ADVANCEMENT IN QFD OPTIMIZATION METHODS

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Summary

Quality Function Deployment (QFD) is a useful method in product design and development and its aim is to improve the quality and better meet customers' needs. Due to cost and other resource constraints, trade-offs are always needed. Though after several years' development, there are still limitations of current QFD methodologies. It may hinder enterprises to implement QFD or mislead enterprises when using QFD. This research focuses on the quantitative methodology, especially optimization, development of QFD. The objective of this research is to develop more effective and applicable quantitative QFD analysis methods to help enterprises provide better products/service to customers.

This dissertation consists of 10 chapters. Chapters 1 and 2, is the introduction of this dissertation. Chapter 1 presents the background, objective, and scope of the current study. The second chapter reviews the QFD literature and points out the limitations and deficiencies involved in the existing research work. At the end of Chapter 2, the research scope for the current study is provided.

Chapters 3 to 4 deal with two important parts of the house of quality (HOQ), the voice of the customer and interrelationships among technical attributes. Chapter 3 introduces a new method on ranking customer requirements in a competitive environment. The proposed method considers competition position, current performance and customers' viewpoint to produce the ratings. Interrelationship of technical attributes in HOQ is

discussed in Chapter 4. The new approach considers normalization of relationship matrix, different effects on each customer requirement and fuzziness in such relationships.

The following 4 chapters discuss new approaches in QFD optimization. Chapter 5 provides a generalized QFD optimization framework and nearly all the current QFD optimization methods can be included under this framework. Chapter 6 deals with the situation when values of technical attributes are discrete variables by proposing a dynamic programming approach for the optimization problem. Chapter 7 introduces a QFD optimization approach that incorporates Kano model which classifies the customer requirements into three fields, namely, "must be", "attractive" and "exciting". This approach will quantify the results from Kano model and goal-programming is used to transfer customer requirements into products' technical attributes. Chapter 8 provides a new QFD optimization approach that does not need to require a priori information for each customer requirement. This new method will apply linear physical programming to generate the weight in a dynamic way during the optimization process and finally derive the global optimal result.

Chapters 9 to 10 present a case study of QFD in the personal computer design and the conclusions of this dissertation. An important aim of the case study is to illustrate some methods proposed in the dissertation. Limitations of the current study and directions for future research are presented in the final concluding chapter.

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m number of customer requirements

n number of engineering characteristics

w_i the relative importance weight of the i_{th} customer requirement $i=1, 2, \ldots m$

x_j the budget allocated to technical attribute j, $j= 1, 2, \ldots n$.

y_i the extent of satisfaction of the i_{th} customer requirement, $i=1, 2, \ldots m$

TA_j fulfilment level of technical attribute j, $j= 1, 2, \ldots n$.

γ_{jk} relationship among technical attribute j and k, $k= 1, 2, \ldots n$, $j= 1, 2, \ldots n$.

R_{ij} the incremental change in the level of fulfillment of the i_{th} customer requirement when the j_{th} technical attribute is fulfilled to a certain level, $i=1, 2, \ldots m$; $j=1, 2, \ldots n$

R_{ij}^{norm} normalized relationship between the i_{th} customer requirement and the j_{th} engineering characteristic, $i=1, 2, \ldots m$, $j=1, 2, \ldots n$

$f_{\min j}$ the minimum fulfilment level of technical attribute j, $j= 1, 2, \ldots n$.

$c_{\max j}$ the maximum cost of technical attribute j, $j= 1, 2, \ldots n$.

$c_{\min j}$ the minimum cost of technical attribute j, $j= 1, 2, \ldots n$.

B the cost limit

Chapter 1 Introduction

Over the past thirty years, with the trend of globalization, enterprises have been facing more intense competitions than ever. The globalization, characterized by international competitions, fragmented markets of discriminating customers and rapid technological development, brought a new industrial revolution (Clark and Fujimoto, 1991). Enterprises have to build their own sustainable competitive advantages to survive in such a competitive environment.

A competitive advantage is “a firm’s ability to achieve market superiority” (Evans and Lindsay, 2002). Wheelwright’s (1989) competitive advantage study identifies six characteristics of a strong competitive advantage and all are related to quality. This finding indicates that quality can be an important source of the competitive advantage. The study by Cole (1999) also finds that the “new industrial revolution” is largely driven by the competition of quality management.

The official definition of *quality* by the International Standards Organization (ISO) is “the totality of features and characteristics of a product or service that bears on its ability to satisfy specified or implied needs”. ISO’s definition points out that the aim of quality is to satisfy specified or implied requirements. Hence, enterprises must focus on customers and there is a need to find a way to translate customer requirements into internal technical responses.

1.1. QFD in the quest of quality

To achieve superior quality, the Total Quality Management (TQM) is widely implemented around the world. Many studies have shown the effectiveness of TQM. For example, a study based on objective data and statistical analysis shows that effectively implemented TQM can dramatically improve financial performance (Hendricks and Singhal, 1997).

The early quality initiatives focused on reducing process variability during manufacturing. Subsequently, with increasingly more emphasis on cost and lead time of new products, and more efforts are placed at product design stage. Concerning costs, several studies show that though product design phase contributes only 5% of the total product cost, it is responsible for 75% of the overall manufacturing cost, about 70% of its lifecycle cost and over 80% of its qualitative characteristics (Huthwaite, 1988; Nevins and Whitney, 1989; Dowlatshahi, 1992). Also, a shorter design stage can reduce the lead time of new products. Concurrent Engineering (CE) is an importance tool to achieve less cost and shorter lead time (Franceschini, 2002).

The definition of CE by Institute for Defence Analysis is, "a systematic approach to intergraded concurrent design of products and their related processes, including manufacture and support." This approach is intended to help designers, from the beginning, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and customer requirements (Franceschini, 2002). Among various methodologies used in CE, Quality Function Deployment (QFD) has its distinct characteristics of focusing on customer requirements from the beginning of product design. It enables quality planning throughout the CE process (Prasad, 1998).

Quality Function Deployment (QFD) is a systematic process of helping companies to focus on customers. Sullivan (1986) defined QFD as "an overall concept that provides a means of translating customer requirements into the appropriate technical requirements for each stage of product development and production (i.e., marketing strategies, planning, product design and engineering, prototype evaluation, production process development, production, sales.). " This definition indicates that QFD is a customer driven design process and essential in the product and process design stage (Akao 1990, Cohen 1995)

Griffin and Hauser (1993) argued that one aspect of the focus on TQM has been the widespread adoption of QFD. Focusing on listening to the voice of customers, QFD is essential in implementing TQM (Guinta and Praizler, 1993). As a prerequisite for successful implementation of any TQM program, QFD guides product managers and design teams through the conceptualization, creation, and realization process of a new product or a new version of an existing product (Govers, 1996).

Yoshizawa (1997) studied two importance contributions of QFD to industry: one is to transform the focus of TQM from process-oriented QA to design-oriented QA and the other one is to provide a communication tool for design department, manufacturing department, and marketing department. In the past century, QFD has been widely used in many parts of the world. Also, papers on QFD and specialized courses to teach QFD appeared regularly (Akao, 2003). During the half past century, QFD has demonstrated its effectiveness in acquiring better customer satisfaction in many industries. QFD is the focus of this thesis.

1.2. Customer satisfaction as a competitive advantage

1.2.1. Customer satisfaction leads to customer loyalty and more profit

Customer satisfaction is a growing concern to many leading companies throughout the world. It is often used as the best indicator of the company's future because a high level of customer satisfaction leads to a high level of customer loyalty that in turn leads to a steady stream of future cash flow. There is a shift in strategic planning promoting strategies for customer satisfaction instead of some form of market share strategy (Matzler and Hinterhuber, 1998).

Finkelman and Goland (1990) and Heskett *et al.* (1994) analysed the impact of customer satisfaction on loyalty. They revealed that the actual loyalty differs substantially depending on whether customers are 'very satisfied' or 'satisfied'. Customers giving 5s (very satisfied) on a five-point scale are six times more likely to repurchase a product than those giving 4s (satisfied). Figure 1.1 illustrates this causal relationship (Matzler and Hinterhuber, 1998).

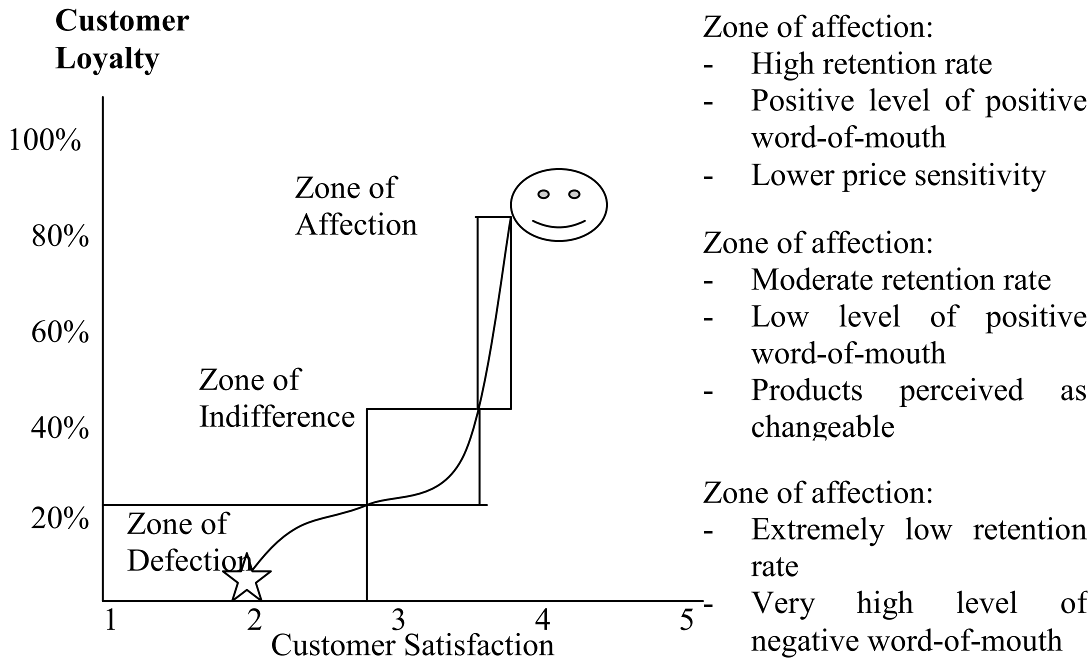


Figure 1.1 Customer satisfaction and customer loyalty

Reichheld and Sasser (1990) found that satisfied customers are likely to buy more frequently and in greater volume and to purchase other goods and services provided by the company. Hanan and Karp (1989) summed it up and state, “Customer satisfaction is the ultimate objective of every business: not to supply, not to sell, not to service, but to satisfy the needs that drive customers to do business.”

In addition, transaction cost will decrease and the costs of attracting new customers should be lower for firms that achieve a high level of customer satisfaction and loyalty. Customer satisfaction reduces price elasticity, as satisfied customers are willing to pay more for high quality products and services.

1.2.2. Customer satisfaction leads to larger market share

Traditional views consider that the maximization of market share will lead to maximization of return on investment (ROI) (Fornell, 1992). This conclusion is based on the effects of economies of scale. a large number of empirical studies have confirmed the impact of market share on profitability (Buzzel and Gale, 1987). Market share in turn is seen as a result of offensive market strategies whose primary goal is to acquire new customers.

But customer retention strategies are becoming increasingly important to a company because increasing competition, low market growth rate and saturated markets make it much more difficult to grow on the basis of offensive strategies. The costs of attracting new customers are much higher than the costs of keeping the present customers through an increased level of loyalty. The American Marketing Association estimates that it costs five or six times more to acquire a new customer than to keep an old customer.

Customer satisfaction leads to loyalty and then market share. The present or future market share of a company is made up of existing, loyal customers and the switching, potentially new customers. The higher the retention rate of a company is, the higher the future market share will be. Due to the positive quality image and the positive word-of-mouth of satisfied customers, high levels of perceived quality and customer satisfaction have an additional positive effect on future market share.

1.2.3. Maximizing Customer Satisfaction with QFD

Traditional quality systems aim at minimizing negative quality (such as defects, poor service). With those systems, the best you can get is zero defects. In an intensive competition environment, it is not competitive when all the players are good. In addition to eliminating defects, we must create value by maximizing customer satisfaction (positive quality).

Quality Function Deployment is a comprehensive quality system aimed specifically at maximizing customer satisfaction. It focuses on delivering value by discovering both spoken and unspoken requirements, then translating them into targets of technical attribute, and communicating this throughout the organization. Further, it analyzes the prioritization of customer requirements, compares the performance of own products with that of competitors, and then optimize the product design that will bring the greatest customer satisfaction and competitive advantage. The ultimate goal of QFD is to meet and exceed customer satisfaction.

1.3. Scope and organization of this thesis

When the concept of QFD spreads all over the world, many methodologies of QFD were developed to apply QFD in a more objective and precise way. The methodological development can be categorized into three categories, namely: Quantitative methods of QFD, Extensions and implementation issues of QFD and Comparative studies (Chan and

Wu, 2002). Quantitative methods mean that mathematical tools have been applied to the QFD applications. These mathematical tools include management science or operations research methods (MS/OR), marketing research and fuzzy logic. The aim of extensions of QFD is to modify the standard QFD or incorporate other tools in the QFD process to make QFD more workable. Studies of implementation issues provide guidelines and useful advice for practitioners. Comparative studies are aimed to compare QFD with other quality management tools. Research on all of the above three categories has been reported in a large number of papers. A detailed list of these articles is reviewed in Chan and Wu (2002).

After several years' development, there are still limitations of current QFD methodology. It may hinder enterprises to implement QFD or mislead enterprises when using QFD. This research focuses on the quantitative methodology, especially optimization, development of QFD. The objective of this research is to develop more effective and applicable quantitative QFD analysis methods to help enterprises provide better products/service to customers.

There are a total of 10 Chapters organized as following. Chapter 2 is a review of the QFD that provides the basics of QFD and reviews the recent methodology development of QFD. Chapter 3 proposed a new approach to rank customer requirements. This new method not only focuses on customers but takes competitors information into consideration. Chapter 4 developed a new approach to analyze the interrelationship among technical attributes. Chapter 5 presented a generalized QFD optimization model with a numerical example. Chapter 6 provided a new QFD optimization method that used dynamic programming. Chapter 7 integrated Kano model into QFD optimization process. Chapter 8 discussed the application of linear physical programming in the QFD optimization. Chapter 9 is a case study of personal computer using QFD optimization method. Chapter 10 concluded this thesis and provided suggestions on future research. Figure 1.2 shows the structure of this thesis.

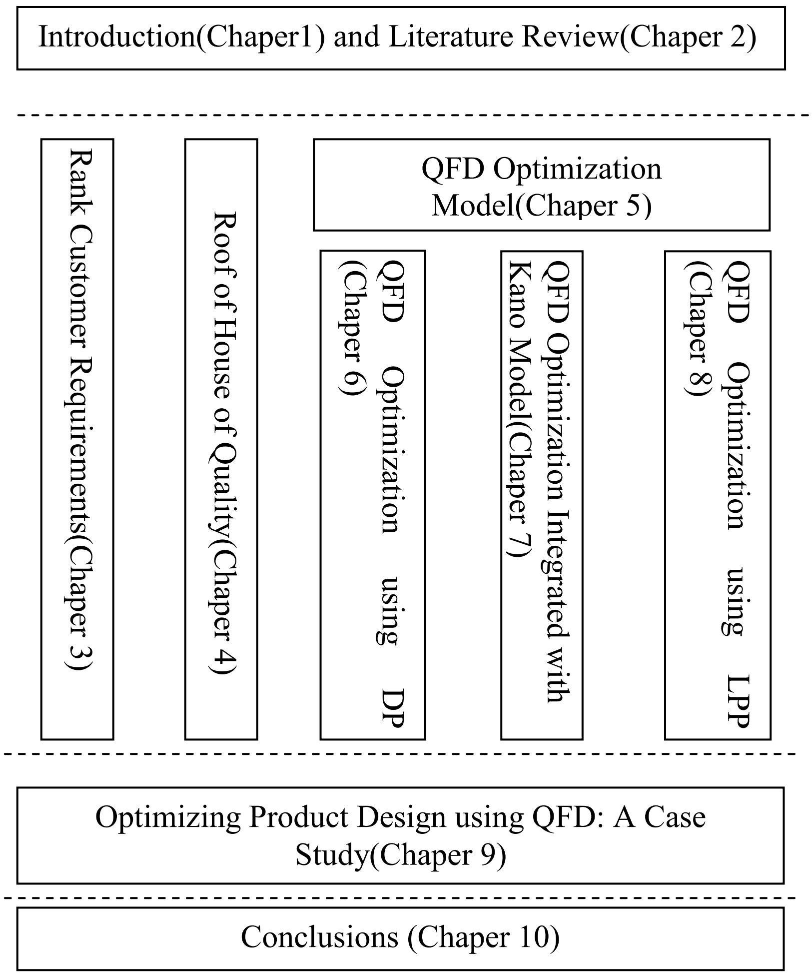


Figure 1.2 Structure of this thesis

In the next chapter, a detailed review on QFD is made. This review will cover the origin, applications, and current developments of QFD.

Chapter 2 Literature Review

The purposes of this chapter are to have a thorough review on the QFD literature, highlight the deficiencies and limitations in the current literature, and stress the motivations of this study for QFD's further advancements.

2.1. QFD related publications statistics

As an important technique of TQM, many QFD and QFD-related materials have been published in many quality-related journals and conferences. The Science Citation Index (SCI®), the well-known and prestigious science publication index, provides access to current and retrospective bibliographic information, author abstracts, and cited references fin the 3,700 world's leading academic scientific and technical journals in more than 100 disciplines. A search for QFD-related publications in Science Citation Index (SCI) database can help reveal the current research of QFD globally. Figure 2.1 shows the number of publications in this area from 1999 to 2005, which is steadily above 20 except 2000 and 2001. Figure 2.2 gives the source countries of these papers. It should be noted that many publications in other sources than the SCI database are not included.

