figure 4.3 as an illustration, the estimates of the technical competitive assessment values are calculated using the customer ratings (i.e., five point absolute scale) and the relationship matrix as summarized in Table 4.3. For

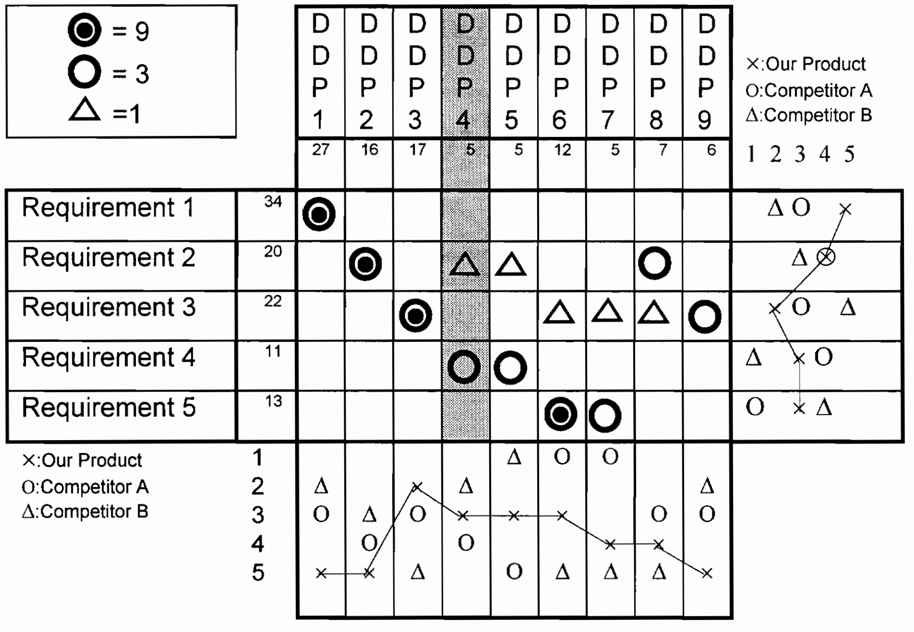

Figure 4.3. Example QFD matrix for use with Equation 4.3.

example, the estimate of the technical competitive assessment value of competitor A for DDP 4, $TCA_{A,4}$, is calculated below using Equation 4.3.

$$TCA_{A,4} = [3(0) + 4(1) + 3(0) + 4(3) + 1(0)] / (0 + 1 + 0 + 3 + 0) = 16/4 = 4.0$$

The discrepancies between the actual and estimated values, including inconsistencies, will be discussed in Section 4.2. Similar to estimating the customer competitive assessments, Equation 4.3 can also be used for relative ratings that have been calculated by paired comparisons.

Table 4.3. Technical competitive assessment value estimates for absolute ratings.

DDP	Company Product (×)		Competitor A (O)		Competitor B (Δ)	
	Estimated TCA	Actual TCA	Estimated TCA	Actual TCA	Estimated TCA	Actual TCA
1	5	5	3	3	2	2
2	4	5	4	4	3	3
3	2	2	3	3	5	5
4	3.3	3	4	4	1.5	2
5	3	3	4	5	2	1
6	2.9	3	1.2	1	4.1	5
7	2.8	4	1.5	1	4.3	5
8	3.5	4	3.8	3	3.5	5
9	2	5	3	3	5	2

4.2. USING THE DEVELOPED RELATIONSHIP TO TEST FOR INCONSISTENCIES IN THE QFD MATRIX

Given the importance of obtaining a consistent QFD matrix, the relationship between the technical and competitive assessments offers the opportunity for another consistency check before continuing the QFD process. Theoretically, if all of the essential DDPs have been identified, if the relationship matrix is consistent, and if the judgments of the customers and the design team are consistent, then the relationship should "perfectly" translate the technical competitive assessments into customer competitive assessments (i.e., the estimates of the customer assessments should exactly match the actual values from the customers). However, since at best, the design team hopes to identify most of the essential DDPs, to have a relatively consistent relationship matrix, and to obtain relatively consistent judgments between the customers and the design team, the estimates will only be consistent with the actual values to the degree in which those individual components are consistent.

Let the term "consistent" be defined as the estimate and the actual value having the same relative rankings with the same relative associated values. For example, for requirement 1, if the customers chose the company's product as the best product, followed by competitor B, and so on, then, under requirement 1, the estimate should also indicate that the company's product is the best product, followed by competitor B, and so on. In addition, the values associated with the assessments do not have to necessarily match, but should be relatively similar to each other. For example, using the customer competitive assessment estimates calculated in Section 4.1 and reillustrated in Table 4.4, for customer requirement 4, the actual customer competitive assessments were 3, 4, and 1, respectively, for the products of the company, competitor A, and competitor B. The estimated customer competitive assessments using the relationship were 3, 4.5, and 1.5, respectively. Clearly, the rankings were consistent and the values associated with the products for the requirement were relatively similar; thus, the estimate was consistent with the actual values. Similarly, the values for customer requirements 1 and 5 are consistent.

Table 4.4. Consistency among actual and estimated customer competitive assessments.

Customer Reqmt	Company Product (×)		Competitor A (O)		Competitor B (Δ)		Consistent ?
	Estimated CCA	Actual CCA	Estimated CCA	Actual CCA	Estimated CCA	Actual CCA	
1	5	5	3	3	2	2	Yes
2	4.5	4	3.9	4	3.2	3	Maybe
3	2.9	2	2.7	3	4.4	5	No
4	3	3	4.5	4	1.5	1	Yes
5	3.3	3	1	1	5	4	Yes

When the rankings between the estimate and the actual values are inconsistent, the values should also be reviewed. Consistency is still possible when the values of two or more of the products are close to one another. For example, suppose that the actual customer competitive assessments were 4, 4, and 3, respectively, for the company's product, competitor A, and competitor B, and that the estimated customer competitive assessments using the relationship were 4.1, 3.9, and 3.2, respectively. In the actual rankings, the company's product and competitor A's product are ranked the same, and in the estimated rankings, the company's product is ranked better than the product of competitor A. However, upon further review of the values, they are similar enough to deem consistent. Looking at the estimates for requirement 2 in Table 4.4, the rankings are inconsistent and the values are somewhat similar. In cases such as this, when it is unclear whether or not the values are consistent, the QFD matrix should be checked for possible inconsistencies.