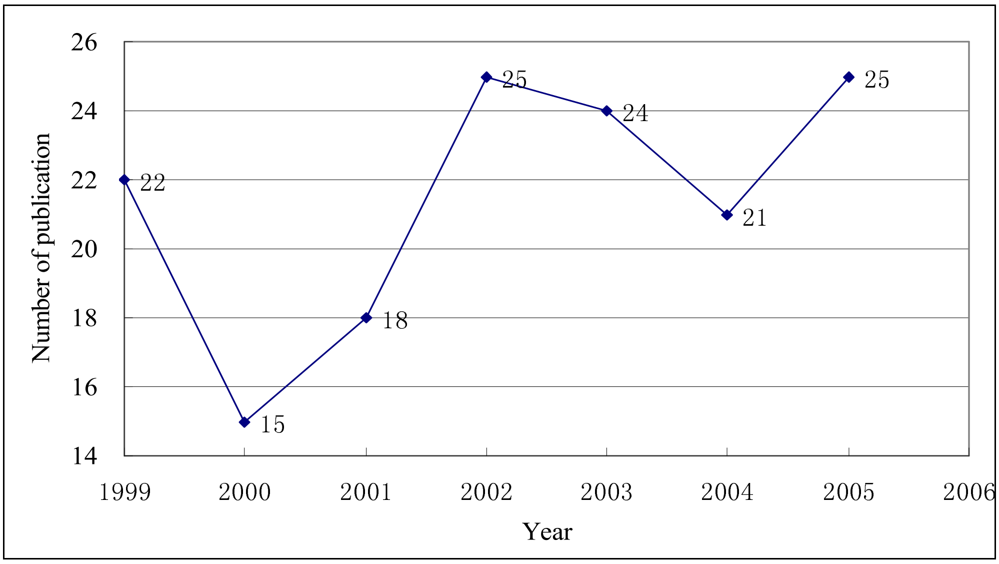


Figure 2.1 Number of SCI publications

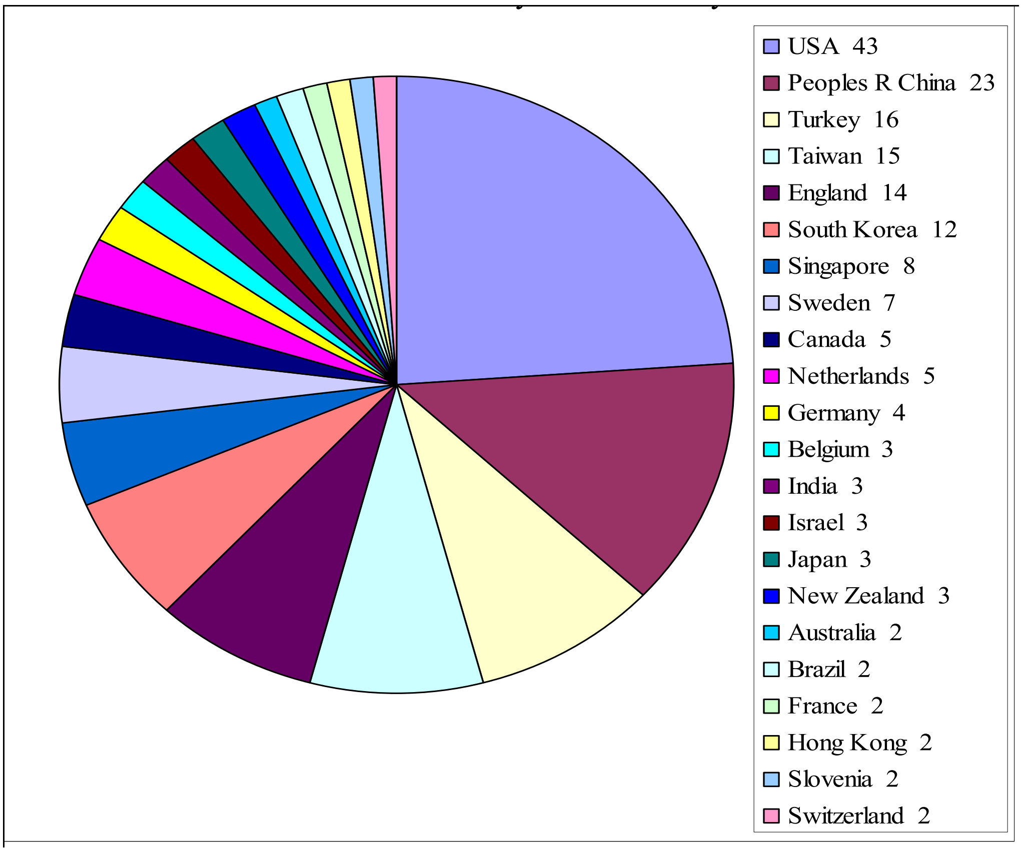


Figure 2.2 Source of SCI publications

The Symposium on QFD is one important source of QFD related publications which is not included in the SCI. It is a public QFD forum held annually by QFD institute in North America where the latest QFD case studies and research are presented and QFD dialogues encouraged. The QFD Institute was sanctioned in 1993 by Dr. Yoji Akao to research and develop state-of-the-art methods, tools, and conduct training. It is the only dedicated QFD education and research organization in the world. Figure 2.3 shows the statistics of publications in the symposiums. The number of papers reached the peak between 1993 and 1998 and reduced gradually after 1998.

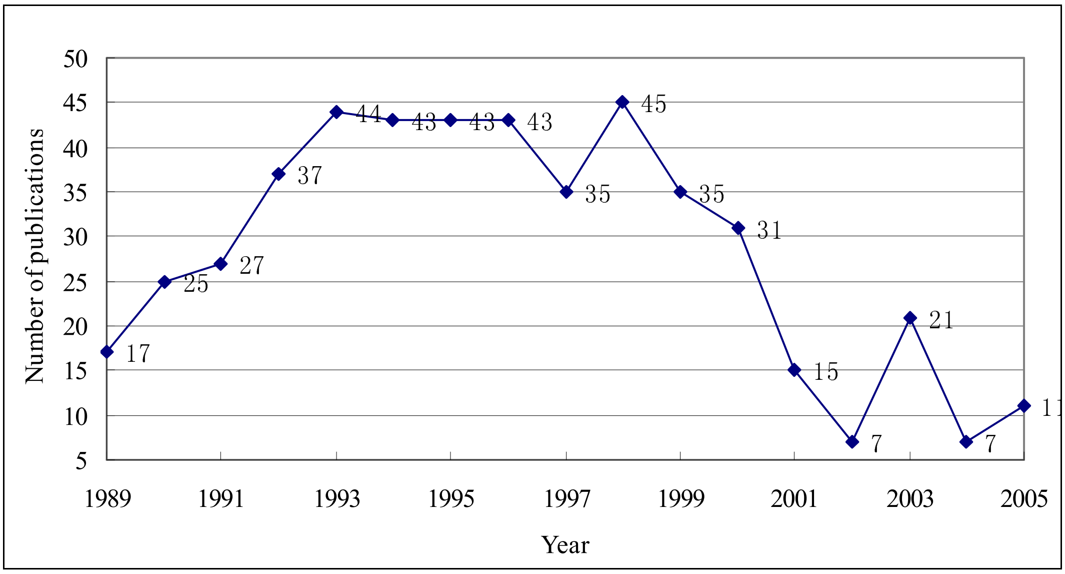


Figure 2.3 QFD symposiums publications statistics

The literature can be roughly categorized along tow major lines: practice and methodology development. In practice, QFD has experienced its widespread dissemination and applications stage. And it has been employed in numerous industries and function areas throughout the world since its inception in Japan. On the other hand, the QFD methodology itself has undergone progressive advances from a theoretical point of view. Various methods and techniques, such as the analytic hierarchy process (AHP), the artificial intelligence (AI), fuzzy mathematics and optimization methods, have been incorporated into QFD method to achieve better development and usage. In order to promote the application of QFD and improve QFD-related methodology research, literature surveys on this topic from the above two perspectives are necessary and desirable. And it may benefit both QFD practitioners and researchers.

2.2. Definitions of QFD

Since QFD has been used in a wide range of industries for decades, it has several definitions. It comes from the original Japanese phrases consisting of three characters Hin Shitsu ("quality", "feature", or "attribute"), Kino("function" or "mechanization") and Ten Kai ("deployment", "diffusion", "development", or "evolution") (Lockamy III and Khurana, 1995). The Akao-prize winner, Glenn Mazur', gave his interpretation of the Japanese characters for QFD as shown in figure 2.4.

品 multitudes' voices
質 ax & shell: money, value
機 frontier guards attend to detail
能 bear: courage
展 unroll train of kimono
開 cooperate to open barriers

Figure 2.4 Interpretation of the Japanese characters for QFD

The founder of QFD, Akao, defined QFD as “A method for developing a design quality aimed at satisfying the consumer and then translating the consumer's demand into design targets and major quality assurance points to be used throughout the production phase” (Akao, 1990).

According to Sullivan (1986), QFD is “an overall concept that provides a means of translating customer requirements into the appropriate technical requirements for each stage of product development and production”. Madu (1999) defined “Quality Function Deployment is a process of listening to the ‘voice of the customer’, identifying the customer’s needs, and incorporating those needs in the design and production of goods and services”. According to American Supplier Institute, QFD is “A system for translating customer requirements into appropriate company requirements at each stage from research and development to engineering and manufacturing to marketing/sales and distribution.”(ASI, 2001). For more views on QFD definitions, see Dean (1992), Cohen (1995).

While the above definitions are slightly different, the objectives are similar: to identify the customers, to determine what they want, and to provide a way to meet their desires (Maddux *et al*., 1991). The bottom line is that QFD includes methods, tools, and techniques that support the process of satisfying customers.

2.3. QFD process and house of quality

There are two popular QFD process models. One is called "Matrix of Matrices", developed by Akao (1990). In Akao's model, the QFD structure is normally presented as a system of thirty matrices, charts, tables, or other diagrams. Therefore, Akao's model is considered gigantic and far-reaching (Cohen, 1995). The other one is four-phase model developed by Hauser and Clausing (1988),which is probably the most widely described and used model. Most current English QFD papers applied the four-phase model. In this thesis it is used as the fundamental model.

Usually the first phase of QFD is called house of quality (HOQ). HOQ is also the basic design tool of quality function deployment (Hauser and Clausing 1988). The name of "house" comes from its physical appearance as shown in figure 2.5. It is a conceptual map that provides means of inter-functional planning and communication between customer requirements and technical responses, with its objective to achieve maximized customer satisfaction. The seven elements in the HOQ are the following.

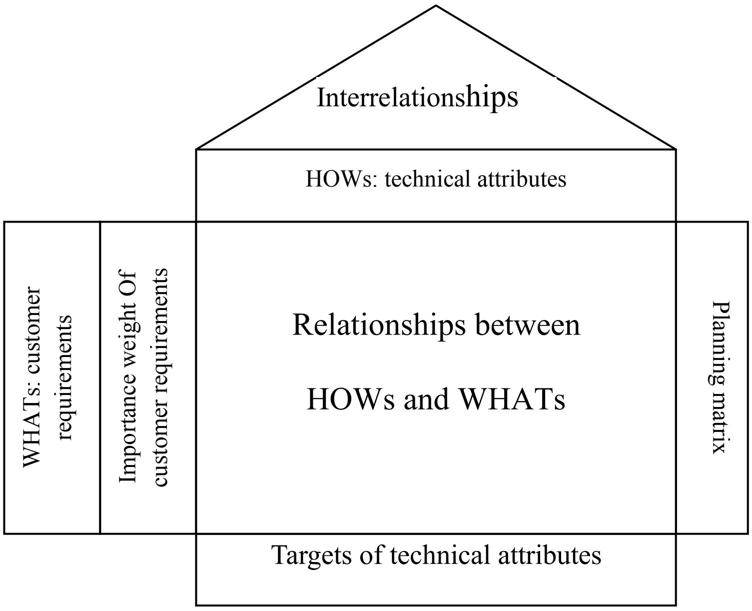


Figure 2.5 House of quality

1. **Whats:** customer requirements. Customer requirements are also called Voice of Customers (VOC), customer attributes, or demanded quality. In this thesis, the term "customer requirements" is used. Usually it is structured by affinity diagram or tree diagram. For an introduction of affinity diagram or the tree diagram, see Evans and Lindsay (2002).

2. **HOWs**: technical attributes. They are also referred as product features, design requirements, engineering attributes and so on. In this thesis, the term "technical attributes" is used. Similar to "Whats", it can also be structured by affinity diagram or tree diagram.

3. **Importance weight of customer requirements**: The item is important because it

affects how companies allocate resources to achieve better customer satisfaction.

4. **Planning Matrix:** This portion of the HOQ contains a competitive analysis of company's product with major competitors' products for each customer need. There are columns to judge how much improvement is needed in the current product, how much sales leverage may result from the improvement, and a final overall score for each customer requirement. Each score is calculated based on customer importance, needed improvement and sales leverage.

5. **Relationships between WHATs and HOWs:** The wall of HOQ contains the relationship matrix to indicate how much each technical attribute affects individual customer requirements.

6. **Interrelationships between engineering characteristics:** The matrix lies in the roof of HOQ. The technical attributes are not orthogonal. Usually the change of one technical attribute will affect the values of other technical attributes. The interrelationship matrix depicts the impact of this effect and helps designers construct models and make trade-offs between technical attributes.

7. **Prioritized technical attribute:** This section is a summation of the effects that all prior variables have on each product feature. It may also contain target measures for technical attributes, as well as a competitive analysis of other manufactures' measures for the same variables.

In the Hauser and Clausing's model, QFD has four phases: product planning, part planning, process planning and production/operation planning. It starts with the customer requirements and applies them to the whole manufacturing process, as shown in figure 2.6.

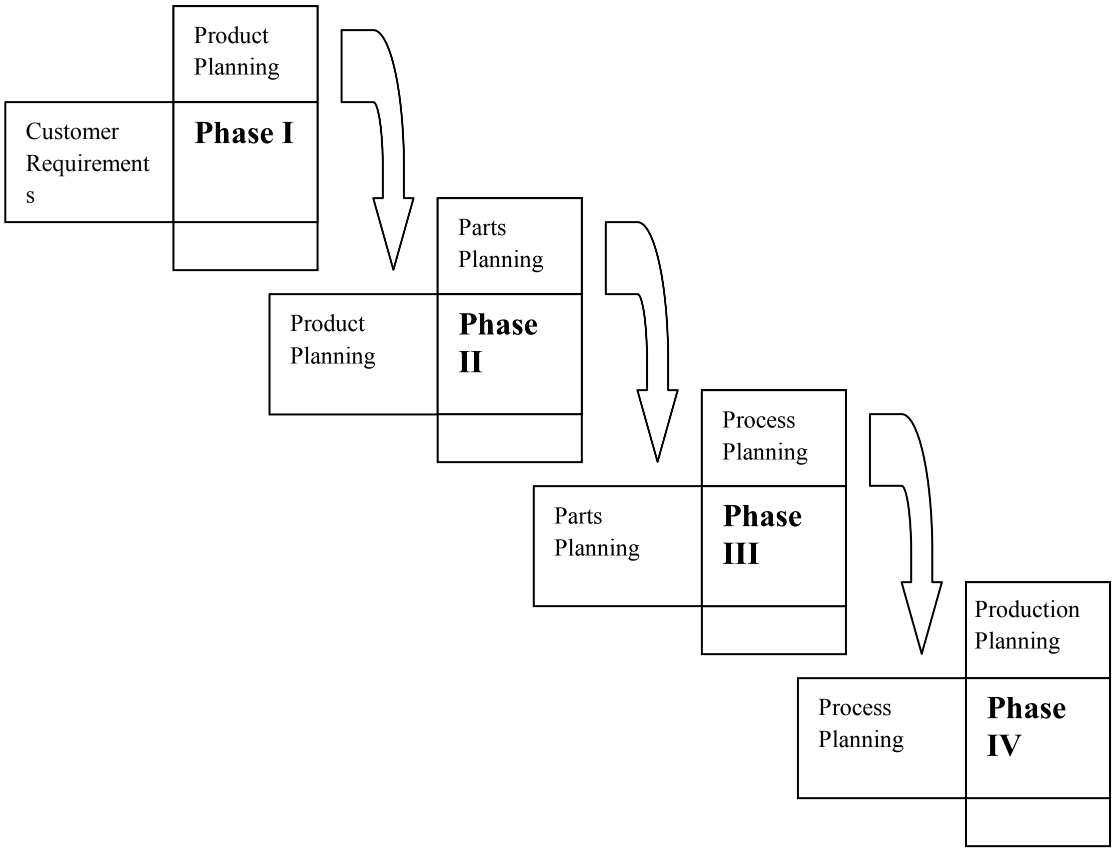


Figure 2.6 The four-phase QFD Process

Phase I: Product planning. The expectations and requirements of customers are translated to the concept of the product. A Competitive analysis is made to evaluate the requirements, which results in the identification of important product properties which are to be transferred to the next step of the QFD analysis.

Phase II: part planning. The product design concept is applied in order to fulfill the prioritized target values. Parts and components that might be important for the product are identified, properties of which are selected and set based on the previous product concept, with critical ones identified for further study.

Phase III: process planning. The critical properties with identified critical parameters are transferred to detailed production operations. Methods for process control and process improvement are set.

Phase IV: production/operation planning. The main objective of this step is to design production instructions that must be developed based on the number of units that need to be measured, the frequency that measurements be performed, as well as tools that be applied. Thus, operators can carry out their measurements according to these exact descriptions.

In the four-phase model, each output of the preceding phase can be regarded as customer requirements, i.e. the input, of the following phase. Each phase can be treated as a HOQ. Most current methodological studies of QFD therefore only deal with HOQ, the first stage of QFD.

2.4. History of QFD

Quality function deployment was initially developed by Yoji Akao in Japan in the 1960s and first applied at Mitsubishi, Heavy Industries, Ltd., in the Kobe Shipyard, Japan, in 1972. Later on, several Japanese companies such as Toyota adopted the QFD system. In 1978, the first book on QFD by Mizuno and Akao was published. During the late 1970s and 1980s, Japanese companies improved communication between departments by developing new QFD metrics. More than 30 popular matrices that were to ensure the right design of a product and process in the first time had been invented by 1987.

Though QFD had considerable applications in Japan, its concept did not appear in the English literature until 1983. In that year, Kogure and Akao published the first paper, "Quality Function Deployment and CWQC in Japan" in Quality Progress. As the QFD was widely used in Japan, it was also introduced to the United States in 1984 by Dr. Clausing for the first time. And a famous paper by Hauser and Clausing (1988) was published in Harvard Business Review. Two organizations, the American Supplier Institute (ASI) and the GOAL/QPC (Growth Opportunity Alliance of Lawrence, Massachusetts/Quality Productivity Center) played an important role in promoting and publicizing QFD in the United States (Cohen 1995, Prasad 1998). Since 1995, the International Symposium on QFD has been held annually. In 1997, the International Council for QFD was founded in Michigan, US as a non-profit organization.

First movers of QFD in the United States are some international companies, i.e. Ford

Motor Company, Digital Equipment Corporation, Procter and Gamble, and 3M Corporation. At the same time, many other companies began to use QFD, and the method continues to spread in the United States (Cohen, 1995). More than 20 US companies had adopted QFD for the product and service development by 1989 and more than 100 firms used QFD by 1991. Cohen (1995) argued that the real application of QFD could be far broader than reported in the existing studies. The reason lies in that the majority of companies that applied QFD considered it as a competitive advantage and thus are reluctant to present their cases publicly.

Countries in Europe and Americas also began to implement QFD since 1980s. For more details of QFD's history, see Akao and Mazur, 2003.

2.5. Applications of QFD

Applications of QFD can be primarily classified into two categories: functional fields and applied industries. At the beginning of QFD development, the primary functions of QFD were product development, quality management, and customer needs analysis. Shipbuilding and electronics were the first two industries in the reported applications of QFD. With the development and wide spread of QFD, both its application areas and applied industries are expanded to much more fields than before.

2.5.1 Functional fields of QFD

The three most popular application fields are customer requirement analysis, product development and quality management. Customer requirement analysis is actually the first step of QFD process. Publications in this field mainly focus on prioritising customer needs. Many approaches have been proposed, such as point scoring scale method (Griffin and Hauser 1993), group decision-making technique (Lai *et al*. 1998, Ho *et al*. 1999), AHP related rating method (Aswad 1989, Akao 1990, Armacost *et al.* 1994, Karsak *et al.* 2003), and fuzzy mathematics to resolve the vagueness, ambiguity and multiple meanings in customers' opinions (Khoo and Ho 1996, Fung *et al*. 1998). Other areas include customer responsiveness (Atkinson, 1990), customer services (Denton, 1990), data collection (Casey *et al*., 1993), and defining quality requirements (Hauser and Klein 1988, Hrones *et al*. 1993, LaSala 1994).

QFD is defined as a product design tool that focuses designed-in quality rather than traditional inspected-in quality. Product design includes new products (Dawson and Askin 1999, Hales and Staley 1995, Holmen and Kristensen 1998, Natter *et al*. 2001, Poolton and Barclay 1996, Rangaswamy and Lilien 1997, Song *et al*. 1997, Tse 1999), model-change products (Hoque *et al*., 2000), product concept (Schmidt, 1997), products and processes (Verma *et al*., 1998), reliability test methods (Kwon and Han, 1999) and so on.

QFD can also be applied to quality management, such as process improvement (Hybert 1996, Richardson 2001, Zaciewski 1994), quality control (Acord 1996, Keenan 1996, Prasad 1997, Kanji 1998), quality information systems (Chang 1989, Lin and Fite 1995), and service quality management systems (Chang and Lin, 1991).

2.5.2 Applications of QFD in industries

QFD continues to attract much attention in various industries. And in the early development of QFD, it focused on automobiles, electronics and software. With the rapid development of QFD, QFD is now used in more industries. The transactions of the Symposium on QFD provide hundreds of papers on QFD applications. These industries can be largely classified into manufacturing, software, service and education.

Manufacturing is one area where QFD was first applied. Along with its fast development, QFD has also been applied to diverse manufacturing areas, such as braking systems (Nickerson, 1993), chocolate (Viaene and Januszewska, 1999), composite material (Karbhari *et al*., 1991), engine filters (Zhang *et al*., 1999), food (Charteris 1993, Costa *et al*. 2000), furniture (Acord 1996, 1997), helmet-mounted displays (Cadogan *et al*., 1994), hybridbicycles (Govindaraju and Mital, 2000), and medical devices (Hauser 1993, Kealin and Klein 1992, Rodriguez-Soria 1989). The applications of QFD in the manufacturing include not only the traditional new product development phase but also some other specific and important manufacturing and engineering design areas, such as the design of quality system (Finley, 1992), rehabilitation engineering (Jacques *et al.,* 1994) and Computer-integrated manufacturing (Boubekri *et al*., 1991).

The concept of software QFD (SQFD) was also originated from Japan in 1984. At that time, Japanese tried to use QFD in the embedded software development (Zulnter, 1990). Four years later, Digital Equipment Corporation (DEC) also announced its adoption of QFD in the software development process (Cohen, 1988). From then on, QFD was more and more widely used in the software development project, as reported by Barnett and Raja (1995), Basili and Musa (1991), Elboushi and Sherif (1997), Haag *et al*. (1996), Herzwurm *et al*. (1997, 2000), Karlsson (1997), Kekre *et al*. (1995), Liu *et al*. (1998), Liu (2001), Richardson (2001), Roche and Jackson (1994), Xiong and Shindo (1995), Yilmaz and Chatterjee (1997), and Zultner (1990, 1992).

The third area of QFD‘s application is in service industries. The early applications of QFD in service were for a shopping mall, a sports complex, and a variety retail store in Japan by Ohfuji, Noda, and Ogino in 1981 (Akao, 1990). With the intensified competition in service industries, more companies are now concerned with the importance of service quality, where QFD can play a very important role. In health care, QFD obtained wide acceptability and generated many applications, such as (Radharamanan and Godoy 1996, Ehrlich 1993, Gibson 1994, Gibson 1995, Tay 1997, Chaplin *et al*. 1999, Chaplin and Terninko 2000, Einspruch *et al*. 1996, Lim and Tang 2000, Lim *et al*. 1999, Matsuda *et al*. 1998, 2000). Other specific areas include banking (Ko and Lee, 2000), engineering services (Pun *et al*., 2000), government services (Lewis and Hartley, 2001), hotels (Dube *et al*. 1999, Stuart and Stephen 1996), on-line bookshops (Barnes and Vidgen, 2001), public sectors (Curry 1999, Curry and Herbert 1998, Ellis 1998; Hallberg 1999), retail (Nagendra and Osborne 2000, Trappey *et al*. 1996) and so on.

In the educational sector, QFD has also been successfully applied. Mazur (1996) used QFD to design a new course in total quality management that increased the student to teacher ratio without reducing the quality of education. Similar studies of designing better curriculum using QFD are reported in Rosenkrantz (1996), Seow and Moody (1996). QFD is also applied in research plan development (Chen and Bullington, 1993), degree program design (Clayton 1993, Pitman *et al*. 1995), teaching improvement (Jaraiedi and Ritz 1994, Zaciewski 1994, Lam and Zhao, 1998).

In addition to the above mentioned, the wide applications of QFD can also be reflected by its usefulness in some other areas, such as transportation (Herrmann *et al*., 2000), construction (Abdul-Rahman *et al*., 1999), military (Filling *et al*., 1998), in environment protection (Berglund 1993, Halog *et al*. 2001, Zhang *et al*. 1999) and so on. In fact, QFD does not have an explicit boundary of its application. Partovi and Corredoira (2001) even applied QFD to soccer. With all these successful implementations of QFD in industries, QFD remain a very important and popular approach for industries.

2.6. Benefits of QFD

The widespread application of QFD lies in its benefits to practitioners. Herzwurm *et al*., (1998) carried out an empirical study and investigated 16 QFD projects, of which seven were software projects, in which product developers were asked about their experiences with QFD. In Herzwurm's paper, the goals of QFD application were classified on product and on project level. The results confirm the effectiveness of QFD in fulfilling the special expectation in product development. The results of product level and project level goals are shown in figure 2.7 and figure 2.8 respectively. Concerning the customer-oriented objectives, the employment of QFD achieves very high satisfaction values. From the project-related goals point of view, QFD particularly improves the co-operation of the persons involved and leads to a higher economy of the product development.

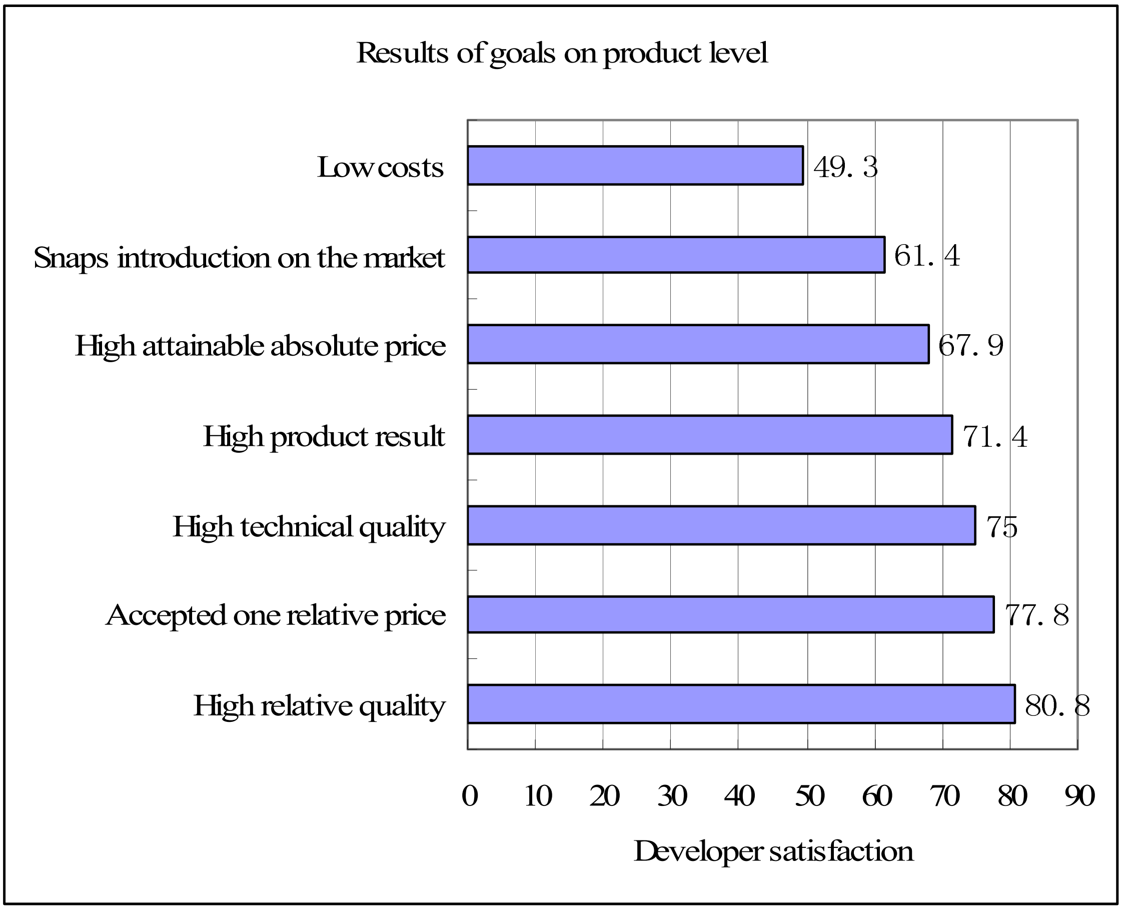


Figure 2.7 Results of goals on product level

(Source: Herzwurm *et al*., 1998)

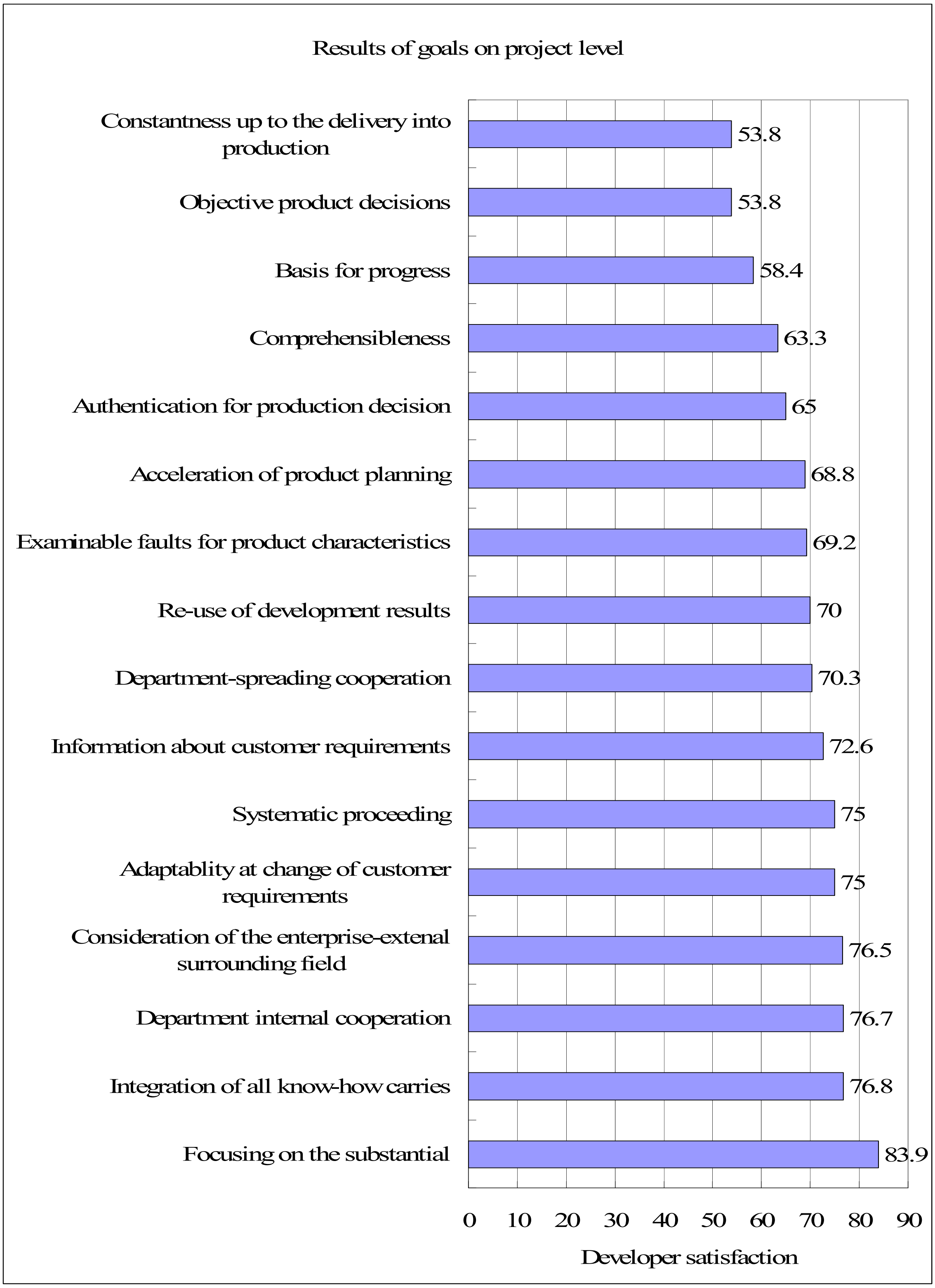


Figure 2.8 Results of goals on product level

(Source: Herzwurm *et al*., 1998)

Many other papers also studied the benefits of QFD, i.e. Sullivan (1986), Fortuna (1988), Kenny (1988), Hauser and Clausing (1988), Griffin (1991), Kathawala and Motwani (1994), and Zairi and Youssef (1995). The following benefits are frequently reported:

- Reduced design cycle time and engineering changes,
- Minimized start-up costs,
- Tremendous efficiency,
- Shorter lead times,
- Reduction in pre-launch time and after-launch tinkering,
- Increased customer satisfaction and market share,
- Reduced warranty claims,
- More stable quality assurance planning and few products returned.

2.7. Quantitative methodological development of QFD

In the early days of Quality Function Deployment, decisions made in QFD process are usually determined by experience of practitioners or experts' opinions. However, experience and experts' opinions may not always be reliable to capture the true customer requirements. To survive in the intensively competitive environment, objective-based methods are needed. Then quantitative methodological development of QFD becomes a hot topic in QFD methodological development.

According to the tools used in QFD, quantitative methods of QFD can be loosely divided into three categories: management science or operations research methods (MS/OR), marketing research, and fuzzy logic. The MS/OR category mainly includes AHP and many multi-objective optimization methods, i.e. linear programming, goal programming, mix-integer programming and so on. Marketing research methods includes conjoint analysis, benchmarking, and aggregate complaint analysis and so on. Most marketing research methods focus on collecting and analyzing VOC. Because of the high uncertainty and ambiguity involved in the QFD process, fuzzy logic methods have been introduced into QFD.

One hot topic in the QFD methodology development is QFD optimization method applying mathematical tools, especially multi-criteria optimization methods. There have been several studies on the QFD optimization since the 1990s, e.g., Chen and Weng (2004), Lai *et al*. (2005), Chen *et al*. (2005).

Wasserman (1993) developed the first mathematical QFD optimization model. This model is a 0-1 integer linear programming in essence. The author simply chose the technical attributes (TA) that have the highest priority. Obviously this method is a very simple and rough one. After Wasserman's study, more sophisticated methods were proposed.

Moskowits and Kim (1997) used Linear Programming (LP) in QFD optimization to allocate resources to each technical attributes. This method obtains more precise results than Wasserman's methods. After Moskowitz and Kim's study, many QFD optimization methods based on LP were developed. The most recent optimization approaches include Askin and Dawson (2000), Sohn and Choi (2001), Fung *et al.* (2002), Tang *et al.* (2002); Karsak *et al.*(2002). These methods work well in their specified fields.

Han *et al.* (1998) and Che and Lin (1998) proposed Goal Programming (GP) in the QFD optimization methods. Han *et al.* (1998) claims that the most important point is to know how to make tradeoffs in the selection of technical attributes that most effectively meet customer's requirements. In this regard, an optimization model was proposed, which provides an objective protocol for selecting technical attributes taking into account cost and other organizational constraints. Che and Lin (1998) proposed a multi-goal programming model to achieve optimized results in QFD, in which the goal of time, quality and cost for QFD and concurrent engineering were embodied.

The above LP- and GP-based optimization methods retain many good attributes. All these methods are effective in finding the optimal set of technical attributes. For example, they are easy to model and solve. Also, sensitive analysis is presented when solving it. However, LP- and GP- based optimization methods may also encounter many difficulties in the real world, which will be further elaborated in discussing research gaps.

Dawson and Askin (1999) proposed a non-linear mathematical programming model to determine the optimal technical attributes during new product development. The model is an equation of elicited customer value functions, development and product cost and time constraints. The authors claim that the heuristic models have similar performance for correlated and uncorrelated technical attributes as well, and therefore the non-linear programming model is more efficient in modelling correlation between technical attributes. However, this statement may not be true since heuristic models are also able to deal with the correlation between technical attributes efficiently. There is no significant evidence that the non-linear programming is better.

Matzler and Hinterbuber (1998) proposed a methodology based on Kano model to explore customers' requirements and combined it with QFD. Kano model is an efficient tool to help understand customer requirements. Integrating Kano model into QFD optimization provides a new way to optimize the product design. This study suggests that the application of QFD can benefit from using the added dimension of quality in the form of customer requirements.

2.8. Research gaps and research scope

The above sections present a literature survey on QFD optimization methods. The review leads to the conclusion that QFD optimization has been studied and developed from various viewpoints. Nevertheless, the review also highlighted the current limitations which need to be resolved. This section will discuss the major limitations that exist in current QFD optimization methodologies.

All current QFD optimization methods model the value of technical attribute as a continuous variable. However, due to practical limitations, the values of technical attributes are often discrete instead of continuous. For example, the diameter of a screw has a standard value set. It is possible and not rare that engineers find that the value is difficult or very costly to achieve when getting “optimal values” from LP or GP-based methods. Furthermore, not all technical attributes can be expressed as numbers, such as colour and shape of a product. Therefore, it is important to develop a QFD method to suit such situations.

All the current QFD optimization methods model the actual relationships between technical attributes and customer requirements as a linear relationship or non-linear one. However, the full curve of this kind of relationship is hard to capture. As mentioned earlier, some technical attributes are discrete variables. Therefore, it is not necessary to depict a full curve of these relationships. We only need such values at a few specific points.

The above methods convert a multi-objective problem into a single objective problem, and then solve this single objective problem for a compromised solution. In this process, the design team has to determine each objective a priori. The weights specified are dicey for it may not be adequate in capturing the nature of the optimization problem. In addition, the aggregate objective function, the constraints, and the bounds on the decision variable constraints need to be clearly expressed in mathematical terms which, however, are hard to express clearly and accurately.

Understanding the voice of customers is the basis and starting point of QFD. The Kano model is a tool to help the design team understand customer requirements. The current applications of the Kano model are mostly qualitative in nature, most of which focus on benefits from its application and its managerial implications. However, the Kano model can be used in a quantitative way and help the design team to mathematically evaluate whether the design meets a customer requirement or not. Quantitative methods, especially optimization methods, can help design team to understand customer requirements and design products better. However, there is no research discussing how to incorporate the Kano model into QFD optimization method.

The ultimate objective of this thesis is to advance QFD optimization methodology development for both researchers and practitioners. The first objective of this thesis is to improve the input of QFD optimization by proposing a new methodology on ranking customer requirements in a competitive environment. The proposed method considered competition position, current performance and customers' viewpoint to produce the ratings. In addition, this method used fuzzy mathematics instead of crisp numbers to capture the true customer requirements.

The second objective is to develop a new method to analyze interrelationship of technical attributes in QFD optimization. This new method considers normalization of relationship matrix, different effects on each customer requirement and fuzziness in such relationships. Furthermore, this method also provided a guide on how to acquire such information.

The third objective is to provide a generalized QFD optimization framework and nearly all the current QFD optimization methods can be included under this framework. This framework will be useful to learners, researchers and practitioners of QFD and further research can also be identified based on the framework developed.

The forth objective is to deal with the situation when values of technical attributes are discrete variables by proposing a dynamic programming approach for the optimization problem. We first use an extended House of Quality (HOQ) to gather more information. Next, limited resources are allocated to the technical attributes using dynamic programming. The value of each technical attribute can be determined according to the resources allocated to them.

The fifth objective is to propose a QFD optimization approach that incorporates Kano model which classifies the customer requirements into three fields, namely, “must be”, “attractive” and “exciting”. This approach will quantify the results from Kano model. Then, goal-programming is used to transfer customer requirements into products’ technical attributes.

The sixth objective is to provide a new QFD optimization approach that does not require a priori information for each customer requirement. This new method applied linear physical programming to generate the weight in a dynamic way during the optimization process and finally derive the global optimal result.

The seventh objective is to present a case study to verify the proposed QFD optimization methods. The case study is a new project to drive the slackening desktop personal computer business. To get the competitive advantage, QFD optimization methods were used to improve the product design.

This thesis is valuable to both researchers and practitioners. The proposed methods in this thesis should improve and consummate the current QFD optimization methodology development. First, the two new methods, to rank customer requirements in a competitive environment and to analyze interrelationships between technical attributes should be more meaningful and precise compared with previous methods, and provide a solid basis for the subsequent QFD optimization. Second, this thesis proposed three different QFD optimization methods. These methods overcome the difficulties that cannot be solved by previous ones. With these methods, practitioners will have more choices to select a more suitable solution when facing product design problems. The case study presented in the thesis provides an example on how to use quantitative QFD methods in real problems which is seldom available in current literature.