If both the rankings and the values are inconsistent, then the estimate is inconsistent with the actual values and the QFD matrix must be checked for possible inconsistencies. Several possible causes of inconsistency include a nonessential DDP, an inconsistency in the relationship matrix, and/or an inconsistency with the technical competitive assessments (and maybe even a problem with the customer competitive assessments, but not as likely). For example, using the data in Table 4.4 for customer requirement 3, the actual customer competitive assessments were 2, 3, and 5, respectively, for the company's product, competitor A, and competitor B. The estimated customer competitive assessments using the relationship were 2.9, 2.7, and 4.4, respectively. Not only are the rankings inconsistent, but also the estimate value for the company's product seems too high relative to the other two products. Therefore, there is a possible inconsistency in this matrix. Further review of the QFD matrix (Figure 4.2) reveals that the company's product is better than competitor A's product for four of the five DDPs related to customer requirement 3, although the customer felt that the company's product was the worst product for requirement 3. Since the relationships of most of the DDPs are weak, some may be unneccessary, depending on their relationship with other customer requirements. In addition, this inconsistency may indicate that more essential DDPs need to be addressed for this requirement.

The technical competitive assessment estimates can also be used to check for inconsistencies. However, since there are generally more DDPs than customer requirements in the QFD matrix, the DDP row may have fewer relationships with the customer requirements. The fewer the number of relationships, especially in the absense of strong relationships, the more sensitive the technical competitive assessment estimates are to inconsistencies. As such, inconsistencies in the estimated technical competitive assessment values can indicate a nonessential DDP (if it only has weak relationships), an inconsistency in the relationship matrix, an inconsistency with the technical competitive assessments, or nothing (i.e., nothing is wrong). To further illustrate, using the data in Table 4.5 for DDP 9, the actual technical competitive assessments were 5, 3, and 2, respectively, for the company's product, competitor A, and competitor B. The estimated technical competitive assessments using the relationship were 2, 3, and 5, respectively. Thus, the rankings and values are completely reversed. Since there is only one relationship for DDP 9, and it is a moderate relationship, the DDP may be nonessential and should be replaced with one that is more strongly related to the customer requirements, if possible. However, if the design team decided that this DDP was essential, then they may have to keep the inconsistency in the QFD matrix. Therefore, both customer and technical competitive assessment estimates should used in conjunction with one another to aid in determining inconsistencies. Table 4.5 summarizes the consistency of each technical competitive assessment estimate.

4.3. AN INDICATOR OF A NEW PRODUCT CONCEPT'S VIABILITY IN THE MARKETPLACE

After the QFD matrix has been checked and corrected for inconsistencies using the techniques developed in this paper as well as from Chilakapati [1995], it can then be used to indicate a new product concept's viability in the marketplace. Using the example QFD matrix in Figure 4.4, which has been checked and corrected for inconsistencies, suppose

Table 4.5. Consistency among actual and estimated technical competitive assessments.

DDP	Company Product (×)		Competitor A (O)		Competitor B (Δ)		Consistent ?
	Estimated TCA	Actual TCA	Estimated TCA	Actual TCA	Estimated TCA	Actual TCA	
1	5	5	3	3	2	2	Yes
2	4	5	4	4	3	3	Yes
3	2	2	3	3	5	5	Yes
4	3.3	3	4	4	1.5	2	Yes
5	3	3	4	5	2	1	Yes
6	2.9	3	1.2	1	4.1	5	Yes
7	2.8	4	1.5	1	4.3	5	Yes
8	3.5	4	3.8	3	3.5	5	No
9	2	5	3	3	5	2	No

the design team has evaluated a new product concept[1] using paired comparisons against the company's two main competitors for each DDP as shown in Figure 4.5 (recall that the evaluation can also be performed using the absolute scale as discussed in Section 4.1).

		DDP 1	DDP 2	DDP 3	DDP 4	DDP 5	DDP 6	DDP 7	DDP 8
		29	17	18	5	5	13	6	7
Requirement 1	34	◉							
Requirement 2	20		◉		△	△			○
Requirement 3	22			◉			△	△	△
Requirement 4	11				○	○			
Requirement 5	13						◉	○	

Figure 4.4. Example QFD matrix to determine a new product concept's viability in the marketplace.

1 Note: The new product concept refers to a hypothetical product consisting of the newly defined DDP target values. No product is actually being produced at this point.

DDP 1

	A1	A2	A3
A1	1	5	7
A2	1/5	1	3
A3	1/7	1/3	1

DDP 2

	B1	B2	B3
B1	1	3	5
B2	1/3	1	3
B3	1/5	1/3	1

DDP 3

	C1	C1	C3
C1	1	1/3	1/7
C2	3	1	1/5
C3	7	5	1

DDP 4

	Co.	A	B
Co.	1	1/3	3
A	3	1	5
B	1/3	1/5	1

DDP 5

	Co.	A	B
Co.	1	1/3	3
A	3	1	5
B	1/3	1/5	1

DDP 6

	Co.	A	B
Co.	1	5	1/3
A	1/5	1	1/7
B	3	7	1

DDP 7

	Co.	A	B
Co.	1	1	1/3
A	1	1	1/3
B	3	3	1

DDP 8

	Co.	A	B
Co.	1	1	3
A	1	1	3
B	1/3	1/3	1

Figure 4.5. Example matrices of paired comparisons for a new product concept.

In order to perform the evaluation, the design team must use the target values for the new product and compare these target values to the current values of the competitors. For example, with respect to a particular DDP, if the actual value of the best competitor was 10 lbs and the target value for the new product was 9 lbs, then the new product would be better than the best competitor if less weight is better. The design team must then determine how much better the new product would be for that particular DDP. Thus, it is essential that the chosen targets be as realistic as possible and that the design team is experienced enough with the product to make such judgments. This may be a difficult task since information during the conceptual design phase is generally poor or unavailable.

Upon completing the product evaluations for each DDP, the technical relative importances are calculated as well as the technical GPW as shown in Table 4.6. Since the new product concept has the highest technical GPW in this instance, it is expected to be better than the two competitors (at their current state) when it is introduced into the marketplace, as long as it is produced to the target specifications in the QFD matrix.

Table 4.6. Summary of all technical relative importances and GPWs.

DDPs	*DDP1*	*DDP2*	*DDP3*	*DDP4*	*DDP5*	*DDP6*	*DDP7*	*DDP8*	**GPW**
DDP Importances	0.285	0.168	0.185	0.049	0.049	0.130	0.057	0.076	N/A
New Product	0.731	0.637	0.081	0.258	0.258	0.279	0.200	0.429	**0.439**
Competitor A	0.188	0.258	0.188	0.637	0.637	0.072	0.200	0.429	**0.247**
Competitor B	0.081	0.105	0.731	0.105	0.105	0.649	0.600	0.143	**0.314**

In addition to calculating the technical GPW, the technical competitive assessments can be "translated" into the customer competitive assessments using Equation 4.2 as summarized in Table 4.7. The customer competitive assessment can be used to indicate what the customers might think of the hypothetical new product for each essential customer requirement without actually showing it to any customers. This is especially helpful when the new product is unavailable to the customers for evaluation.

Thereafter, the customer GPW can be calculated, as shown in Table 4.7, for comparison with the technical GPW. Since inconsistencies have been identified and corrected prior to the evaluations of the new concept, the two indicators of product viability in the marketplace should be consistent with one another, as shown by comparing Table 4.6 and 4.7. However, by performing both GPWs, the design team is reassured of the results. Also, having two measures might help during analysis, especially when two products are closely rated. Finally, with the absense of better indicators, the new customer GPW calculated from the translated competitive assessments is the best indicator of how the customers might evaluate the conceptual product against the competitors.

Table 4.7. Summary of expected customer relative importances and GPWs.

Requirements	*Reqmt 1*	*Reqmt 2*	*Reqmt 3*	*Reqmt 4*	*Reqmt 5*	**GPW**
Importances	0.34	0.20	0.22	0.11	0.13	N/A
New Product	0.731	0.538	0.136	0.258	0.259	**0.448**
Competitor A	0.188	0.349	0.199	0.637	0.104	**0.261**
Competitor B	0.081	0.113	0.664	0.105	0.637	**0.291**

4.4. PERFORMING TRADE-OFF ANALYSES

In section 4.3, the application of the AHP to QFD was used to indicate a new product concept's viability in the marketplace without actually producing the product. The process assumed that the design team has determined the "best estimate" targets for each DDP. However, the design team may have to make trade-offs on the targets due to budgetary constraints, technology constraints, knowledge constraints, material constraints, and other resource constraints. Thus, one natural extension to this process is to use it to facilitate trade-off analyses.

The trade-off of DDPs is a function of DDP relative importances, the technical competitive assessments, and the ease and cost of improving the DDPs. Although the design team may be able to determine the ease and cost of improving individual DDPs as well as the other factors, they may not be able to determine the optimal design improvement targets to maximize overall customer satisfaction and profits.

There are several methods the design team can use for trade-off analyses. One method would be to determine the marginal value of dollars spent for each DDP. That is, the target value of one DDP at a time (from the current design) can be altered and then the change (in percent) from the new resulting GPW to the old GPW can be divided by the expected dollars needed for the enhancement multiplied by a factor such as 100,000 (to convert to a larger scale). The result is a measure of percentage change in GPW per $100,000. For example suppose it costs $500,000 to decrease the DDP target value by one unit, which increases the new technical GPW by 5%. Then, the percentage change in GPW per $100,000 would be 1.0. The value is then compared to the other marginal values while changing one DDP target value at a time. This method assumes that the investment in design is continuous, when it actually it is often a step function (e.g., must spend at least $400,000 for design change, etc.). However, this is a simple means of determining marginal value of dollars.

Another method of performing trade-off analyses is to calculate the GPWs for all possible combinations of DDP improvements that meet the resource constraints. The combination that results in the highest GPW is the optimal combination. For example, suppose that a design team is limited to spending up to $1,000,000 for design improvements. The design team has two options: 1) spend all the capital on one difficult to improve DDP with a high relative importance, in which the company is lagging behind their competitors or 2) spend the capital on three easy to improve DDPs with moderate relative importances, in which the company is at par with their best competitors, but the improvements would help differentiate the company's product from the competitors. In determining the best option, the design team can calculate the GPWs for both options and use the result as an input into the budget allocation decision process.

CHAPTER 5

SUMMARY, EXTENSIONS, AND CONCLUSIONS

This chapter begins by summarizing the contributions of this research. Thereafter, some possible research extensions are discussed. Finally, the relevance of this research is discussed as part of the conclusions.

5.1. SUMMARY OF RESEARCH CONTRIBUTIONS

This research adds to the body of knowledge pertaining to the conceptual system design phase within systems engineering and analysis. Specifically, this research concludes with the integration of a multi-attribute decision-support methodology, the Analytic Hierarchy Process (AHP), with a customer-focused design methodology, Quality Function Deployment (QFD). The resulting hybrid is more complete than either of the two alone, involving the synthesis, analysis, and evaluation activities necessary for completing conceptual system design. Specific and unique contributions of this research are:

1. *Summarization of the QFD methodology.* The basic QFD methodology was discussed along with a compilation of some relevant new advancements to QFD. (Chapter 2)

2. *Development of an indicator for the overall performance of an organization's product and its competitors using the QFD matrix and the*

AHP. An indicator was developed to determine the overall performance of the products under the customer and technical competitive assessments by extending the basic QFD technique with the AHP. To develop the indicator, the AHP was used to aggregate the customer requirements, the relative importances of the customer requirements, and the customer competitive assessments to determine a normalized set of priorities (called customer global priority weights, GPWs) for each product under consideration. The product with the highest priority is the most preferred, and so on. Similarly, the AHP was used to aggregate the design dependent parameters (DDPs), the relative importances of the DDPs, and the technical competitive assessments to determine another normalized set of priorities (called technical GPWs) for each product under consideration. (Chapter 3)

3. *Development of a methodology to assess if the essential customer requirements have been identified in the QFD matrix.* Given the importance of identifying the essential customer requirements in the QFD matrix due to the downstream activities affected by the this step, a methodology was developed to assess if the essential customer requirements have been identified. To determine if the essential customer requirements have been identified in the QFD matrix, the customer GPWs are compared with a new set of ratings on the overall performance of the products given by potential customers. If the two indicators of product performance are consistent, then the essential customer requirements are sufficiently identified and the QFD matrix is representative of the voice of the customer. However, if the two indicators of product performance are inconsistent, then the QFD matrix does not adequately reflect the voice of the customer and the design team should check that the essential customer requirements have been identified. (Chapter 3)