All the new approaches in this thesis focus on the first stage of QFD, house of quality (HOQ). There are several reasons to focus on HOQ. First, HOQ is the most commonly used matrix in QFD. Second, the subsequent three stages of QFD are similar to the first stage. Therefore, all the methodology applicable to HOQ can also be applied to the following three stages.

Chapter 3 Ranking of Customer Requirements in a Competitive Environment

3.1. Introduction

Correctly rating the importance of every customer requirement is essential to the QFD process for it will largely affect the final target value of a product's technical attributes. This chapter proposed a new customer requirements ranking method that considers competitors' information. Most previous methods focus only on the customer perspective, and ignore the competitive environment. The proposed method considers competition position, current performance and customers' viewpoint to produce the ratings. In addition, this method uses fuzzy mathematics instead of crisp numbers to capture the true customer requirements.

Traditionally, capturing customer requirements involves three steps in QFD:

1. Identifying customer requirements
2. Structuring customer requirements
3. Determining the importance weight for the individual customer requirement

The first two steps are usually accomplished via market survey with expert opinion. Many mature methods have been proposed on this topic. This chapter focuses on the third step to rate the customer requirements' importance.

Today, the success of a product in a competitive market place depends not only on how well it meets the customers' requirements, but also how it compares with competitors' products. Therefore, it is important to integrate competitive analysis into product design and development. Then, the ranking of customer requirements for the allocation of development resources should be based also on competitive analysis.

This chapter introduces a new customer requirements rating method that takes competitors into consideration. This new method rates customer requirements from three perspectives: competition, performance and customer. This method gives more priority to those requirements that lags behind competitors, have a lower customer satisfaction and that customers think more important. The weights indicate the most important customer requirements that companies should focus on in order to be competitive.

This chapter is organized as follows. Section 2 introduces the existing rating methods and discusses their pros and cons. Section 3 presents the details of the new method. Section 4 provides an example to illustrate how the procedure is used. The final section discusses the results and several extensions.

3.2. Existing rating methods

Many papers have been published in this field, and several rating methods have been proposed. The earliest method is to use a point scoring scale, such as 1, 3, 5, and so on. More precise scoring methods, such as 1 to 10 (Griffin and Hauser 1993), are also used. The score is often obtained from customer survey or expert opinion. However, different customers or experts have different attitudes toward the same requirement. To cope with this situation, Lai *et al*. (1998) and Ho *et al*. (1999) used a group decision-making technique to obtain the importance weights for customer requirements. However, this method fails to work effectively on many occasions because many customers tend to rate every requirement to the highest importance. Consequently, AHP is proposed to rate customer requirements (Aswad 1989, Akao 1990, Armacost *et al.* 1994, and Karsak *et al.* 2002). Xie *et al*. (1998) analyzed the sensitivity of the customer voice in QFD. However, customers' opinions are often vague and contain ambiguity and multiple meanings (Khoo and Ho 1996, Fung *et al*. 1998). Fuzzy mathematics is used in AHP (Vanegas and Labib 2001, Kwong and Bai 2002). Other methods are also used, such as Gustafsson and Gustafsson (1994) which proposed a conjoint analysis method to determine the relative importance of the customer requirements.

From the customer perspective, all the above methods have the same characteristics i.e., they are consistent with the basic spirit of QFD, customer-driven design. However, in the current highly competitive environment, many products can satisfy the customers. In such a situation, simply meeting customer requirements cannot guarantee a product successfully on the market. Companies must consider competitors' positions so as to make sure that their own products would not lag behind their competitors' products.

In the current literature, there are some existing methods that incorporate competitors' information to prioritize customer requirements. The first widely used method is the sales point method and the second method is the entropy method.

3.2.1. Sales point method

Cohen (1995) defines a sales point as 'contains information characterizing the ability to sell the product or service, based on how well each customer need is met.' Usually a sales point indicates a unique selling position to separate one's own product from that of competitors. The company can be proud of this selling position because competitors may not perform well in this respect. Sales point can be found in the areas that competitors perform poorly, a bottleneck or breakthrough in technology.

Sales point can be categorized into three types: Strong, Moderate, and Poor, indicating the business opportunity from most to least correspondingly. Every customer requirement can be categorized into one of the three categories. Based on this categorization, a coefficient can be assigned to each type of sales point. The most commonly used values are 1, 1.25, and 1.5, corresponding poor sales point, moderate sales point, and strong sales point, respectively. The final importance weight is computed as follows:

$$\text{Final importance weight} = \text{relative importance rating} \times \text{sales point value} \quad (3.1)$$

The ‘relative importance rating’ is obtained from the traditional rating methods, such as customer survey, expert opinion, AHP, and so on.

The above sales point method is straightforward, and many papers have implemented it in QFD, e.g. Cohen (1995) and Robertshaw (1995). However, this method suffers from its subjectivity and may cause some problems. Cohen (1995) argues that a form of “double accounting” problem might occur in the above formulation. In addition, the sales point method cannot help designers find the potential customer requirement that can be a strong sales point. It can only help to highlight the customer requirements that designers have decided to be a strong sales point or not.

3.2.2. Entropy method

The use of the entropy method in product planning was first proposed by Chan *et al.* (1999). Entropy is a concept in information theory. It measures the expected information content of a certain message and has become an important concept in social sciences. This method analyzes customers’ assessment of a company’s performance and its competitors’ information to generate the competitive priority ratings. It gives the highest value to the customer requirement in which all the companies perform the same. It assumes that when all companies perform the same, it means there is a good opportunity to be outstanding. In fact, these assumptions may not be correct in many situations. For example, a company performs badly in one customer requirement, and according to the entropy method, this requirement is not important. However, the company cannot simply overlook its disadvantage. It may be a good opportunity for competitors to attack one's own products.

The following section will introduce a new method that can be used to obtain the importance weights of customers' requirements on the company's product systematically. The model also analyzes its competitors' performance information to generate the weights. The difference is that the proposed method does not simply overlook its products' disadvantages. Instead, it can help the company find out where the improvement should be made.

3.3. Rating method in a competitive environment

The proposed method is to help a design team to find the most important customer requirements for its company. In this way, they can set these customer requirements at a prior position and devote time and effort to improving to get the competitive advantage. Before presenting the mathematical model, we firstly discuss the general issues of product design strategy in a competitive environment. This is important, as all models come with certain assumptions.

First, in a mature market, there are many similar products which meet the customer requirements. However, these products do not perform equally well for every customer requirement. In this situation, suppose that company A wants to improve its own product to be competitive or catch up with its competitors. Usually it cannot be the best one at every aspect. A should choose the most important customer requirement(s) to improve. The question is which one should be improved first. Generally it is the one that A performs worst among competitors. If A does not improve this customer requirement, it can very likely be others' strong sales point and makes A in an adverse situation. Therefore, we should bestow a higher priority to the customer requirements that the company performs worse than competitors.

Generally, if one customer requirement performs badly, it requires many efforts to improve. In the proposed method, we therefore assign more priority to those customer requirements that have a larger gap with these of customer expectations. If one product cannot meet customer requirements, it will not be accepted by the market, even though it is better than its competitors'. Please note that though the company performs badly on one customer requirement, it may be better than others do.

QFD is a customer-driven product design tool. Though the proposed method emphasizes the competition environment, we cannot overlook customers' views. It is important to incorporate voice of customer to the importance rating of the customer requirements. For instance, if the performance of its own product on one customer requirement is extremely poor, worst of all competitors, we have to put many efforts to improve it. However, most customers never care about this kind of requirement. Therefore, a great improvement on this customer requirement will not help this product be competitive in the market. Spending excessive effort on it is obviously a waste of resources.

Therefore, as mentioned earlier, the proposed rating method can provide the final weight from three perspectives: competition, performance and customers. The conceptual process of this model is given as follows in Figure 3.1.

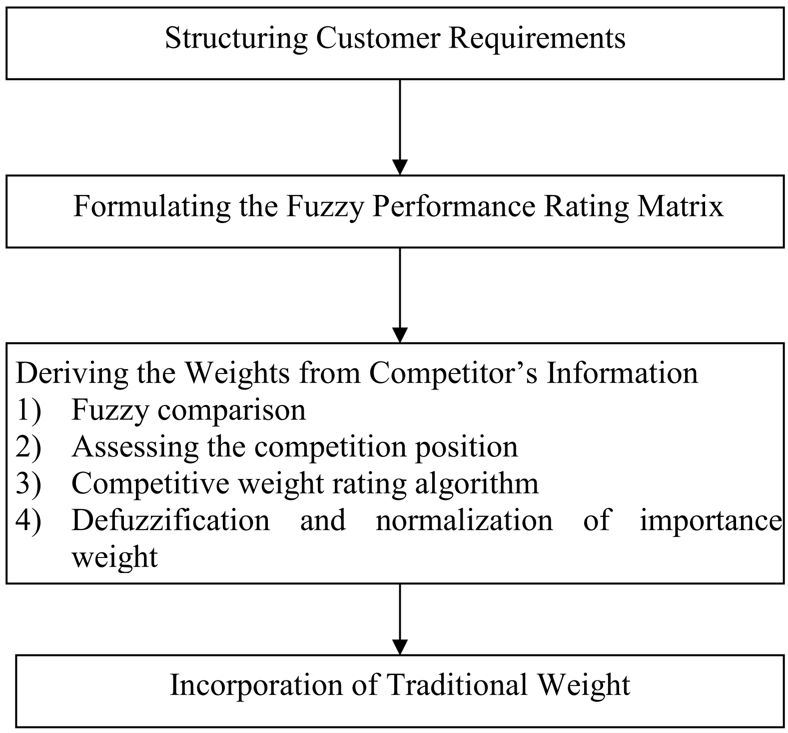


Figure 3.1 Conceptual process of proposed mode

Step 1: Structuring customer requirements

This is the project preparation step and involves varied activities, of which the most important goal is to derive the customer requirements structure. Customer requirements can be obtained from several means, e.g. comment cards, formal surveys, focus group, direct customer contact, field intelligence, complaint analysis, and internet monitoring etc.

The customer requirements structure is usually obtained from affinity or tree diagrams (Evans and Lindsay, 2002). A well-defined customer requirement structure using tree diagram looks as shown in Figure 3.2.

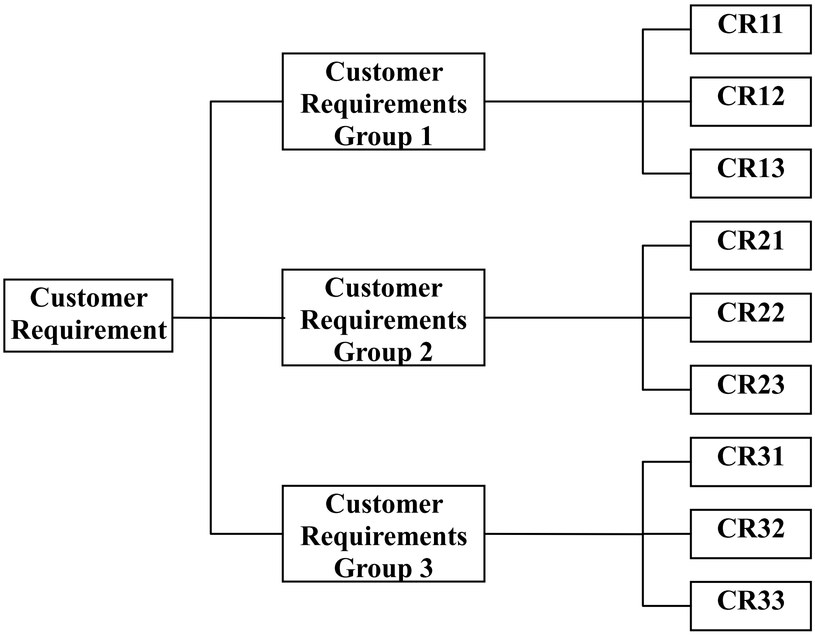


Figure 3.2 Customer requirement structure

The customer requirements structure provides the direction of comparing competitors' products. Other activities, such as deciding the aim of the product design project, identifying the competitive environment, defining the target customer segment and so on, are also prepared in this step.

Step 2: Formulating the fuzzy performance-rating matrix

The fuzzy performance-rating matrix presents how well each competitive product performs on each customer requirement. In traditional QFD, the performance-rating matrix is listed at the right side of the House of Quality (HOQ), indicating where the current market position of the company's own product is.

Traditionally, point scales, e.g. 1-3-5, 1-9 and so on, are used to evaluate the performance of each product (Hauser and Clausing 1988, 1996). The matrix is usually obtained from customer surveys. However, it is only an ideal situation. Crisp numbers cannot clearly identify the true performance of a product. In practice, different customers have different attitudes toward the same product. Their ratings cannot be the same as one another. What is needed a suitable tool to capture the information of a product performance. Fuzzy mathematics is an ideal tool to capture the highly uncertain information. Many papers have introduced fuzzy math into QFD, e.g. Zhou (1998), Wang (1999), Temponi *et al*. (1999), Shen *et al*. (2001), Karsak（2004）, Fung *et al.* (2006) and Chen and Weng (2006).. To present the true rating information, we use the fuzzy performance-rating matrix. Suppose that there are *k* companies (competitors) and *m* customer requirements, denoted by C_k and CR_m respectively. Here x_{ij} means the j_{th} company's performance on the i_{th} customer requirement. The matrix looks as follows in Figure 3.3.

$$
\begin{array}{c}
\\
\mathrm{CR}_1 \\
\mathrm{CR}_2 \\
\vdots \\
\mathrm{CR}_m
\end{array}
\begin{bmatrix}
C_1 & C_2 & \cdots & C_k \\
x_{11} & x_{12} & \cdots & x_{1k} \\
x_{21} & x_{22} & \cdots & x_{2k} \\
\vdots & \vdots & \ddots & \vdots \\
x_{m1} & x_{m2} & \cdots & x_{mk}
\end{bmatrix}
$$

Figure 3.3 Performance-rating matrix

The above looks similar to a traditional performance-rating matrix. The difference lies in that the numbers in the matrix are not crisp numbers, but fuzzy numbers. The following explains how the fuzzy rankings are obtained.

The membership function is defined according to the true performance of each product. First, a customer survey is carried out to find out the performance of the company's own product and the competitors'. In this survey, customers will be asked to rate the performance of each customer requirement. The performance is evaluated using a 9-point scale, as shown in Figure 3.4.

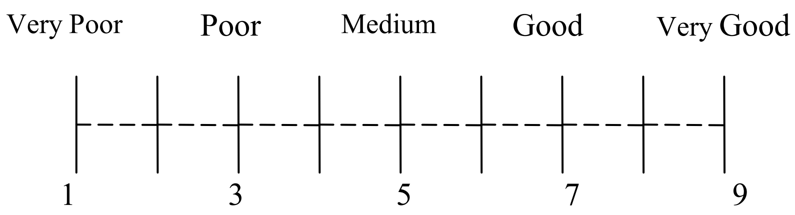


Figure 3.4 9-point scale rating

After the customer survey, a distribution of its score for each customer requirement is obtained. Then, we use this distribution to construct the membership function. For example, forty customers were surveyed. One rate 4, eight rated 5, seventeen rated 6, twelve rated 7 and two rated 8. The distribution is shown in Figure 3.5. Then, Figure 3.5 is used to construct the membership function. According to the ranking distribution, the fuzzy rating can be identified as $\tilde{x}$ = (4/6/8).

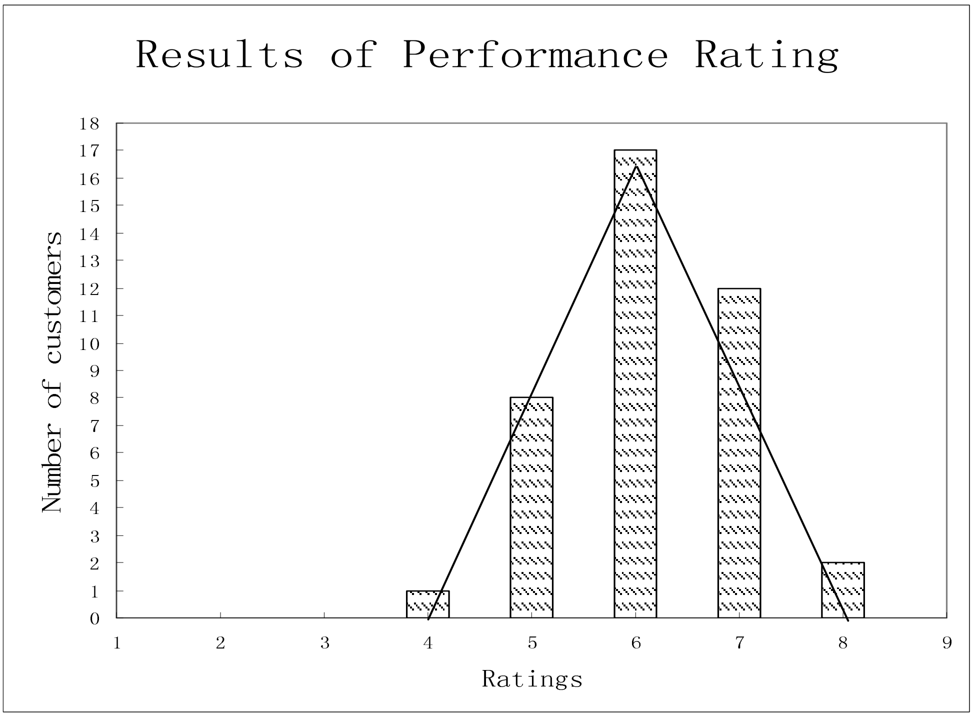


Figure 3.5 Results of performance rating

In this way, we use triangular fuzzy numbers as an example. In practice, other formats of fuzzy numbers, such as trapezoidal, Gaussian, or sigmoidal can be also used (Kaufmann 1985).

Step 3: Deriving the weight from competitor's information

The aim/purpose of this step is to obtain the weight from the analysis of competitive environment. The weight is generated from two aspects: competition and performance. The step consists of four sub- steps. First, we use the fuzzy performance rating matrix to compare the performance of the company's own product and competitors'. Based on the comparison, we assess the competition position of the product by classifying its performance into several ranges. After that, we developed an algorithm to derive the fuzzy weight from competition and performance points of view. Finally, we defuzzify and normalize the weight for the next step.

1) Fuzzy comparison

First, the ratings need to be sorted to display the competition positions of one's own products and the competitors'. The ratings are fuzzy numbers and therefore need to be defuzzified. Various defuzzification techniques have been proposed, such as the mean-of-maxima (MOM) method, and the fuzzy mean (FM) method (Zhao and Govind 1991, Runkler 1997).

The MOM method is the simplest one to implement. It selects a non-fuzzy output value corresponding to the maximum value of the membership function. This method results in the most possible solution, but does not take into account the remaining information given in the fuzzy set. Hence, the FM method is used, defined by:

$$A_D = \frac{\int_X \mu_A(x) \cdot x dx}{\int_X \mu_A(x) dx} \tag{3.2}$$

A_D is the defuzzified value of set A. $\mu_A(x)$ is the membership function of A. Unlike the MOM method, the FM method makes a compromise between all possible solutions. Therefore, it can represent the ratings more accurately. After we obtained the crisp ratings, they can be sorted in the ascending order.

2) Assessing the competition position

Suppose that there are five competitors and the company's product. Then, we can classify the competition position into six ranges according to the five competitors' performance. The six ranges are: ideal range, desirable range, tolerable range, undesirable range, highly undesirable range, and unacceptable range, as shown in Figure 3.6.