4. *Development of a methodology to assess if the customer inputs have been sufficiently translated into design dependent parameters in the QFD matrix.* Given the importance of identifying the essential DDPs in the QFD matrix due to the downstream activities affected by the this step, another methodology was developed to assess if the essential DDPs have been identified. Similar to identifying if the essential customer requirements have been determined, the identification of sufficient translation of customer requirements into DDPs is performed by comparing the technical GPWs with the overall ratings of product performance given by potential customers. If the two indicators of product performance are consistent, then the customer requirements have been sufficiently translated into DDPs. However, if the two indicators of product performance are inconsistent, then the customer requirements have not been sufficiently translated into DDPs and the design team should check that the essential DDPs have been identified. (Chapter 3)

5. *Development of a mathematical relationship between the customer and technical competitive assessments within the QFD matrix.* A mathematical relationship was developed between the customer and technical competitive assessments in the QFD matrix through the use of a weighted average technique. (Chapter 4)

6. *Development of a methodology to test for inconsistencies in the QFD matrix.* The mathematical relationship between the customer and technical competitive assessments within the QFD matrix can be used to translate actual technical competitive assessment values into estimated customer competitive assessment values. The estimated customer competitive assessment values can then be compared with the actual customer competitive assessment values. If the two assessment values are consistent, then the QFD matrix is consistent. However, if the two

assessment values are inconsistent, then the QFD matrix is inconsistent and the design team should check for sources of inconsistencies. Similarly, the mathematical relationship between the customer and technical competitive assessments within the QFD matrix can also be used to translate actual customer competitive assessment values into estimated technical competitive assessment values. The estimated technical competitive assessment values can then be compared with the actual technical competitive assessment values. If the two assessment values are consistent, then the QFD matrix is consistent. However, if the two assessment values are inconsistent, then the QFD matrix is inconsistent and the design team should check, again, for sources of inconsistencies. (Chapter 4)

7. *Development of an indicator to assess how well a new product concept would perform in the marketplace using the QFD matrix and the AHP.* After any inconsistencies within the QFD matrix have been identified, the design team can perform a technical competitive assessment on a new product concept and then utilize the AHP to calculate the new technical GPWs. This overall indicator of product performance can be used to indicate the viability of the new product concept in the marketplace. In addition, the relationship between the customer and technical competitive assessments can be used to translate the technical competitive assessment values of the new product concept into estimated customer competitive assessment values. Thereafter, the AHP can be used to calculate the new customer GPWs based on the estimated values. Again, this can be used to indicate the viability of the new product concept in the marketplace. (Chapter 4)

8. *Development of a methodology to facilitate trade-off analyses using the QFD matrix and the AHP.* Given the limitations of designs due to

restrained budgets and other resource constraints, the design team must perform trade-off analyses between design options. Thus, a methodology was developed to facilitate design trade-offs using the information in the QFD matrix in conjunction with the AHP. (Chapter 4)

5.2. POSSIBLE RESEARCH EXTENSIONS

This research has investigated the integration of two separate methodologies in the search for obtaining a more complete methodology than either of the two alone. Some possible research extensions for further exploration are:

1. *Application of fuzzy set theory.* Fuzzy set theory is often used to address uncertainty. Both the QFD methodology and the AHP lend themselves well to fuzzy set theory because customers often describe customer requirements in linguistic terms and often use linguistic scales to describe satisfaction levels (such as absolute satisfaction to absolute dissatisfaction). Although fuzzy set theory has been applied to both methodologies individually, it may be also be applied to the hybrid methodology described herein to capture the imprecision and uncertainty of design variables. This further research could enhance the applicability of the methodology.

2. *Validation of methodology.* Validation of the methodology developed in this research was considered beyond the scope of this research. However, this should be conducted through applying it to a real case. Such a study is also likely to identify further extensions.

3. *Development of a measure of inconsistency for comparison between the customers' overall indicators and the GPWs.* When comparing the customers' overall indicators with the GPWs, the methodology requires that the design team manually examine the rankings of the products and

the values associated with the rankings. However, an indicator should be developed to determine the level of inconsistency between the customers' overall indicators and the GPWs. This would eliminate any confusion as to whether or not the design team has sufficiently identified the essential customer requirements and DDPs in the QFD matrix. Depending on the level of inconsistency, the design team should either continue the QFD methodology or check for sources of inconsistency.

4. *Development of an indicator of inconsistency for comparison between the estimated customer (or technical) competitive assessments and the actual values.* When comparing the estimated customer (or technical) competitive assessments with the actual values, the methodology requires that the design team manually examine the rankings of the products and the values associated with the rankings. However, an indicator should be developed to determine the level of inconsistency between the estimated and actual values. This would eliminate any confusion as to whether or not the QFD matrix is consistent. Depending on the level of inconsistency, the design team should either continue the QFD methodology or check for sources of inconsistency.

5. *Development of a computer model integrating the methodology.* Although the design team can manually perform the methodologies presented herein, the work would be tedious and time consuming. Accordingly, the development of a computer tool integrating the methodologies would be invaluable to the design team. In addition, further additions to the computer tool can be added as needed, such as a decision support system to help identify inconsistencies.

6. *Development of an aggregate measure that integrates the customer requirements, relative importances of customer requirements, competitive assessments, ease of change, and resource constraints to facilitate trade-*

off analyses. The methodologies for trade-off analyses presented in this research focused mainly on the GPWs, which are an aggregate of the customer requirements (or DDPs), the relative importances, and the competitive assessments. However, a broader indicator consisting also of ease of change and resource constraints, such as cost, should be developed to further facilitate trade-off analyses.

7. *Application to downstream QFD matrices*. The methodologies presented herein were applied to the first QFD matrix called the House of Quality. However, the methodologies may also be applied to downstream QFD matrices. This should be further refined to enhance the applicability of the methodology.

8. *Integration with Pugh's concept generation and evaluation methodology*. Pugh [1990] has developed an approach in which a design team considers a number of concepts and selects the one that best fits the requirements. The method uses a matrix called the Controlled Convergence Matrix (CCM), which compares every concept against the most essential criteria for a product. Concepts are assessed to be "better" (+), "worse" (-) or the "same" (s) as the best of the competition. Weak concepts are dropped and new concepts are developed that produce more +s, evolving the product towards requirements. The application of Pugh's concept generation and evaluation methodology to QFD has been performed by several companies and its application should be pursued with the hybrid methodology presented herein.