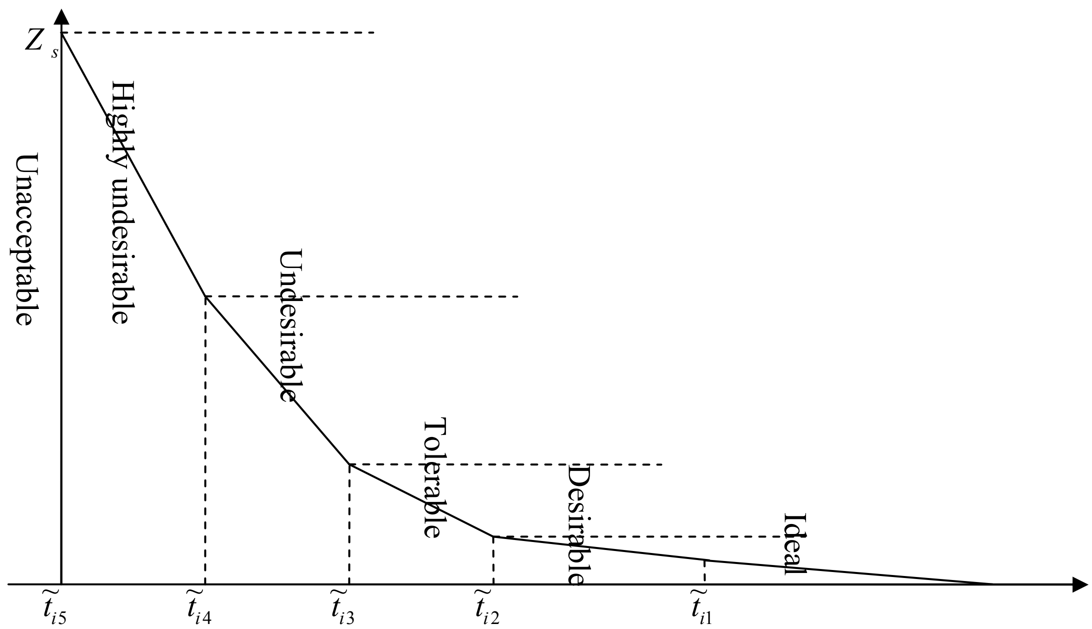


Figure 3.6 Competition position of customer requirement *i*

$\tilde{z}_s$ is the competition position indicator, *s* denotes a range. A higher $\tilde{z}_s$ means that it is more urgent to improve. $\tilde{z}_s$ is the same for all customer requirements and will be used for the following calculation. $\tilde{t}_{is}$ is the limit of different ranges. $\tilde{t}_{is}$ is decided according to the performance ratings of competitors. The best is $\tilde{t}_{i1}$ and the worst is $\tilde{t}_{i5}$. Note that $\tilde{t}_{is}$ is not a crisp number, but a fuzzy number. And $\tilde{g}_i$ is the value of the performance rating under consideration (own product). The competition position is classified as following:

1. Ideal range ($\tilde{g}_i \geq \tilde{t}_{i1}$)
2. Desirable range ($\tilde{t}_{i1} \geq \tilde{g}_i \geq \tilde{t}_{i2}$)
3. Tolerable range ($\tilde{t}_{i2} \geq \tilde{g}_i \geq \tilde{t}_{i3}$)

4. Undesirable range ($\tilde{t}_{i3} \geq \tilde{g}_i \geq \tilde{t}_{i4}$)
5. Highly undesirable range ($\tilde{t}_{i4} \geq \tilde{g}_i \geq \tilde{t}_{i5}$)
6. Unacceptable range ($\tilde{g}_i \leq \tilde{t}_{i5}$)

The number of competitors varies greatly with different markets. Therefore, the competition position is not necessarily be classified into six ranges. The method provided above is not a rigid rule but a way to specify the customer satisfaction range. This process should take into account the design team's manual judgment to choose suitable competitors and decide the number of competition position ranges.

The value of z_s can be defined as follows.

Set $a_0 = 1$, $\beta = 2$, then,

$$a_s = \beta^s a_0 \tag{3.3}$$

Then,

$$\tilde{z}_s = (a_{s-1} / a_s / a_{s+1}) \quad s = 1,2,\ldots,5 \tag{3.4}$$

Because we use triangular fuzzy numbers before, therefore $\tilde{z}_s$ is also modelled as a triangular fuzzy number. $\tilde{z}_s$ increases as s increases. One customer requirement needs more efforts to improve if there is a higher $\tilde{z}_s$. The values of a_0 and β depends on how bad if the performance of own product lags behind that of competitors. The worse the situation, the higher a_0 and β. However, a decision of the values of a_0 and β can only be done in a qualitative way depending on the product designer's experiences.

3) Rating algorithm

First, we can obtain the importance weight of each range of competition position. We define $\tilde{w}_{is}^{'}$ is the weight of range *s* of customer requirement *i*. as

$$\tilde{w}_{is}^{'} = \tilde{z}_s / \tilde{t}_{is} \tag{3.5}$$

We use $\tilde{w}_{in}^{'}$ to denote the weight of customer requirement *i* of own product. Then, $\tilde{w}_{in}^{'}$ can be decided according to the competition position that own product belongs to using following formula:

$$\tilde{w}_{in}^{'} = \tilde{w}_{is}^{'} \text{ when } \tilde{t}_{i,s-1} \geq \tilde{g}_i > \tilde{t}_{i,s} \quad s = 1,2,\ldots,5 \tag{3.6}$$

In this way, we give a higher rate to those requirements on which A's product lags behind competitors and performs worse than other customer requirements. Here, we can define $\tilde{t}_{i,0}$ is (9/9/9), the possible highest performance rating. Please note that we did not define the weight of unacceptable range. Because it is unacceptable, we can use a large number to indicate the weight and ensure that the performance on this customer requirement will be improved.

4) Defuzzification and normalization of importance weight

In step 3, we obtain the fuzzy ratings from competitive analysis. Here again, we defuzzify $\tilde{w}_{in}^{'}$ using the FM method and get the defuzzified weight of customer requirement *i*, denoted by w_{in}. After defuzzification, the weights are normalized to be consistent with the traditional weights.

$$w_{in}^{norm} = \frac{w_{in}}{\sum_i w_{in}} \text{ for each } i \tag{3.7}$$

Step 4 Incorporation of traditional weight

Most traditional methods emphasize customers' views, while overlooking competitive information. However, we cannot overreact and overlook the voice of customers. In this step, we incorporate the importance weight information from customers. The traditional weight can be obtained by many methods as discussed previously. In here, we just assume that the weight is known. Then, the compound weight of customer requirement *i* can be computed as follows:

$$w_{ic}^{'} = rw_{in}^{norm} + w_{it} \tag{3.8}$$

Where $w_{ic}^{'}$ is the compounded weight, w_{it} the weight from customers' view and r is a coefficient. The value of r can be equal, larger, or smaller than one, which is decided by the design team according to the specific competitive environment. If the competition is very keen, r can be larger than one. If the market is fast growing, customers' views are more important and r can be lower than one. After $w_{ic}^{'}$ is obtained, we can normalize it to deduct the final weight w_{ic} using equation (3.9). The obtained weight w_{ic} can be used in the following QFD activities.

$$w_{ic} = \frac{w_{ic}^{'}}{\sum_i w_{ic}^{'}} \text{ for each } i \tag{3.9}$$

Then, the final importance weight can be obtained by combining the factors of competition, performance and customers.

3.4. An illustrative example

Here, we use design of a removable mountain bicycle splashguard (Ullman 1992, Kwong and Bai 2002) as an example to illustrate how to rate customer requirements in a competitive environment. The removable mountain bicycle splashguard has seven customer requirements and they can be divided into three categories: functional performance, spatial constraints and appearance. The customer requirement structure is shown in Figure 3.7.

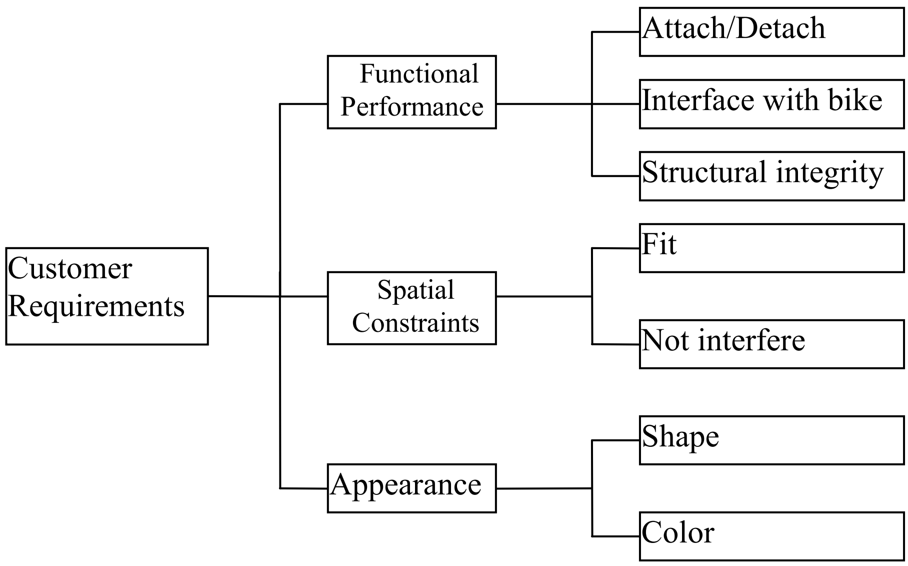


Figure 3.7 Customer requirement structure

3.4.1. Fuzzy performance rating matrix

In practice, the fuzzy performance-rating matrix can be obtained after the customer survey. In this illustration, we use hypothetical data as shown in Table 3.1. Note that the following figure is only for illustrative purpose, and may not represent the actual market situation. Then, the weight algorithm can be used to calculate the importance weight.

Table 3.1 Fuzzy performance rating matrix

	Own Product	Competitor A	Competitor B	Competitor C	Competitor D	Competitor E
Attach/Detach	(3,5,6)	(2,3,4)	(2,3,5)	(4,5,6)	(8,8.1,9)	(7,8,9)
Interface with bike	(8,8.1,9)	(3,4,5)	(2,3,6)	(5,6,7)	(7,8,9)	(6,8,9)
Structural integrity	(6,6.1,7)	(4,5,6)	(5,6,8)	(5,6,7)	(5,5.1,6)	(8,8.1,9)
Fit	(7,8,8.1)	(3,5,6)	(6,7,8)	(4,4.1,6)	(5,8,9)	(7,8,9)
Not interfere	(3,4,7)	(2,4,5)	(4,5,6)	(5,5.1,5.2)	(4,5,7)	(6,8,9)
Shape	(6,8,9)	(4,5,6)	(7,8,9)	(4,6,6.1)	(6,7,8)	(8,8.9,9)
Color	(5,6,8)	(4,5,7)	(6,7,8)	(8,8.1,9)	（7,8,9）	(6,7,7.1)

3.4.2. Fuzzy comparison and classifying competition position

After the use of the defuzzification method, the performance-rating matrix is calculated as shown in Table 3.2.

For the customer requirement of “attach/detach”, the sequence of ranking should be: competitor D (8.3667) > competitor E (8.0000) > competitor C (5.0000) > competitor B (3.3333) > competitor A (3.0000). Then, the competition position level can be set as the following bellow.

Table 3.2 Defuzzified performance rating matrix

	Own Product	Competitor A	Competitor B	Competitor C	Competitor D	Competitor E
Attach/Detach	4.6667	3.0000	3.3333	5.0000	8.3667	8.0000
Interface with bike	8.3667	4.0000	3.6667	6.0000	8.0000	7.6667
Structural integrity	6.3667	5.0000	6.3333	6.0000	5.3667	8.3667
Fit	7.7000	4.6667	7.0000	4.7000	7.3333	8.0000
Not interfere	4.6667	3.6667	5.0000	5.1000	5.3333	7.6667
Shape	7.6667	5.0000	8.0000	5.3667	7.0000	8.6333
Color	6.3333	5.3333	7.0000	8.3667	8.0000	6.7000

1. Ideal range [$\tilde{g}_i \geq (8,8.1,9)$]
2. Desirable range [$(8,8.1,9) \geq \tilde{g}_i \geq (7,8,9)$]
3. Tolerable range [$(7,8,9) \geq \tilde{g}_i \geq (4,5,6)$]
4. Undesirable range [$(4,5,6) \geq \tilde{g}_i \geq (2,3,5)$]
5. Highly undesirable range [$(2,3,5) \geq \tilde{g}_i \geq (2,3,4)$]
6. Unacceptable range [$\tilde{g}_i \leq (2,3,4)$]

The above results are shown in Figure 3.8. The other five customer requirements can be treated in the same way.

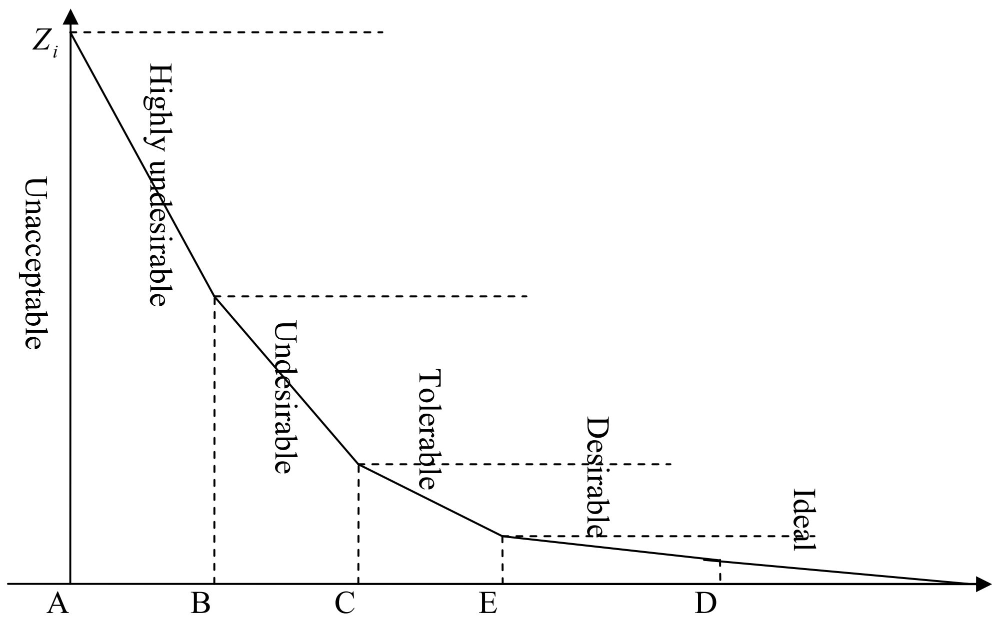


Figure 3.8 Competition position of customer requirement attach/detach

3.4.3. Competitive weight rating algorithm

Matlab was used for computation of the competitive weight rating. The result is as shown in Table 3.3. The competitors' information is used to generate the importance weight of each customer requirement at each range.

Table 3.3 Results of rating algorithm

	Ideal range	Desirable range	Tolerable range	Undesirable range	Highly undesirable
Attach/Detach	0.11, 0.25, 0.50	0.22, 0.50, 1.14	0.67, 1.60, 4.00	1.60, 5.33, 16.00	4.00, 10.67, 32.00
Interface with bike	0.11, 0.25, 0.57	0.22, 0.50, 1.33	0.57, 1.33, 3.20	1.60, 4.00, 10.67	2.67, 10.67, 32.00
Structural integrity	0.11, 0.25, 0.50	0.25, 0.67, 1.60	0.57, 1.33, 3.20	1.33, 3.14, 6.40	2.67, 6.40, 16.00
Fit	0.11, 0.25, 0.57	0.22, 0.50, 1.60	0.50, 1.14, 2.67	1.33, 3.90, 8.00	2.67, 6.40, 21.33
Not interfere	0.11, 0.25, 0.67	0.29, 0.80, 2.00	0.77, 1.57, 3.20	1.33, 3.20, 8.00	3.20, 8.00, 32.00
Shape	0.11, 0.22, 0.50	0.22, 0.50, 1.14	0.50, 1.14, 2.67	1.31, 2.67, 8.00	2.67, 6.40, 16.00
Color	0.11, 0.25, 0.50	0.22, 0.50, 1.14	0.50, 1.14, 2.67	1.17, 2.29, 5.33	2.29, 6.40, 16.00

The importance weight of each customer requirement is then decided according to the range that one's own product performance should belong to. In this example, the obtained weights are as shown in Table 3.4.

Table 3.4 Result of fuzzy importance weight

	Attach /Detach	Interface with bike	Structural integrity	Fit	Not interfere	Shape	Color
Weight	1.60, 5.33, 16.00	0.11, 0.25, 0.57	0.25, 0.67, 1.60	0.22, 0.50, 1.60	3.20, 8.00, 32.00	0.50, 1.14, 2.67	2.29, 6.40, 16.00

Using the defuzzification method as previously shown, the crisp importance weights are obtained. After normalization, the importance weights are obtained from competition and performance. The results are shown in Table 3.5. The second row shows the crisp importance weights and the third row shows the normalized results.

Table 3.5 Crisp importance weight result

	Attach/Detach	Interface with bike	Structural integrity	Fit	Not interfere	Shape	Color
Weight	7.64	0.31	0.84	0.77	14.40	1.44	8.23
Normalized Weight	0.2273	0.0092	0.0250	0.0230	0.4281	0.0427	0.2447

3.4.4. Incorporating the traditional weight

From the traditional customer survey, we have the importance rating. Here, we use the weight from fuzzy AHP approach of that in Kwong and Bai (2002), as shown in the first row of Table 3.6. Here, we set $r=1$ and compound the two importance weight. After normalization, we obtain the normalized compound importance weight as shown in the third row of Table 3.6. The final ranking is:

Attach/Detach>Not interfere>Structural integrity>Colour>Interface with bike>Shape>Fit

Table 3.6 Traditional importance weight

	Attach/Detach	**Interface with bike**	**Structural integrity**	**Fit**	**Not interfere**	**Shape**	**Colour**
Traditional Weight	0.3130	0.1128	0.3130	0.0635	0.0898	0.0447	0.0633
Final Weight	0.2701	0.0610	0.1690	0.0432	0.2589	0.0437	0.1540

3.4.5. Comparison

To signify the difference between the proposed method and previous methods, we did a comparison of the results from the traditional method, the use of entropy method, and the newly proposed method. The results are shown Table 3.7. As seen from Table 3.7, he rankings of the proposed method are very different from those of traditional methods and the use of entropy method.. The reason lies in the fact that A's product performance varies among the seven customer requirements. Although some customer requirements are very important, if A's product performs very well on these customer requirements, the design teams should not devote too much time and cost on these customer requirements. The proposed method puts more emphasis on aspects where one's own product lags behind.

Table 3.7 Comparison of different method

Rank	1	2	3	4	5	6	7
Traditional Method	Attach/Detach & Structural integrity		Interface with bike	Not interfere	Fit	Colour	Shape
Use of Entropy Method	Structural integrity	Attach/Detach	Interface with bike	Not interfere	Color	Fit	Shape
Proposed Method	Attach/Detach	Not interfere	Structural integrity	Color	Interface with bike	Shape	Fit

3.5. Conclusion

In a competitive environment, the success of a product depends on not only its own performance, but also its competitors. For example, the product may perform poorly in meeting one kind of customer requirement. However, if its competitors are not as good, it might stand out in the market, even though the customer satisfaction level is low. On the other hand, it may perform quite well in meeting a different customer requirement. However, if its competitors are better, the product can be viewed to be relatively poorer for the particular customer requirement. Therefore, it is important to incorporate competition analysis early in the product design stage.

The proposed method can be viewed as a framework that utilizes competitors' information to generate the importance weights. Compared with previous methods, this method is more meaningful to companies. It provides a way to find the best product design strategy for the specific company. Though the algorithm is more complicated, the calculation can be carried out in light of standard computer programs. Therefore, it can be easy to implement.

This new method has several advantages compared with previous methods. First, this new method not only focuses on the voice of the customer, but considers the competitive environment. Second, this method helps in finding out the most important customer requirements, and provides a way to combine them with the importance weights from customers' point of view. Finally, this method uses fuzzy mathematics instead of crisp numbers to capture the true customer requirements.