9. *Classification of the scales produced from the AHP*. Saaty [1990] and Vargas [1979] assert that the pairwise comparison process produces ratio scales and that the resulting Global Priority Weights (GPWs) are also ratio scales (for more information regarding scaling properties, see [Torgerson, 1958]). However, it appears that the scales produced throughout the AHP

may merely be ordinal scales. That is, using the AHP, one could deem an alternative to be better than another, but could not use the results to determine how much better. Under Saaty's and Vargas' assertion, the scales <u>could</u> be used to determine how much better one alternative is than another. This should be further investigated to aid in the interpretation of the results obtained from the AHP.

5.3. CONCLUSIONS

This research was successful in integrating the QFD methodology and the AHP into a hybrid methodology more complete than either of the two alone. Some concluding observations and comments on relevance may help to facilitate the application of the methods developed in this thesis.

First, when the overall customer assessment of products is calculated using the AHP and the QFD matrix and compared with the customers' overall assessment, the design team gains insight relative to the completeness of the "model" they have developed. It is then possible to make changes in order to realize improvements. This is an iterative process that refines the "model" as new customer requirements are determined.

Similarly, when the overall technical assessment is compared with the customers' overall assessment and the estimated competitive assessments are compared with the actual competitive assessments, the design team gains more insight relative to how well they have addressed the customers' requirements. Again, it is then possible to make changes to realize improvements in terms of changing the design dependent parameters and the relationship matrix.

Finally, the design team can gain insight as to a product concept's viability in the marketplace using the methodology developed in this research. Although this methodology is clearly not as complete as actually producing the product and presenting it to potential customers for evaluation, it can still save the design team in terms of time and resources during the early phases of conceptual design.

APPENDIX
THE ANALYTIC HIERARCHY PROCESS (AHP)

The purpose of this appendix is to briefly describe the Analytic Hierarchy Process (AHP). An example is integrated with the discussion to help convey the concepts. For a more exhaustive coverage of the AHP, refer to [Canada et al, 1996; Saaty, 1990; Vargas, 1990].

A.1. INTRODUCTION AND BACKGROUND

The Analytic Hierarchy Process (AHP) is a theory of measurement predominantly used as a decision tool for dealing with quantifiable and/or intangible criteria (i.e., unquantifiable criteria). The AHP, which was first developed by Thomas Saaty in 1980, has reported applications in numerous fields, such as economic/management problems, political problems, social problems, and technological problems [Saaty, 1990; Vargas, 1990]. The AHP enables the comparison of tangible criteria along with intangible criteria (e.g., *Life-Cycle Cost* would be tangible/quantifiable whereas *Quality* would be somewhat intangible/unquantifiable) through normalization and the use of unitless ratios (i.e., by dividing the *Life-Cycle Cost* for alternative A by the *Life-Cycle Cost* for alternative B, the dollars would cancel out leaving a unitless ratio that can be compared to other unitless ratios). In addition, the AHP forces a problem to be broken into its constituent parts, which allows the problem to be solved by applying simple paired (or pairwise) comparison judgments. Finally, the AHP is attractive to users because it includes a consistency checking mechanism for the paired comparisons. The following discussion will provide a detailed orientation of the AHP theory including paired comparisons, consistency ratios, and priority weights.

Selected commercial software packages are available which implement the AHP method. The package developed by Decision Support, Inc., **Expert Choice**®, is a generic decision problem software package. Another package (public domain) developed by the U.S. Department of Commerce, **AutoMan**®, is specifically designed for evaluating manufacturing alternatives, but can be used for general decision problems as well.

The AHP consists of three phases: (a) synthesis of the relevant parameter hierarchy, (b) its analysis, and (c) evaluation. In synthesizing the hierarchy, Level I (i.e., top level; also called the *Focus*) of the hierarchy represents the overall objective of the decision, followed by subsequent levels consisting of attributes and sub-attributes (see Figures A.1 and A.2). The attributes of each level must be of same magnitude since they are compared with one another at the next higher level [Vargas, 1990]. For example, *Reliability*, *Maintainability*, and *Supportability* are subsets of *Availability*. Therefore, they cannot be on the same level as *Availability*; but can be on the next lower level.

Figure A.1 shows the typical form of the hierarchy of the AHP. The number of levels used in the hierarchy must be chosen to effectively represent the overall objective. In addition, each attribute should be limited to between 5 and 9 subattributes to remain effective; enough to describe the level in adequate detail, but without excessive complexity [Canada, et al, 1996]. The design of hierarchies can be an iterative process and must be done with care [Vargas, 1990].

A.2. THEORY AND CONCEPTS

Synthesis of relevant parameter hierarchies is unique to each individual designer. Thus, the AHP requires experience and knowledge of the problem area. A group of people may design the hierarchy by reaching consensus [Vargas, 1990]. Figure A.2 illustrates an example hierarchy design for a project in which the objective of the decision is to determine which commercial off-the-shelf (COTS) alternative is to be procured.

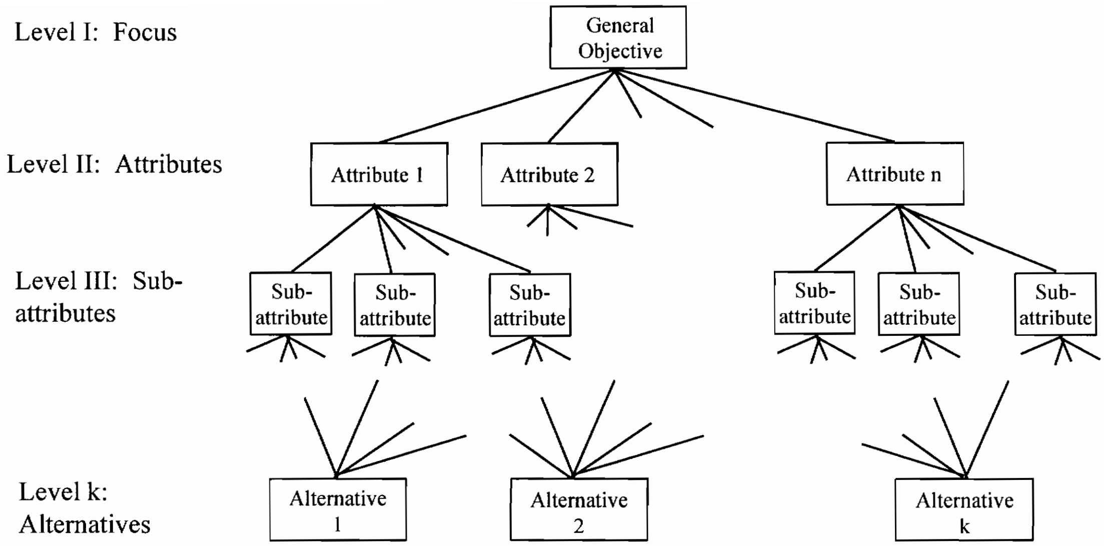

Figure A.1. A typical parameter/attribute hierarchy.

The analysis phase of the AHP begins with paired comparisons. The attributes in each level of the hierarchy are compared with one another in relative terms as to their importance/contribution to the criterion that occupies the level immediately above the attributes being compared. For example, a decision maker responds to a question that compares two attributes *a* and *b* in terms of importance or preference: "With respect to [overall objective], how much more important/preferred is [attribute *a*] than [attribute *b*]." The choices of answers to the above question are listed in Table A.1. In addition, the answers are "converted" into a numerical equivalent ranging from 1 to 9 (and their reciprocals). However, if it turns out that attribute *a* is **less** important/preferred than attribute *b* (as opposed to **more** important/preferred), then the numerical numbers would be the reciprocals, e.g., *x* would be *1/x* [Canada, et al, 1996].

When all paired comparisons for Level II are completed, the result is a matrix of paired comparisons (note that if *a* has been compared to *b*, then the comparison if *b* to *a* is merely the reciprocal; also the comparison of *a* to *a* is always 1). Table A.2 illustrates an example matrix of the paired comparisons for the COTS decision example shown in Figure A.2. For example, in Table A.2, *Life-Cycle Cost* (A) is equally important as

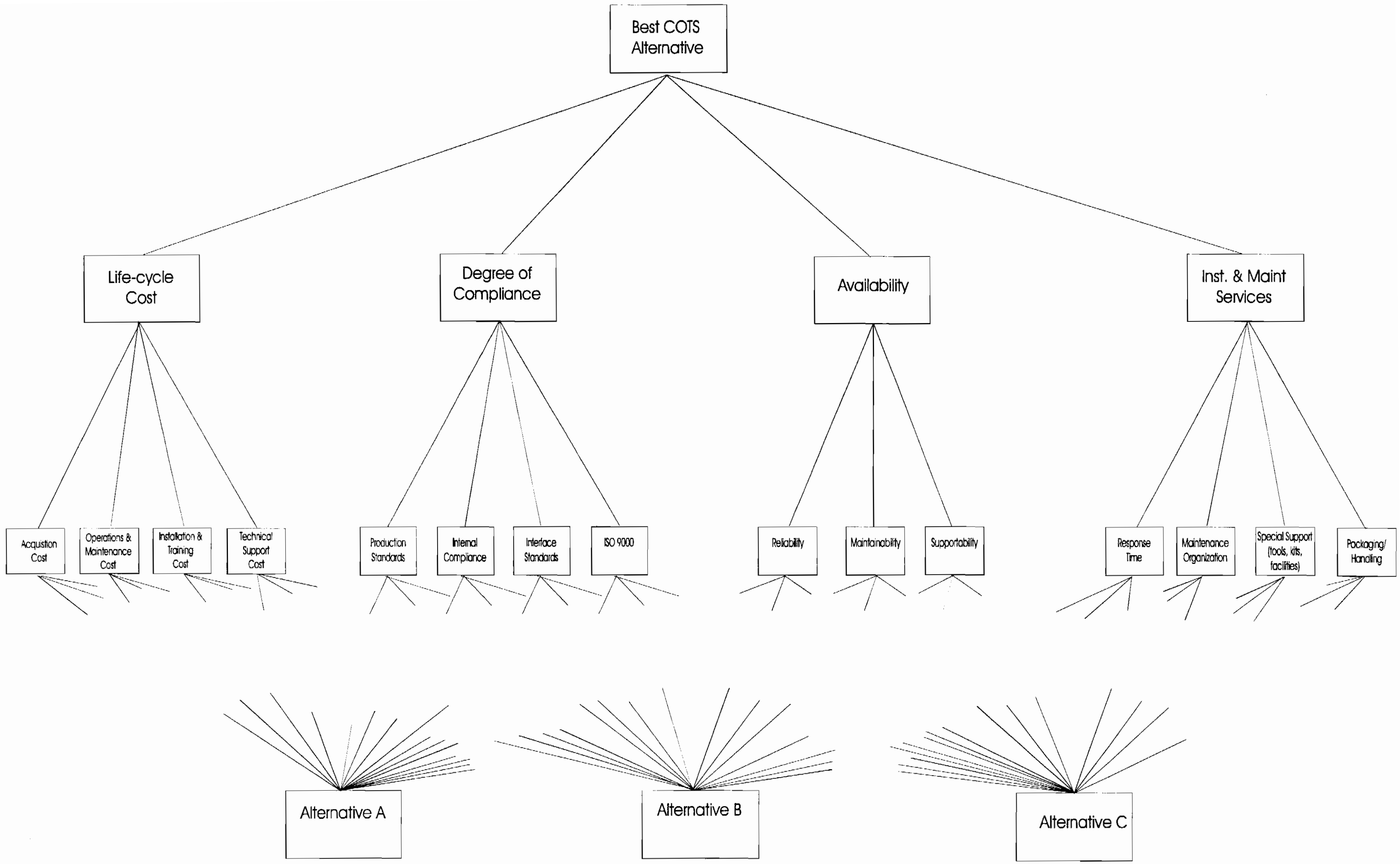

Figure A.2. Sample hierarchy design for a COTS decision.

Table A.1. Suggested degrees of preference.

If answer is	then the numerical preference is $a \geq b$	$a \leq b$
equally important/preferred,	1	1
weakly (less) more important/preferred,	3	(1/3)
strongly more (less) important/preferred,	5	(1/5)
very strongly more (less) important/preferred,	7	(1/7)
absolutely more (less) important/preferred,	9	(1/9)
Note that even numbers (2, 4, 6, 8) are used to represent compromises between the above preferences.		