Chapter 4 Fuzzy Approach to Exploit the Roof of House of Quality

4.1. Introduction

In the product design, usually the change of one of technical attributes will affect the value of other technical attributes and then affect their effect on the customer requirements. For example, a change of the material of the notebook cover from plastic to metal will make other technical attributes, such as total weight, thermodynamic characteristics, change correspondingly and the customer requirements, such as comfort, portability, also change. HOQ's distinctive "roof", interrelationship matrix among technical attributes, depicts the impact of this fact and helps designers model and make trade-offs among engineering characteristics. Traditionally, such a kind of relationships is represented by symbols in Figure 4.1 (Wasserman, 1993).

●	Very strong
○	Fairly strong
◇	Moderate
△	Fairly weak
▲	Very weak

Figure 4.1 An example of symbols

These symbols provide a direct expression of the interrelationships among technical attributes. However, such expression is very imprecise. To better help product design, the information needs to be quantified and expressed in mathematical terms. As the emergence of quantitative QFD methods, especially QFD optimization methods, a practical and meaningful way to quantify this information is essential. However, there is no previous research specifically focuses on this aspect. Only a few studies can be found in literature on QFD optimization related areas. Compared with customer requirements, another part in HOQ, on which many papers have been published, study on interrelationships of technical attributes got much less attention in the past. Therefore, there is a strong need to provide a thorough study in this area.

A good method should retain the following properties. First, the final result should be a normalized one. The importance of normalization was revealed by Lyman (1990) and Wasserman (1993). Normalization helps to avoid the distortion of importance weights of technical attributes by sub-technical attributes. Second, the roof of HOQ should be expanded to a square matrix to accommodate an asymmetrical matrix. Third, a series of matrix, not a single one, should be used to satisfy different impacts on each customer requirement. Last but not least, the final result should be easily visualized, an important property which can help designers assess the impact of dependency among technical attributes directly. This chapter is to propose such a method.

4.2. A review on previous study

The relationship among engineering characteristics can eventually affect the relationships between engineering characteristics and customer satisfaction level. Incorporating the information in the roof to the relationship matrix of technical attributes and customer requirements is a natural way to quantify the interrelationships among technical attributes.

Wasserman (1993) proposed a normalization method to incorporate the information of interrelationships among technical attributes. In the Wasserman's model, the relationship matrix is normalized according to the relationship among technical attributes (TA) with the following formula:

$$R_{ij}^{norm} = \frac{\sum_{k=1}^{n} R_{ik} \cdot \gamma_{kj}}{\sum_{j=1}^{n} \sum_{k=1}^{n} R_{ij} \cdot \gamma_{jk}} \tag{4.1}$$

R_{ij} can be interpreted as the incremental change in the level of fulfilment of the i_{th} customer requirement when the j_{th} technical attribute is fulfilled to a certain level. γ_{kj} is the degree of interdependence of the k_{th} TA on the j_{th} TA. R_{ij}^{norm} is R_{ij} after considering dependencies among technical attributes.

This is the first quantitative method that accommodates these interdependences. Wasserman's method is very straightforward and easy to understand. It was used intensively in many subsequent research. However, it overlooks the direction of the dependency among technical attributes. For example, technical attribute A depends on technical attribute B, but it doesn't mean that technical attribute B depends on technical A to the same extent. In the Wasserman's method, these two kinds of dependency are assumed to be the same. The shape of the roof in HOQ is a triangle and it represents a symmetrical matrix. To represent this asymmetrical dependency, we need to use a square asymmetrical matrix.

Moskowitz and Kim (1997) proposed a square matrix to represent the dependency among technical attributes in their QFD optimization model. The formula used in this method is similar with that in Wasserman's method. The difference is that this model overcomes the deficiency of symmetrical matrix. However, the interrelationship among technical attributes also depends on specific customer requirements, which means that one matrix is not sufficient. Each customer requirement should have a relationship matrix of technical attributes.

Fung *et al.* (2003) suggested another approach to model the interrelationship among technical attributes. In this model, the concepts of "planned attainment" and "actual attainment" are introduced. The "actual attainment" is formulated as:

$$TA_j = T\hat{A}_j + \sum_{k \neq j} \gamma_{kj} T\hat{A}_k \tag{4.2}$$

TA_j is actual attainment, $T\hat{A}_j$ is planned attainment. This formula looks intuitive, straightforward and useful. However, it has at least two disadvantages. First, it does not provide a direct result that can represent the effect of dependency among technical attributes. In contrast, Wasserman's method provides a normalized relationship matrix which displays the final result incorporating dependency among technical attributes. Second, due to the lack of normalization process inherited in the above formula, the maximum actual attainment value may be volatile. This will cause inconvenience in interpreting the final result.

Yoram and Levy (2004) proposed a new approach based on Fung's method. The method uses asymmetrical matrix and customer requirement specified matrix to capture interdependency among technical attributes. It is an improvement from Fung's method. However, despite of the disadvantages inherited in Fung *et al.* (2003), this method applies specific matrix and mixes them by using weights of customer requirements. The last additional step weakens the benefit from using specific matrix for each customer requirement.

In summary, all the previous methods have some deficiencies. Because the interdependency among technical attributes is very important and widely used in quantitative QFD methodology development, there is a strong need to develop a new method that can overcome the proficiencies encountered in the previous methods.

This chapter proposed a new approach to analyze the interrelationship among technical attributes. This approach overcomes the deficiencies in the previous methods. What's more, this method applies fuzzy mathematics to capture the vagueness when assessing the interrelationship among technical attributes. The scales used are often symbols, or 1-3-9 scale, or 1-9 scale, or even verbal expressions. The scale itself is imprecise and ambiguous. Fuzzy mathematics is a good tool to capture such ambiguity. Many papers have introduced fuzzy mathematics into QFD, e.g. Zhou (1998), Wang (1999), Temponi *et al*. (1999), Shen *et al*. (2001), and Karsak (2004). This approach can be easily applied together with other QFD technique. The following section will discuss the proposed approach.

4.3. The new approach

This new approach evaluates the interrelationships among technical attributes and then incorporates this information into the relationship matrix of technical attributes and customer requirements. The final output will be a normalized fuzzy relationship matrix between technical attributes and customer requirements that can be used in the following QFD activities.

4.3.1. Construct a linguistic-evaluation system

Linguistic term is a natural and easy way for designers to evaluate the interrelationships among technical attributes. However, linguistic terms are usually subjective and uncertain. To make them intuitive and more meaningful, fuzzy mathematics is used to capture the vagueness and ambiguity inherent in the linguistic terms. In this approach, the relationship strengths are evaluated by five linguistic terms, i.e. weak, fairly weak, moderate, fairly strong and very strong, to evaluate the strength of interrelationship among technical attributes. The membership functions associated with the linguistic terms are defined as follows. Figure 4.2 shows the plot of membership functions.

$$\mu_{\text{very weak}}(x) = \begin{cases} x/0.15 & 0 \le x \le 0.15 \\ 2 - x/0.15 & 0.15 \le x \le 0.2 \end{cases} \quad (4.3)$$

$$\mu_{\text{fairly weak}}(x) = \begin{cases} x/0.15 - 4/3 & 0.2 \le x \le 0.35 \\ 10/3 - x/0.15 & 0.35 \le x \le 0.5 \end{cases} \quad (4.4)$$

$$\mu_{\text{moderate}}(x)=\begin{cases}5x-1.5 & 0.3\le x\le 0.5\\ 3.5-5x & 0.5\le x\le 0.7\end{cases} \quad (4.5)$$

$$\mu_{\text{fairly strong}}(x)=\begin{cases}x/0.15-10/3 & 0.5\le x\le 0.65\\ 16/3-x/0.15 & 0.65\le x\le 0.8\end{cases} \quad (4.6)$$

$$\mu_{\text{very strong}}(x)=\begin{cases}x/0.15-14/3 & 0.7\le x\le 0.85\\ 20/3-x/0.15 & 0.85\le x\le 1\end{cases} \quad (4.7)$$

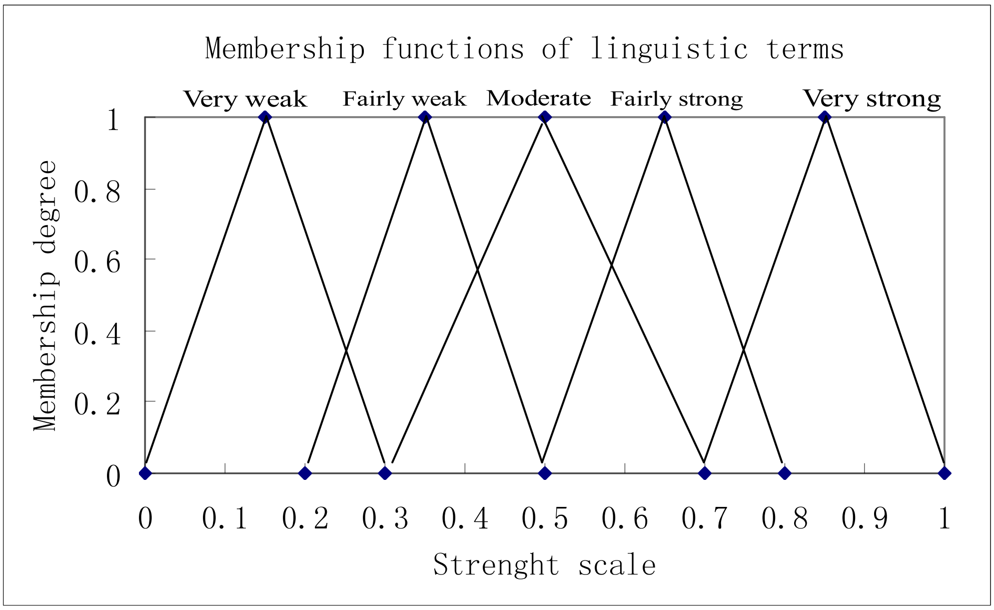


Figure 4.2 Membership functions of linguistic terms for relationships

In the roof of HOQ, we use five different symbols to illustrate the five scales as shown in Figure 4.3.

TA1					
TA2			◇		◇
TA3		△			●
TA4					
TA5		○	○		
	TA1	**TA2**	**TA3**	**TA4**	**TA5**

●	Very strong
○	Fairly strong
◇	Moderate
△	Fairly weak
▲	Very weak

Figure 4.3 Example of roof of HOQ

4.3.2. Evaluating the strength of interrelationships for each customer requirement

As discussed earlier, one matrix is not sufficient to model the dependency among technical attributes. Therefore, multiple HOQ roofs are constructed for different customer requirements. In each roof, the dependency among technical attributes for a customer requirement is evaluated. An example is shown in Figure 4.4.

TA1					
TA2			◇		◇
TA3		△			●
TA4					
TA5		○	○		
	TA1	**TA2**	**TA3**	**TA4**	**TA5**
CR_i	◇				●

Figure 4.4 Roof for customer requirement *i*

4.3.3. Deriving the normalized relationship matrix

After obtained the multiple roofs for customer requirements, we can derive the final result, normalized relationship matrix among technical attributes and customer requirements. In this approach, the relationship is evaluated in linguistic terms. Therefore, fuzzy mathematics is employed to represent the fuzzy relationship among technical attributes. The formula is as follows:

$$\tilde{R}_{ij}^{norm} = \frac{\sum_{k=1}^{n} \tilde{R}_{ik} \tilde{\gamma}_{kj}}{\sum_{j=1}^{n} \sum_{k=1}^{n} \tilde{R}_{ik} \tilde{\gamma}_{kj}} \tag{4.8}$$

where

$\tilde{R}_{ij}^{norm}$ = normalized relationship between customer requirement *i* and technical attribute *j* incorporating interrelationship among technical attributes, *j*=1,2,…,*n*;

$\tilde{R}_{jk}$ = fuzzy relationship between customer requirement *i* and technical attribute *j*, *j*=1,2,…,*n*;

$\tilde{\gamma}_{kj}$ = quantified impact of technical attribute *k* on technical attribute *j*;

The formula above is similar to Wasserman's method in terms of the form, but they are two totally different methods. The above formula is not easy to solve because it contains multiplication and addition in both numerator and denominator. Chen and Weng (2003) provided an a -cut approach by finding the lower and upper bonds of a -cut of $\tilde{R}_{ij}^{norm}$ based on Kao and Liu (2000). The formulas are as followings:

$$(\tilde{R}_{ij}^{norm})_{\alpha}^{L} = \frac{\sum_{k=1}^{n} (\tilde{R}_{jk})_{\partial}^{L} (\tilde{\gamma}_{kj})_{\alpha}^{L}}{\sum_{l \neq j, l=1,}^{n} \sum_{k=1}^{n} (\tilde{R}_{jk})_{\partial}^{U} (\tilde{\gamma}_{kl})_{\alpha}^{U} + \sum_{k=1}^{n} (\tilde{R}_{jk})_{\partial}^{L} (\tilde{\gamma}_{kj})_{\alpha}^{L}} \tag{4.9}$$

$$(\tilde{R}_{ij}^{norm})_{\alpha}^{U} = \frac{\sum_{k=1}^{n} (\tilde{R}_{jk})_{\partial}^{U} (\tilde{\gamma}_{kj})_{\alpha}^{U}}{\sum_{l \neq j, l=1,}^{n} \sum_{k=1}^{n} (\tilde{R}_{jk})_{\partial}^{L} (\tilde{\gamma}_{kl})_{\alpha}^{L} + \sum_{k=1}^{n} (\tilde{R}_{jk})_{\partial}^{U} (\tilde{\gamma}_{kj})_{\alpha}^{U}} \tag{4.10}$$

Where

$(\quad)_{\partial}^{L}$ = lower bond of a -cut;

$(\quad)_{\partial}^{U}$ = upper bond of a -cut;

The above formulas are complicate but are suitable for all kinds of membership functions. Mathematical software, e.g. Matlab®, can help to solve the computation problem.

Because in this approach all the fuzzy membership functions are triangular, alternatively, we can use a simplified algorithm that is only specifically suitable for triangular membership function to find the membership function of $\widetilde{R}_{ij}^{norm}$. The algorithm is as follows.

Addition:

$$(a, b, c) + (d, e, f) = (a+d, b+e, c+f) \tag{4.11}$$

Multiplication:

$$(a, b, c) * (d, e, f) = (a*d, b*e, c*f) \tag{4.12}$$

Division:

$$(a, b, c) / (d, e, f) = (a/f, b/e, c/d) \tag{4.13}$$

Using the above formulas, we can also obtain the triangular membership function of $\widetilde{R}_{ij}^{norm}$. It is much easier than Chen and Weng's method. However, the above three formula will provide a much larger range than that of Chen and Weng's method. Therefore, this simplified method is not recommended.

4.4. Examples

In order to demonstrate the feasibility of the proposed approach, an example of a writing instrument design from Wasserman (1993) is used to illustrate the application of the proposed model. The writing instrument has four customer requirements: easy hold (expressed as CR1 in the following discussions), does not smear (CR2), point last (CR3) and does not roll (CR4). Five technical attributes are length of pencil (expressed as TA1 in the following discussions), time between sharpening (TA2), lead dust generated (TA3), Hexagonality (TA4) and minimal erasure residue (TA5). Figure 4.5 is an excerpted HOQ from Wasserman's work.

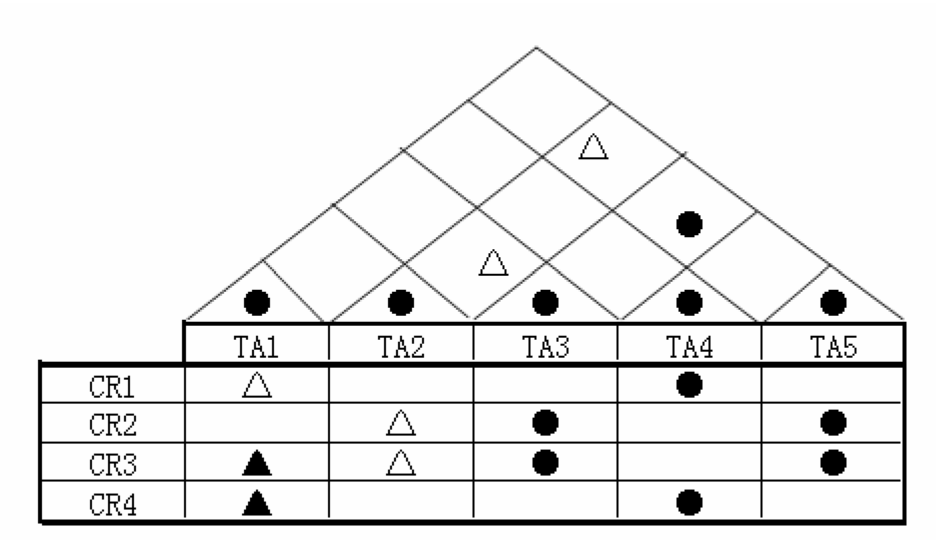


Figure 4.5 Excerpted HOQ

As discussed earlier, single symmetrical relationship matrix is not sufficient. Therefore, four asymmetrical relationship matrixes are constructed for the four customer requirements. These matrixes are shown in Figure 4.6, Figure 4.7, Figure 4.8 and Figure 4.9 respectively. The symbols have the same meaning as that in Figure 4.3.

TA1	●				
TA2		●	◇		◇
TA3		△	●		●
TA4				●	
TA5		○	○		●
	TA1	**TA2**	**TA3**	**TA4**	**TA5**
CR1	◇			●	

Figure 4.6 Roof for customer requirement 1

TA1	●				
TA2		●	◇		△
TA3		○	●		○
TA4				●	
TA5		○	△		●
	TA1	**TA2**	**TA3**	**TA4**	**TA5**
CR2		△	●		●

Figure 4.7 Roof for customer requirement 2

TA1	●				
TA2		●	◇		◇
TA3		△	●		○
TA4				●	
TA5		△	●		●
	TA1	**TA2**	**TA3**	**TA4**	**TA5**
CR3	▲	△	●		●

Figure 4.8 Roof for customer requirement 3

TA1	●				
TA2		●	△		○
TA3		△	●		●
TA4				●	
TA5		●	○		●
	TA1	**TA2**	**TA3**	**TA4**	**TA5**
CR4	▲			●	

Figure 4.9 Roof for customer requirement 4

After evaluating the interdependence among technical attributes according to each customer requirements, we can incorporate such information into relationship between customer requirements and derive the fuzzy normalized relationship matrix among customer requirements and technical attributes. The symbols, corresponding linguistic terms, membership functions and a -cut formulas are summarized in Table 4.1.

Table 4.1 Summary of symbols and their meanings

Symbol	**Linguistic term**	**Membership function**	$(\quad)_{\partial}^{L}$	$(\quad)_{\partial}^{U}$
●	Very strong	(0.7, 0.85, 1)	0.7+0.15a	1-0.15a
○	Fairly strong	(0.5, 0.65, 0.8)	0.5+0.15a	0.8-0.15a
◇	Moderate	(0.3, 0.5, 0.7)	0.3+0.2a	0.7-0.2a
△	Fairly weak	(0.2, 0.35, 0.5)	0.2+0.15a	0.5-0.15a
▲	Very weak	(0, 0.15, 0.3)	0.15a	0.3-0.15a

a-cut approach is applied here. The mathematical software, Matlab, is implemented to expedite the computation process. Different levels of a (from 0.05 to 1) are used to calculate the a-cut value. Then the membership function of $\widetilde{R}_{ij}^{norm}$ can be constructed. The results are shown in Table 4.2. The results above can be used in the following QFD activities either in the fuzzy form or crisp form. It depends on the requirements of the following QFD activities.

Table 4.2 Normalized relationship matrix

	TA1	**TA2**	**TA3**	**TA4**	**TA5**
CR1	0.18, 0.37, 0.58	0, 0, 0	0, 0, 0	0.42, 0.63, 0.82	0, 0, 0
CR2	0, 0, 0	0.18, 0.35, 0.56	0.15, 0.30, 0.51	0, 0, 0	0.19, 0.35, 0.56
CR3	0, 0.03, 0.11	0.09, 0.22, 0.42	0.22, 0.40, 0.63	0, 0, 0	0.19, 0.35, 0.58
CR4	0.01, 0.15, 0.37	0, 0, 0	0, 0, 0	0.63, 0.85, 0.99	0, 0, 0

4.5. Results comparison of proposed method and previous methods

To study the usefulness and effectiveness of proposed method, the results of the proposed method and Wasserman's method was compared. Because the previous results are crisp numbers, we need to defuzzify the results in Table 4.2 to make the two results comparable using MOM method and FM method that are discussed in Chapter 3.