Degree of Compliance (B) and strongly more important than *Installation & Maint. Services* (D). Subsequent to the paired comparisons, a relative scale of measurement of the attributes' priorities or weights can be calculated using the principal right eigenvector method (for more information, see [Saaty, 1990]). These relative weights, which are normalized to one, are calculated for all attributes in the hierarchy [Canada, et al, 1996].

The eigenvector of a matrix can be calculated by most matrix/math computer programs such as MatLab®, which raise the matrix to a large power until the numbers converge [Saaty, 1990]. After the eigenvectors are determined, they are normalized to 1 simply by dividing each value by the total sum. Saaty has developed an approximation method for calculating the eigenvectors of a matrix, but with the aid of computers, this is unnecessary (for more information regarding this approximation method, see [Canada, et al, 1996]). Note that the normalized eigenvectors have been calculated in Table A.2.

Table A.2. Matrix of paired comparisons for Level II.

With Respect to the "Best COTS Alternative"	A	B	C	D	Normalized Eigenvectors
A. Life-Cycle Cost	1	1	3	5	0.390
B. Degree of Compliance	1	1	3	5	0.390
C. Availability	1/3	1/3	1	3	0.152
D. Inst. & Maint. Services	1/5	1/5	1/3	1	0.068

The next step is to perform a consistency check to ensure validity for the suggested degrees of preference of the attributes. The consistency ratio (CR) is an approximate indicator of the consistency of the paired comparisons. It is based on the deviation from the perfect cardinal consistency (i.e., if attribute X is 3 times more important than attribute Y, and alternative Y is 3 times more important than alternative Z, then alternative X should be 9 times more important than alternative Z; the CR is based on the deviation of the paired comparisons from these relationships; for more information regarding this see [Saaty, 1990]). Saaty [1990] suggests that if the CR is less than or equal to 0.10, then the consistency is generally acceptable. However, if the CR is greater than 0.10, the paired comparisons should be rechecked [Canada, et al, 1996].

To compute the CR, the matrix of paired comparisons (i.e., the matrix in Table A.2) must be multiplied with the principle vector of priority weights (i.e., the normalized eigenvectors in Table A.2). This procedure is shown below using the values from Table A.2. Note the resulting vector is labeled "[C]".

$$\underset{[A]}{\begin{bmatrix} 1 & 1 & 3 & 5 \\ 1 & 1 & 3 & 5 \\ 1/3 & 1/3 & 1 & 3 \\ 1/5 & 1/5 & 1/3 & 1 \end{bmatrix}} \bullet \underset{[B]}{\begin{bmatrix} 0.390 \\ 0.390 \\ 0.152 \\ 0.068 \end{bmatrix}} = \underset{[C]}{\begin{bmatrix} 1.576 \\ 1.576 \\ 0.616 \\ 0.275 \end{bmatrix}}$$

The next step is to divide the elements in vector [C] by the corresponding elements in vector [B]. The result is vector [D], whose average is the approximate maximum eigenvalue, λ_{max}. λ_{max} is used to calculate the consistency index (CI) (see below for the sample calculations).

Using the vectors from the previous sample calculations:

$$[D] = |1.576/0.39,\ 1.576/0.39,\ 0.616/0.152,\ 0.275/0.068|$$

$$= |4.04,\ 4.04,\ 4.05,\ 4.04|$$

$$\lambda_{max} = [4.04 + 4.04 + 4.05 + 4.04]/4 = 4.04$$

The consistency index (CI) of a matrix of rank N is

$$CI = (\lambda_{max} - N)/(N - 1)$$

In this example, the CI is

$$CI = (4.04 - 4)/(4 - 1) = 0.01$$

Finally, the CI is compared (via ratio) to the random index (RI), which is based on values that would have been obtained had the paired comparison matrix been filled "randomly" (i.e., placing numbers from 1 to 9 and their reciprocals in the paired comparison matrix randomly without using any judgment). Saaty has calculated the RI (given in Table A.3), which were obtained from large numbers of simulation runs on a computer [Canada, et al, 1996].

Table A.3. The random indexes for various matrices of rank N.

N	1	2	3	4	5	6	7	8	9	. . .
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	. . .

Source: [Canada, et al, 1996].

Using the values from the sample calculations above, the calculation of the consistency ratio (CR) is shown below. Note that in this example, a matrix of rank N = 4 in Table A.2 has a corresponding RI of 0.90.

$$CR = CI/RI = 0.01/0.90 = 0.01$$

Since the CR < 0.10, the paired comparisons are reasonably consistent. The AHP process may continue. If the CR had been > 0.10, then the paired comparisons would have been rechecked. Expert Choice® contains an expert system to determine where the inconsistencies are possibly located. AutoMan® does not have this capability.

If there are levels below Level II (recall that Level I is the overall objective of the decision) consisting of sub-attributes such as in the example shown by Figure A.2, the sub-attributes also must be compared pairwise with respect to their parent attribute (as well as the consistency check). For example, under the attribute *Life-Cycle Cost*, the four sub-attributes (i.e., *Acquisition Cost*, *Operations & Maintenance Cost*, *Installation & Training Cost*, and *Technical Support Cost*) must be compared with one another with respect to *Life-Cycle Cost*. Table A.4 summarizes the matrix. In this example, the paired comparison matrix contains the same numbers as in Table A.2. Thus, the eigenvectors are the same as well as the CR.

When all sub-attributes have been compared pairwise, the alternatives must be compared pairwise with respect to the sub-attributes. For example, with respect to *Acquisition Cost*, *Alternative A* must be compared with *Alternative B*, and so on. The unique feature of these sets of paired comparisons is that the alternatives may be pairwise compared using subjective judgments (as previously done with the 1 to 9 scale) or compared using performance data (when available). For example, as shown in Table A.5, the *Acquisition Cost* (dollars) or the *Internal Compliance* (number or percentage of requirements satisfied) may be available or estimable. In this case, it is desirable to perform comparisons using the performance data since it is objective. However, the performance data must have a linear relationship for this method to work, i.e., $100 is twice as good (or bad) as $50.

Table A.4. Matrix of pairwise comparisons for the sub-attributes of Life-Cycle Cost.

With Respect to the "Life-Cycle Cost"	A	B	C	D	Normalized Eigenvectors
A. Acquisition Cost	1	1	3	5	0.390
B. Operations & Maint Cost	1	1	3	5	0.390
C. Installation & Training Cost	1/3	1/3	1	3	0.152
D. Technical Support Cost	1/5	1/5	1/3	1	0.068

Table A.5. Performance data for selected alternatives.

Attribute	Units	Alt A	Alt B	Alt C	Is higher better?
Internal Compliance	Req'ts Satisfied	1350	1000	1500	Yes
Acquisition Cost	Dollars	$3M	$5M	$3.5M	No

Referring to Table A.5, note that *Internal Compliance* is better with higher values (e.g., 1500 requirements satisfied is better than 1000 requirements satisfied; therefore Alternative C is better than Alternative B with respect to *Internal Compliance*). Conversely, *Acquisition Cost* is better with lower numbers (e.g., a cost of $3.5 million is better than a cost of $5 million; therefore Alternative C is better than Alternative B with respect to *Acquisition Cost*). In the case that higher is better, the numbers are simply normalized to 1 as shown below using the *Internal Compliance* data from Table A.5:

Alt A	1350 / (1350 + 1000 + 1500)	= 0.35
Alt B	1000 / (1350 + 1000 + 1500)	= 0.26
Alt C	1500 / (1350 + 1000 + 1500)	= 0.39
	Σ	= 1.00

In the case that lower is better, the minimum value (i.e., "best") is divided by each performance value. Then, the numbers are normalized to one as shown below using the *Acquisition Cost* data from Table A.5:

	Ratio		Normalized
Alt A	$3M / $3M	= 1.000	0.41
Alt B	$3M / $5M	= 0.600	0.24
Alt C	$3M / $3.5M	= 0.857	0.35
		Σ =	1.00

Table A.6 provides an example summary of all the calculated eigenvectors (also called priority weights) for the hierarchy design illustrated in Figure A.2 that would have been calculated up to this point. The top row of numbers, labeled "Attribute Weights", were the numbers calculated in Table A.2. The next row of numbers, labeled "Subattribute Weights", were calculated for *Life-Cycle Cost* in Table A.4. Finally, the next three rows of numbers, labeled "Alt A (Level IV) Weights", "Alt B (Level IV) Weights", and "Alt C (Level IV) Weights", were calculated by using the paired comparison method for subjective data or by using the performance data method described by using the data in Table A.5.

The global priority weight (GPW) is the overall priority weight (or eigenvector) of the alternatives in the form of a ratio scale, which sum to 1 [Saaty, 1990]. To determine the global priority weights (GPW) of the alternatives, compute the sum of the product of weights for all branches that include the alternative. For example, using Table A.5, the GPW for Alternative A is:

$$
\begin{aligned}
GPW(A) = \ & (0.39)[(0.390)(0.407) + (0.390)(0.319) + (0.152)(0.231) + (0.068)(0.400)] + \\
& (0.39)[(0.056)(0.188) + (0.650)(0.351) + (0.147)(0.178) + (0.147)(0.243)] + \\
& (0.152)[(0.333)(0.143) + (0.333)(0.258) + (0.333)(0.105)] + \\
& (0.068)[(0.522)(0.785) + (0.078)(0.429) + (0.200)(0.731) + (0.200)(0.655)] \\
= \ & 0.327
\end{aligned}
$$

Similarly, the GPW for Alternatives B and C are 0.253 and 0.422, respectively. Since the GPW for C is the highest (i.e., best), Alternative C is the recommended alternative to choose, given the inputs.

The AHP has proven to be an effective tool for making multicriteria decisions. It is relatively simple to use; it breaks down a problem into smaller, more manageable components by designing a hierarchy; it provides an effective means in quantifying intangible criteria; and it includes a consistency checking mechanism. However, there are several criticisms of using the AHP [Canada, et al, 1996]. First, since the method deals with intangible data, the judgments of relative importance should be performed by experts. Also, care must be taken not to violate the axioms of the AHP (listed below) when designing the hierarchy. An example of a problem with the AHP caused by violating axioms 3 and 4 is known as rank reversal, which is the reversing of rankings when a new alternative is introduced [Belton & Gear, 1983, Dyer, 1990, Watson & Freeling, 1982]. The axioms of the AHP [Vargas, 1990] are:

Axiom 1: *(Reciprocal Comparison). The decision maker must be able to make comparisons and state the strength of his preferences. The intensity of these preferences must satisfy the reciprocal condition: If A is x times more preferred than B, then B is 1/x times more preferred than A.*

Axiom 2: *(Homogeneity). The preference are represented by means of a bounded scale.*

Axiom 3: *(Independence). When expressing preferences, criteria are assumed independent of the properties of the alternatives.*

Axiom 4: *(Expectations). For the purpose of making a decision, the hierarchic structure is assumed to be complete.*

As stated in the introduction, the AHP has found uses in a wide range of decision problems (for a comprehensive listing of the AHP applications, see [Vargas, 1990]). In addition, since descriptions and judgments are linguistic and qualitative, new research is being done with the AHP by applying fuzzy logic [Mon, et al, 1994; Mon, 1994]. Finally, many researchers are looking at combining the AHP with other tools to create more robust tools. For example, the use of the AHP to prioritize customer requirements for use in Quality Function Deployment (QFD) is being studied [Wasserman, 1993; Armacost, et al, 1994].

Table A.6. Summary of all priority weights for the COTS example.

	Life-Cycle Cost				*Compliance*				*Availability*			*Installation & Maintenance Services*				GPW
Attribute Weights	**0.39**				**0.39**				**0.152**			**0.068**				N/A
Sub-attributes	Acq Cost	O&M Cost	Inst & Trng Cost	Tech Supp Cost	Prod Stds	Internal Com-pliance	Industry Stds	ISO 9000	Reli-ability	Maintain-ability	Support-ability	Response time	Maint. Org.	Special Support	Packaging & Handling	N/A
Subattribute Weights	.390	.390	.152	.068	.056	.650	.147	.147	.333	.333	.333	.522	.078	.200	.200	N/A
Alt A (Level IV) Weights	.407	.319	.231	.400	.188	.351	.178	.243	.143	.258	.105	.785	.429	.731	.655	**.327**
Alt B (Level IV) Weights	.244	.255	.462	.300	.081	.260	.070	.088	.429	.105	.637	.066	.143	.081	.055	**.253**
Alt C (Level IV) Weights	.349	.426	.308	.300	.731	.390	.751	.669	.429	.637	.258	.149	.429	.188	.290	**.422**

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