Table 3 shows the relationships among customer requirements and technical attributes obtained from different methods. The 'Crisp' column lists the results from traditional approach, Wassernman's approach. The results from proposed fuzzy methods are defuzzified using MOM and FM method and the defuzzified results are listed under MOM and FM columns respectively. As we can see from Table 3, the results in the 'Crisp' column are quite different from the defuzzified results from MOM and FM methods. For instance, the relationship between CR2 and TA2 obtained from traditional method is 0.1900 which is about half of the results from MOM method (0.35) and FM method (0.36). The relationship between CR2 and TA3 obtained from traditional method was 0.405 which is larger than the results from both MOM method (0.30) and FM methods (0.32). We can conclude that the results from traditional methods are not the most probable results because they are different from MOM method's results, nor the compromised results which are different from FM method's results. Furthermore, there is no uniform pattern of the difference between results obtained using traditional methods and results using MOM and FM defuzzified methods. The difference can be positive or negative. Therefore, traditional method is not accurate and the proposed fuzzy method reveals information that is much more valuable.

Table 4.3 Summary of different Results

	TA1			**TA2**			**TA3**			**TA4**			**TA5**		
	Crisp	**MOM**	**FM**	**Crisp**	**MOM**	**FM**	**Crisp**	**MOM**	**FM**	**Crisp**	**MOM**	**FM**	**Crisp**	**MOM**	**FM**
CR1	0.25	0.37	0.38	0	0	0	0	0	0	0.75	0.63	0.62	0	0	0
CR2	0	0	0	0.19	0.35	0.36	0.41	0.30	0.32	0	0	0	0.41	0.35	0.37
CR3	0.02	0.03	0.05	0.19	0.22	0.24	0.40	0.40	0.42	0	0	0	0.40	0.35	0.37
CR4	0.10	0.15	0.18	0	0	0	0	0	0	0.90	0.85	0.82	0	0	0

4.6. Discussion and conclusions

It is a great advantage that HOQ has the ability to reveal and explicitly display the interrelationship among technical attributes. How to exploiting such kind of information contained in the roof of HOQ is crucial. Though there were some studies on this field, as discussed earlier, all of them can not meet the requirements disucssed in section 4.1 and had their deficiencies. This chapter developed a new approach to interpret the roof of HOQ and incorporate this information into the relationship matrix between customer requirements and technical attributes. This new approach effectively deals with the complicity of dependency among technical attributes. It considers the asymmetrical nature of the dependency, customer requirement's impact on the dependency and applies fuzzy mathematics to capture the vagueness in product design.

A writing instrument example is used to illustrate how to use the proposed method. In this example, a comparative study between proposed method and Wassernman's method is carried out. The study shows the usefulness and effectiveness of proposed method. The old method is not accurate and the new method can provide much more meaningful information.

Chapter 5 Optimization Models for Quality Function Deployment

In the previous two chapters, we discussed the rankings of customer requirements and relationships among technical attributes. In this chapter, we will take all parts of HOQ into consideration and form a QFD optimization model.

5.1. Introduction

In the recent years, many optimization methods were introduced into QFD process to maximize customer satisfaction under certain constraints. However, there is lack of a generalized QFD optimization framework that can guide researchers and practitioners. There are many stages in the QFD optimization process. Most current optimization methods focus on only part of the QFD process though all of them are called QFD optimization. This may cause some misunderstanding to researchers and practitioners. To overcome these problems, this chapter is aimed to provide a generalized QFD optimization framework and nearly all the current QFD optimization methods can be included under this framework. In this model, this whole QFD optimization process is divided into several steps, and each step has its distinct function.

There are two forms of optimization process. The first one is the investment form whose aim is to maximize customer satisfaction given a limited amount of investment. The second is quality form with its aim to minimize total investment given a fulfilment level of each customer requirement. There are the two most common situations that happen in a company. However, in methodology development, these two forms can be transferred from one to the other easily. Therefore, this study will focus on the first form of QFD optimization, maximizing customer satisfaction under limitation of resources.

Compared with traditional QFD models or framework, this model is focused on optimization. It has three characteristics:

1. All the activities within this model are aimed to contribute to the quantitative analysis of QFD.
2. The aim of this model is to find the optimal solution under certain constraints.
3. It may require external data support besides the data in QFD

This model will be useful to both practitioners and researchers. First, this model helps practitioners to understand the QFD optimization methods. Also, with this model, practitioners can use it as a step by step guide to apply quantitative analysis of QFD and find the optimal solution. This model provides a breakdown of the whole QFD optimization process, and each step has its own methods. Practitioners can choose the best or most suitable methods of each step and create the most suitable specialized QFD optimization model for themselves. This model can also help researchers understand QFD optimization process. Using this model, researchers can better analysis and break down others' methods, and then get better understanding of them. This model can also help researchers find a possible research area. The following part will describe each step of the model in detail. And a review of current studies of each step is also provided.

This chapter is organized as following. The second part provides the generalized QFD optimization model. In this part, each step of QFD optimization model is clearly analyzed. The third part is a simple illustration. Finally there is a conclusion.

5.2. Generalized QFD optimization model

In product/service design, there are always kinds of constraints, e.g. time, cost, people and so on. Therefore, there are many trade-off decisions which have to be made during the design process. Then, the QFD optimization problems can be defined as that under certain design constraints, e.g. time, cost, and people, etc, technical attributes are decided to satisfy each customer requirement and then maximize the overall customer satisfaction.

Here, we propose generalized QFD optimization model. Though there are many QFD optimization models, nearly all these optimization models can be fitted into this generalized model. Optimization process can be expressed in Figure 5.1.

Figure 5.1 represents not only the exhaustive search method but also other search method. The difference is how to search the optimal solution. It is determined by the specific mathematical model. Different mathematical model has different search method and may have special constraints on the feasible solution space.

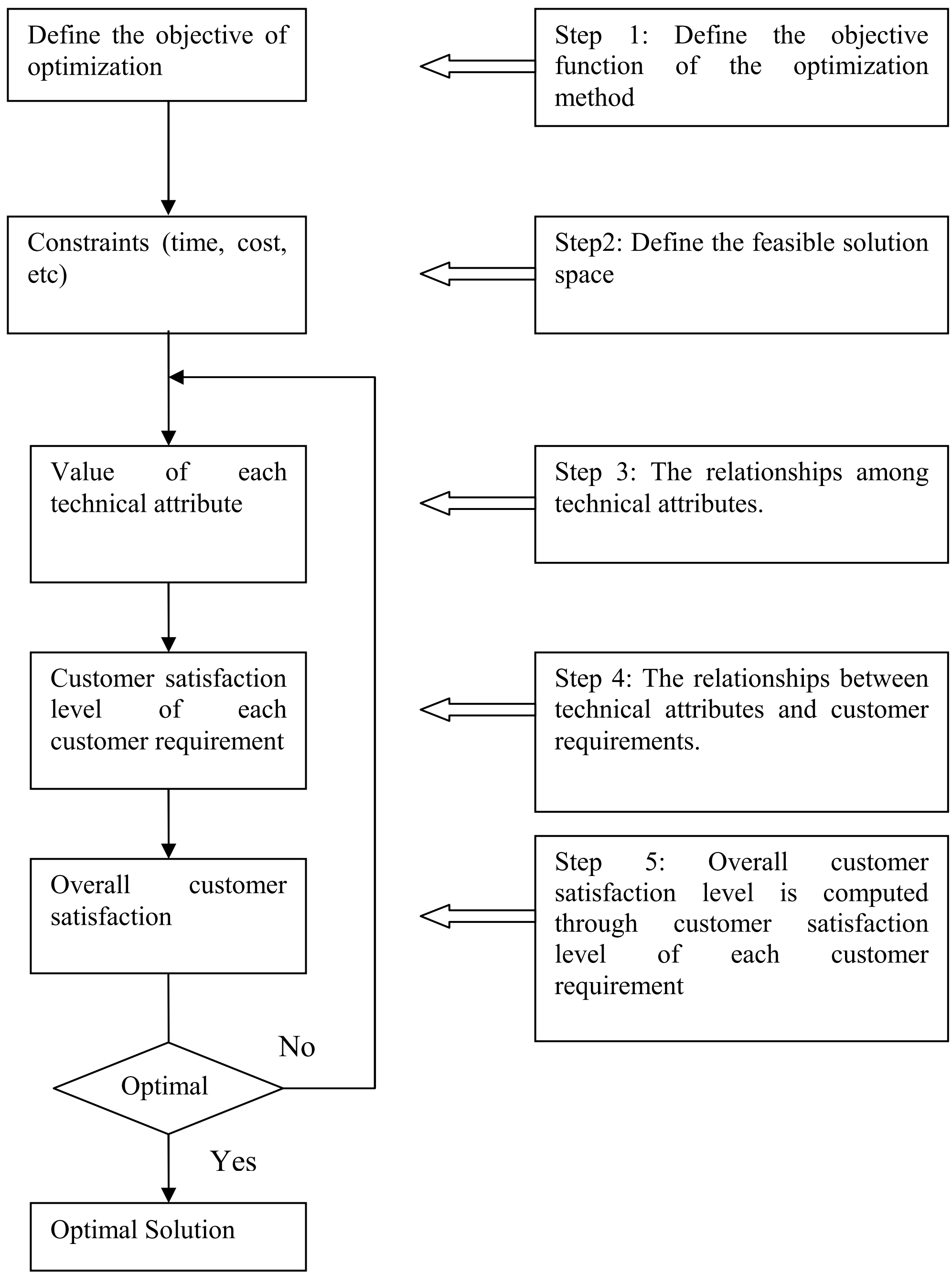


Figure 5.1 Flow chart of QFD optimization process

5.2.1. Formulation of the objective function

At this step, the objective function is defined. Usually the objective is to maximize the overall customer satisfaction level and it is a function of customer satisfaction on each customer requirement. Mathematically, it can be represented as:

$$Max \quad S(y_1, y_2, ..., y_m) \tag{5.1}$$

Another possible objective is to achieve certain goals of customer satisfaction as close as possible under certain constraints. It is a variation from formula 5.1. Mathematically it usually can be represented as:

$$Min \;\; S(|y_1 - \hat{y}_1|, |y_2 - \hat{y}_2|, ..., |y_m - \hat{y}_m|) \tag{5.2}$$

where S is the functional relationship between overall customer satisfaction and customer satisfaction on each customer requirements. Note that y_i = customer satisfaction level is the goal on the ith customer requirement i=1,2,…,m, $\hat{y}_i$ is the goals on the customer requirement i.

To model the objective function, the first thing is to figure out the relationship between satisfaction level of each customer requirement and overall customer satisfaction level. In practice, the relationship may be addictive or multiple or in a mixed way. Nearly in all the current papers, the relationship is modeled as an additive one, e.g. Xie *et al*. (2003). That is, the overall customer satisfaction is the weighted sum of customer satisfaction on each customer requirement. Mathematically, it can be represented as:

$$\text{Overall Customer Satisfaction} = \sum w_i y_i \tag{5.3}$$

where w_i is the importance weight of the i th customer requirement.

However, the relationships between each customer requirement are very complicated, and this kind of relationship may not be true at certain situation. For example, there is a three-component system which is shown in Figure 5.2, and the customer requirement is the overall reliability of the system. The three components have their own reliability characteristics, r_1, r_2, r_3. Because it is a series system, the overall reliability of the system should be the product of r_1, r_2 and r_3.

Figure 5.2 A three components system

It is difficult to decide which kind of relationship is more appropriate and it is highly dependent on the specific product that is to be designed. Different products have different relationships. It should be decided by the design teams using their experience or customer survey.

Weighted sum method is still the most common method used in practice. To use this method, it must determine the relative importance weight of each customer requirement. A lot of papers have been published in this area. In the traditional QFD approach, absolute importance rate is used to identify the degree of importance for each customer requirement. Usually these importance rates are obtained from many qualitative methods, such as interviews, mail questionnaires, and product clinics and so on. However, in practice, Chuang (2001) argues that "customers tend to rate almost everything as being important". Therefore, it is very hard for design team to identify the true importance weight. The consequence is that the design team have to make trade-offs themselves. This activity will lead to bias in product design.

In the recent years, many mathematical methods to rank customer requirements were proposed (e.g. Armacost *et al*. 1994, Chan and Wu 1998, Chuang 2001, Ho *et al.* 1999, Lin and Fite 1995, Lu *et al.* 1994, Madu and Kuei 1994, Shen *et al.* 2000, Vairaktarakis 1999). Xie *et al.* (1995) suggested that Analytic Hierarchy Process (AHP) can be used to provide better prioritization while using QFD as a preliminary selection of factors. AHP is a frequently used mathematical method to rank customer requirements and many papers (Armacost *et al*. 1994, Chan and Wu 1998, Che and Lin 1998, Ho *et al.* 1999, Lin and Fite 1995, Lu *et al.* 1994) are about it. AHP can help to generate the final importance rate by comparing two different requirements at a time. By comparing each pair of customer requirements to indicate how much more important one of each pair is than the other, AHP can measure the relative degree of importance of each customer requirement.

Thus, AHP is a very useful tool to assist the product design team to rank the customer requirements. Xie *et al.* (1998) studied the sensitivity related to customer requirements using AHP method. The ranking is not sensitive to customer voice as the discrete weight is used for the correlation matrix.

Chan *et al*. (1999) proposed to use fuzzy entropy method to rate "what". This method makes full use of customer input to reveal the relative importance of their requirements and is easy to apply. The fuzzy method is used to convert the customers' importance assessments of the requirements to fuzzy numbers, and the relative importance ratings of the customer requirements are then obtained using fuzzy arithmetic. The entropy method of information theory is used in analyzing the customers' assessments of the performance of the company and its related competitors for obtaining the competitive priority ratings of the customer requirements. Then, design team combines the two sets of ratings to obtain the final importance ratings of the customer requirements.

5.2.2. Relationships between technical attributes and design constraints

There are many constraints in engineering design, such as cost, time, people, and minimum customer satisfaction level and so on. These constraints define the feasible solution space of the design problem. To define the design space, we must figure out the relationships between technical attributes and design constraints, for example, the relationship between cost and technical attributes.

This kind of relationship is mainly determined by the engineers' experiences. Sometimes, these relationships are very easy to capture, e.g., linear relationship, but sometimes the relationship is very hard to be represented in a mathematical formula to be used in optimization model. In general, this kind of relationship is mathematically represented as:

$$C_k \nabla Q_k(TA), k = 1,2,..., p \tag{5.4}$$

Where C_k is constraint k, k=1,2,…,p, TA is the technical attributes vector, and Q_k is the functional relationship between constraints and technical attributes. All the functional relationship can be any format, e.g. linear, non-linear, and fuzzy, etc. $Y = (y_1,..., y_m)^T$, $TA = (TA_1,...,TA_n)^T$, ∇ is a sign, e.g. $\le, \ge, \ne, =$, etc. It depends on the nature of the constraint.

The most common relationship is between cost and technical attributes. In the current literature, this kind of relationship is usually treated as linear relationship. Zhou (1998) suggested that cost is often a combination of a fixed and variable part as shown in Figure 5.3, e.g. $D_i + W_i$. D_i is the fixed cost for technical attribute i, and W_i is variable part and depends on the value of technical attribute i. Tsai and Chang (2004) discussed a more sophisticated cost function that can be used in QFD.

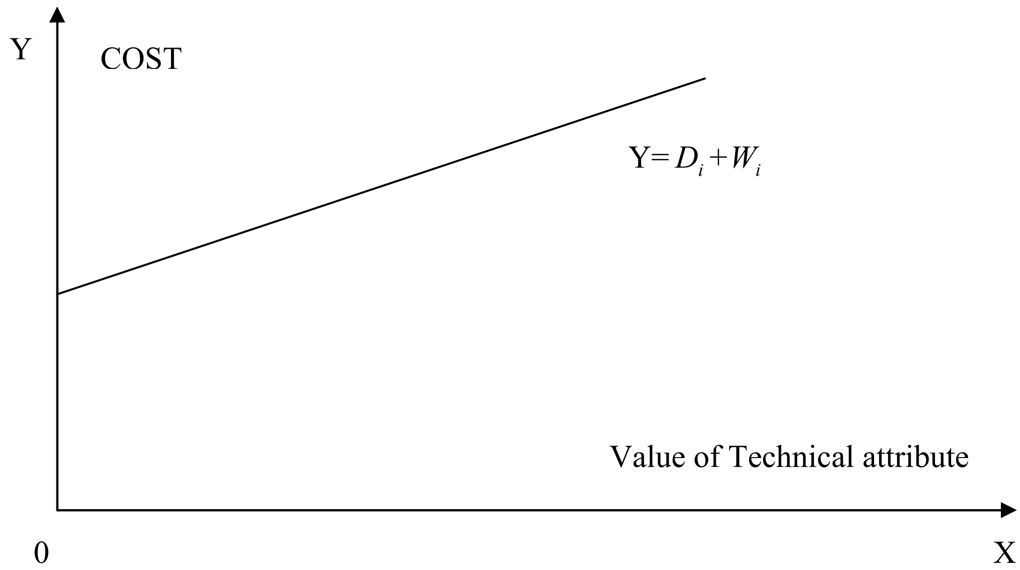


Figure 5.3 Cost function

Despite the nature of technical attribute, the mathematical optimization method used in the following steps will also affect the cost function. For example, if linear programming is used, the relationship between cost and technical attribute must be modeled as linear relationship; if non-linear programming is used, then it can be model as a non-linear one. If we use the dynamic programming, a mathematical presentation is not need. Dynamic programming is to get the optimized solution from limited, discrete alternatives. Therefore, it only needs the cost information at some points. It is more accurate and easy for people to implement.

5.2.3. Relationships between technical attributes

Technical attributes are often inter-related. Changing the value of one technical attribute may alter the other technical attributes' value and then influence the customer satisfaction level. Generally this kind of relationship can be represented as:

$$TA_j = g_j(TA^j), j = 1,2,...n \tag{5.5}$$

Where g_j is the functional relationship within technical attributes, and $TA^j = (TA_1,...,TA_{j-1},TA_{j+1},...,TA_n)^T$.

However, only a few papers discuss this field. Most common used method is proposed by Wasserman (1993). Chapter 4 proposed a new approach based on Wasserman's work.The relationship between technical attributes will finally affect the relationships between technical attributes and customer satisfaction level. In the Wasserman's model, the relationship matrix is normalized according to the relationship between technical attributes. The design requirements are spanned by the unit vector, $\{\underline{v}_k\}$, k = 1, 2,…, n, which does not necessarily comprise an orthogonal vector basis. To represent dependencies between design requirements, the notation, γ_{jk} , was introduced, to denote elements of γ , the correlation matrix, describing the correlation between design requirements j and k:

$$\gamma_{jk} \equiv \underline{v}_j \cdot \underline{v}_k \tag{5.6}$$

Thus, the transformation is

$$R_{ij}^{norm} = \frac{\sum_{k=1}^{n} R_{ik} \cdot \gamma_{kj}}{\sum_{j=1}^{n}\sum_{k=1}^{n} R_{ij} \cdot \gamma_{jk}} \tag{5.7}$$

5.2.4. Relationships between technical attributes and customer requirements

Technical attributes have direct impact on the satisfaction level of customer requirement. Though not many papers discuss this issue separately, a large number of papers involve this issue (e.g. Askin and Dawson 2000, Belhe and Kusiak 1996, Kim et *al*. 2000, Dawson and Askin 1999, Joos 1999, Park and Kim 1998, Partovi and Epperly 1999, Zhou 1998). Value functions are used to capture the relationships between technical attributes and customer requirements (Askin and Dawson 2000, Dawson and Askin 1999). These value functions can be linear or non-linear. It is due to the specific products or service to be designed and should be decided by design teams. Mathematically, it can be represented as:

$$y_i = f_i(TA), i = 1,2,...,m \tag{5.8}$$

Where f_i is the functional relationship between each customer requirement and technical attributes.

Dawson and Askin (1999) argues that a first-order statistical model will often suffice, the reality of numerous parameters (technical attributes) and non-linear relationships can limit the utility of regression-derived value functions. Then, they suggest a second-order polynomial model:

$$y = \beta_0 + \beta_1 TA_1 + ... + \beta_n TA_n + \beta_{11} TA_1^2 + ... + \beta_{nn} TA_n^2 + \beta_{12} TA_1 TA_2 + ... + \beta_{n-1,n} TA_{n-1} TA_n + \varepsilon \tag{5.9}$$

where $\beta_{i,j}\,(i,j=1,...,n)$ is the coefficient. This model contains $p = 1 + 2n + (n^2 - n)/2$ distinct parameters. The interaction terms in the above formula also describe the relationships between technical attributes.

5.2.5. Mathematical solution model

If we can get the clear relationships mentioned above, with a set of technical attributes values, we can deduct the final customer satisfaction level. Then, we can at least get the optimal solution through exhaustive search. However, many mathematical models can be applied in the optimization process to reduce effort and expedite the optimization process. The design problem is turned into a mathematical problem at this step. Here, we present the generalized mathematical model. This model can be specialized according the specific problems.

Following are the mathematical expression of optimization model.

y_i = customer satisfaction level on the i_{th} customer requirement i=1,2,…,m

TA_j = value of technical attributes j, j=1,2,…,n

C_k = constraint k, k=1,2,…,p

$Y = (y_1, ..., y_m)^T$

$TA = (TA_1, ..., TA_n)^T$

$TA^j = (TA_1, ..., TA_{j-1}, TA_{j+1}, ..., TA_n)^T$

S is the functional relationship between overall customer satisfaction and each customer satisfaction on each customer requirements

f_i is the functional relationship between each customer requirement and technical attributes

g_i is the functional relationship within technical attributes

Q_k is the functional relationship between each constraint and technical attributes

∇ is a sign, e.g. $\leq, \geq, \neq, =$, etc. It depends on the nature of constraint.

Objective function

$$\text{Overall Customer Satisfaction} = S(\text{Y}) \tag{5.10}$$

Subject to:

$$y_i = f_i(TA), i = 1,2,..., m \tag{5.11}$$

$$x_j = g_j(TA^j), j = 1,2,...n \tag{5.12}$$

$$C_k \nabla Q_k(TA), k = 1,2,..., p \tag{5.13}$$

All the functional relationships can be any format, e.g. linear, non-linear, and fuzzy, etc.

Here, we briefly introduce some frequently used methods. Linear Programming (LP) is one of the first methods that are used in QFD optimization. LP is often used to allocate resources to each technical attribute to maximize overall customer satisfaction. Many papers have been published in this field, e.g. (Ho *et al*. 1999, Moskowitz and Kim 1997).

Goal Programming (GP) is also a very popular method that can be used in QFD optimization process. Han *et al.* (1998) and Che and Lin (1998) address this issue in their papers respectively. Dawson and Askin (1999) proposes a non-linear mathematical programming model for determining the optimal technical attributes during new product development as a function of elicited customer value functions, engineering development and product costs and development time constraints.

All the above mathematical models deal with continuous situations. In practice, sometimes the values of individual technical attribute can be discrete and usually there are only a few alternatives for single technical attribute. Dynamic programming is only to solve the optimization problems in this situation. Dynamic programming provides a systematic procedure for determining the optimal combination of a sequence of interrelated decisions. QFD application of dynamic programming is a special kind of problem called resource distribution problem.

5.3. Application example

Here, we use an example adapted from Fung *et al*. (1998) to illustrate the whole QFD optimization process. Please note that the information provided in this example is only for illustration purpose and may not present the accurate market and product information. The product to be designed is a mid-range Hi-Fi. The Hi-Fi has 6 customer requirements including Good Sound Quality (CR1), More Functional Feature (CR2), More Sound

Feature (CR3), Good System Performance (CR4), Easy to Use (CR5) and Aesthetics (CR6). The six technical attributes are CD player (EC1), Amplifier (EC2), Loudspeaker (EC3), Tuner (EC4), Cassette Deck (EC5) and Remote Control (EC6).

5.3.1. Modeling the objective function

There are six customer requirements and the design team decides that the overall customer satisfaction should be the weight sum of customer satisfaction on the six customer requirements. Then, the objective function should be:

$$Y = \sum_{i=1}^{6} w_i y_i \tag{5.14}$$

Then, the next step is to find out the value of w_i for each customer requirement. The design team decides to use a fuzzy AHP method proposed by Kwong and Bai (2002). After the customer survey and calculation, the result is shown below.

Table 5.1 Importance weight of customer requirement

	Good Sound Quality	**More Functional Feature**	**More Sound Feature**	**Good System Performance**	**Easy to Use**	**Aesthetics**
Weight	0.1942	0.0564	0.1573	0.0333	0.2721	0.0281

The final ranking is:

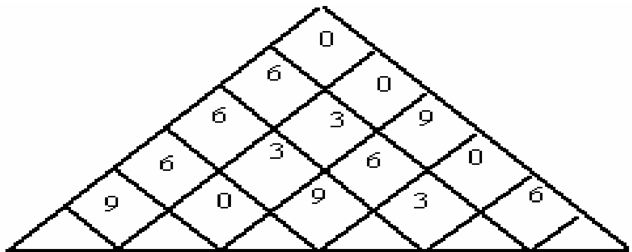
Easy to Use > Good Sound Quality > More Sound Feature > More Functional Feature > Good System Performance > Aesthetics

The final objective function can be modeled as:

$$\max Y = 0.1648 y_1 + 0.067 y_2 + 0.0966 y_3 + 0.06775 y_4 + 0.50185 y_5 + 0.102 y_6 \quad (5.15)$$

5.3.2. Construction of the HOQ

Then, the design team will decide the relationship between technical attributes and customer requirements and the relationship within technical attributes using their experience or exports' opinions. After we get this information, we can construct the HOQ, which is shown below in Figure 5.4. This HOQ is simplified and only keep the information needed.



		EC1	EC2	EC3	EC4	EC5	EC6
CR1	0.168	9	9	6	6	3	3
CR2	0.067	9	9	0	0	3	6
CR3	0.097	0	0	9	6	6	6
CR4	0.068	0	0	9	0	0	9
CR5	0.502	9	9	0	0	6	9
CR6	0.102	0	0	9	3	0	3

Figure 5.4 HOQ

5.3.3. The relationships among technical attributes

In this part, we will use the most commonly used method which is proposed by Wasserman (1993). Using the formula 5.7, we can calculate the normalized relationship matrix. The result is shown in Table 5.2.

Table 5.2 Normalized relationship matrix

	Importance	EC1	EC2	EC3	EC4	EC5	EC6
CR1	0.1648	0.227642	0.170732	0.186992	0.178862	0.162602	0.089431
CR2	0.067	0.224719	0.213483	0.157303	0.11236	0.179775	0.089888
CR3	0.0966	0.145833	0.041667	0.260417	0.177083	0.1875	0.197917
CR4	0.06775	0.090909	0	0.272727	0.136364	0.181818	0.272727
CR5	0.50185	0.201835	0.183486	0.174312	0.100917	0.192661	0.119266
CR6	0.102	0.145455	0.018182	0.272727	0.218182	0.163636	0.218182

5.3.4. The relationships between technical attributes and customer requirements

If the design team to choose use dynamic programming to solve this optimization problem, then, it only needs to decide the customer satisfaction level of each technical attribute at each level. This value is determined by the knowledge of design teams. The value is as following in Table 5.3. For the simplification purpose, each technical attribute has 3 levels, donated by L1, L2 and L3 from the best to the worst. The customer satisfaction of each customer requirement at each level of technical attribute is determined using a 0-1 scale. A bigger value means better customer satisfaction level.

Table 5.3 The expanded central wall of HOQ

		EC1			EC2			EC3			EC4			EC5			EC6		
CR1	0.16	0.23	L1	1	0.17	L1	1	0.19	L1	1	0.18	L1	1	0.16	L1	1	0.09	L1	1
			L2	0.85		L2	0.75		L2	0.90		L2	0.55		L2	0.65		L2	0.5
			L3	0.60		L3	0.25		L3	0.70		L3	0.45		L3	0.45		L3	0.2
CR2	0.07	0.22	L1	1	0.21	L1	1	0.16	L1	1	0.11	L1	1	0.18	L1	1	0.09	L1	1
			L2	0.65		L2	0.65		L2	0.80		L2	0.50		L2	0.85		L2	0.7
			L3	0.40		L3	0.40		L3	0.65		L3	0.20		L3	0.45		L3	0.4
CR3	0.10	0.15	L1	1	0.04	L1	1	0.26	L1	1	0.18	L1	1	0.19	L1	1	0.20	L1	1
			L2	0.80		L2	0.85		L2	0.55		L2	0.85		L2	0.8		L2	0.85
			L3	0.45		L3	0.45		L3	0.45		L3	0.45		L3	0.6		L3	0.45
CR4	0.08	0.09	L1	1	0	L1	1	0.27	L1	1	0.14	L1	1	0.18	L1	1	0.27	L1	1
			L2	0.85		L2	0.50		L2	0.85		L2	0.75		L2	0.5		L2	0.65
			L3	0.45		L3	0.20		L3	0.45		L3	0.5		L3	0.2		L3	0.5
CR5	0.50	0.20	L1	1	0.18	L1	1	0.17	L1	1	0.10	L1	1	0.19	L1	1	0.12	L1	1
			L2	0.70		L2	0.60		L2	0.65		L2	0.80		L2	0.65		L2	0.5
			L3	0.25		L3	0.30		L3	0.40		L3	0.60		L3	0.4		L3	0.2
CR6	0.10	0.15	L1	1	0.02	L1	1	0.27	L1	1	0.22	L1	1	0.16	L1	1	0.22	L1	1
			L2	0.50		L2	0.50		L2	0.80		L2	0.65		L2	0.5		L2	0.75
			L3	0.20		L3	0.20		L3	0.60		L3	0.40		L3	0.2		L3	0.25

For the above table, we can derive the contribution to overall customer satisfaction level of each technical attribute at each level. The derived table is shown below in Table 5.4.

Table 5.4 Relationships between customer satisfaction and the value of technical attributes

EC1		EC2		EC3		EC4		EC5		EC7	
L1	0.19	L1	0.14	L1	0.20	L1	0.14	L1	0.18	L1	0.14
L2	0.17	L2	0.12	L2	0.18	L2	0.11	L2	0.15	L2	0.12
L3	0.14	L3	0.10	L3	0.15	L3	0.09	L3	0.13	L3	0.09

5.3.5. Relationships between constraints and technical attributes

The constraint in this example is only cost. That's, we must maximize the customer overall satisfaction level in a given amount of money. In this example, the total amount of money is 23. In the previous step, we have decided to us dynamic programming to solve the optimization problem. So, at the step, the task is quite easy. The design team only needs to determine the cost of each technical attribute at a certain level. The result is as following in Table 5.5:

Table 5.5 Relationships between constraints and technical attributes

EC1		Cost	EC2		Cost	EC3		Cost	EC4		Cost	EC5		Cost	EC6		Cost
L1	0.19	7	L1	0.14	3	L1	0.20	4	L1	0.14	7	L1	0.18	6	L1	0.14	5
L2	0.17	5	L2	0.12	2	L2	0.18	2	L2	0.11	4	L2	0.15	5	L2	0.12	4
L3	0.14	2	L3	0.10	1	L3	0.15	1	L3	0.09	3	L3	0.13	4	L3	0.09	3

5.3.6. Mathematical optimal solution searching model

The design team has already decided to use dynamic programming to solve this problem. The final result is shown blow in Table 5.6. And the total customer satisfaction level is 0.89.

Table 5.6 Result of dynamic programming

	EC1	EC2	EC3	EC4	EC5	EC7
Budget	2	3	4	4	6	4
Level	L3	L1	L1	L2	L1	L2
Customer Satisfaction	0.1400	0.1400	0.2000	0.1100	0.1800	0.1200

5.4. Conclusion

This chapter proposes a generalized QFD optimization model. This model clearly analyzes the whole process of QFD optimization process and divides the whole process into five steps. Also, this chapter clearly points out the four relationships existing in HOQ, namely, the relationships between customer requirements, the relationships between customer requirements and technical attributes, the relationships between technical attributes, and the relationships between constraints and technical attributes. In this way, the proposed model provides a framework and guideline for both researchers and practitioners. In the following three chapters, three different QFD quantitative optimization methods will be introduced.

Chapter 6 Dynamic Programming for QFD Optimization

6.1. Introduction

Different optimization approaches have been applied in QFD analysis during recent years. Most of these optimization approaches are based on integer programming or linear programming. These approaches perform well in certain circumstances, but there are problems that impair the practical use of them and could even be misleading in some other situations. These problems include overlooking some technical attributes, lack of or very costly to get supporting information, unrealistic results and so on. This paper proposes a new approach that incorporates dynamic programming in quality function deployment to find the optimal set of technical attributes. The dynamic programming approach requires less information and it is very easy to use. Furthermore, the optimal result is practical and easy to implement.

This article is organized as follows. Section 2 focuses on the existing optimisation methods and discusses their pros and cons. Section 3 presents the dynamic programming approach that can resolve the QFD optimisation problem. In Section 4, a numerical example is used to illustrate the application of the new approach. At the end of the paper, some related discussions are given.

6.2. Some existing QFD optimization approaches

6.2.1. Use of integer programming

Quality function deployment collects the competitors' information and carries out a competitive analysis. Then, benchmark is an important way to obtain the design characteristics. Benchmark can be considered as the continuous process of measuring our products, services, and business practices against the toughest competitors or those companies recognized as industry leaders (Zairi, 1992). Benchmark alone cannot get the optimal design, but along with integer programming, often 0-1 programming, useful results can be obtained when there is a need to prioritise the improvement needs. The core concept is that it chooses some among all the technical attributes to make the chosen attribute get best value. Park and Kim (1998) used the following objective function and obtained optimal solution

$$\max f(x) = \sum_{j=1}^{n} w_j d_j \tag{6.1}$$

In this formula w_j is the absolute technical importance rating of technical attributes *j* and d_j =0-1 decision variable for technical attributes *j* (i.e. if technical attributes *j* is selected, d_j =1; otherwise, d_j =0). Halog *et al*. (2001) proposed a similar concept in their paper.

This approach gives the most important attention to the most important technical attributes and resources can be better utilized in this way. However, when using this kind of method, much effort is put in the selected technical attributes and the other technical attributes are overlooked. In fact, in practice, the components of customer satisfaction are very complicated and customer may not be satisfied only because of extreme excellence on some aspects of products. The disposed technical attributes may hamper the overall customer satisfaction greatly and attention should be given to all the technical attributes though not equally distributed. In the most recent discussions, linear programming discussed in the following is more frequently used.

6.2.2. Use of linear programming

The most recent of optimisation approaches are related to linear programming of some kind of extent (i.e. Moskowitz and Kim 1997, Zhou 1998, Fung *et al*. 2002, Tang *et al* 2002). It is true that linear programming is a good method to find the optimal set of technical attributes; however, it also encounters many problems in the real situation. There are three categories of difficulties.

The first category of difficulties is the value of technical attributes. In linear programming, the values of technical attributes are often assumed to be a continuous range. The value can be any point in this range. However, due to practical limitations, the values of technical attributes are often discrete instead of continuous. For example, the diameter of screw has its own standard values and non-standard screw costs much more than standard ones. Another example is the power of light bulb. No one has a light bulb which power is 57W or 133W or some other odd values. Usually the power of light bulb is 25W, 60W, 100W etc. It is not a continuous range but some discrete values. It is possible and not unusual that when getting an "optimal" value from linear programming optimisation, engineers found that the value is hard or very costly to achieve. Furthermore, not all technical attributes can be expressed as numbers, such as the colour of a product and the shape of product. In such situation, linear programming is difficult to use in quality function deployment.

The second category of difficulties is about the actual relationships between technical attributes and customer satisfaction. The objective function of linear programming usually is to maximize the customer satisfaction; therefore, there must be a clear relationship between customer satisfaction and technical attributes. Unfortunately, such relationship is hard to represent. Some papers provide some approaches to solve this problem as presented below.

Bode and Fung (1998) proposed a concept of degree of attaining the target for technical attribute and the customer satisfaction is the function of degree of attaining the target $T\hat{A}_j$ and the weight of technical attribute w_j, which is shown below:

$$\text{Customer Satisfaction} = \sum_{j=1}^{n} w_j T\hat{A}_j \tag{6.2}$$

The question is that how does one define the degree of attaining the target $T\hat{A}_j$. Moskowitz and Kim (1997) used a linear function to capture the relationships between technical attributes and customer satisfaction based on fuzzy linear regression. It deals with the situation when the known data set is small and the relationship is vogue.

However, in some cases, because of the lack of data, the result may be unreliable or not achievable.

Some papers proposed to use Taguchi method, design of experiment and empirical experiment to find the relationships between technical attributes and customer satisfaction. Taguchi method for determining the optimal settings focuses on the product with one technical attribute; however, most products have multi technical attributes. To solve this problem, Kumar *et al*. (2000) used Multi-characteristic response optimisation based on Taguchi's approach. Dawson and Askin (1999) found the lack of a formal mechanism for trading off customer satisfaction with technical attributes and proposed a non-linear mathematical program for determining the optimal value of technical attributes. Their approach also elicited value functions relating cost and time constraint.

All of these above approaches obtain the optimal solution under their defined circumstance. However, there are also some other troubles. For example, one could wonder whether the relationship between customer satisfaction and technical attributes is linear or non-linear. Most of utility type functions are highly non-linear. The relationships between the customer satisfaction and technical attributes seem to be highly non-linear. However, Yoder and Mason (1993) felt that it could not benefit from the non-linear terms. Even the non-linear relationship is better, which order should be used is another question. Another constraint is the cost and time related with these experiments. Many products need to optimise among tens, even over hundreds of technical attributes. In such situation, using experiments to obtain the optimal solution becomes nearly impossible.

The third category of difficulties are about the relationship between cost and technical attributes. It is similar to the relationship between customer satisfaction and technical attributes. There is no cost-effective method to quantify the relationships between cost and technical attributes. All of these remain problems to be solved.

6.3. The dynamic programming approach

In practice, the values of individual technical attributes can be discrete and usually there are only a few alternatives for single technical attributes. What engineers need to do is to choose the best one among all the possible alternatives. Furthermore, it is relatively much easier to assign the customer satisfaction and related cost to a single value of technical attributes than to clarify the precise relationships among them. For example, an experienced engineer can specify the cost to achieve certain degree of requirement on technical attribute and decide the extent of customer satisfaction on one aspect of customer requirement in the given degree of the technical attribute. Things are then modified to find a way to get the optimised solution from a limited number of alternatives. Dynamic programming is such a tool that fits this situation.

Dynamic programming is a useful mathematical technique developed especially for making a set of inter-related decisions. The set of inter-related decisions in quality function deployment are decisions on the value of each technical attribute. Dynamic programming provides a systematic procedure for determining the optimal combination of decisions. In the following sections we will describe the procedure to use dynamic programming to find the combination of optimal values of technical attributes.

6.3.1. The expanded HOQ

The first step is to build a traditional House of Quality. Suppose that a product has m customer requirements and n technical attributes. An example is shown in Figure 6.1. The roof, interrelationship between technical attributes, and the competitors' assessments are not the emphasis of this paper and therefore they are only listed in the HOQ without much description. Those who are not familiar with QFD/HOQ could refer to any standard texts on this subject.

From Figure 6.1, we can obtain the relative importance among several customer requirements w_i and the relationships betweens customer requirements and technical attributes R_{ij} . Wasserman (1993) proposed a useful approach to normalize the relationship matrix considering the inter-relationships among technical attributes. Here we assume that the relationship matrix has already been normalized.

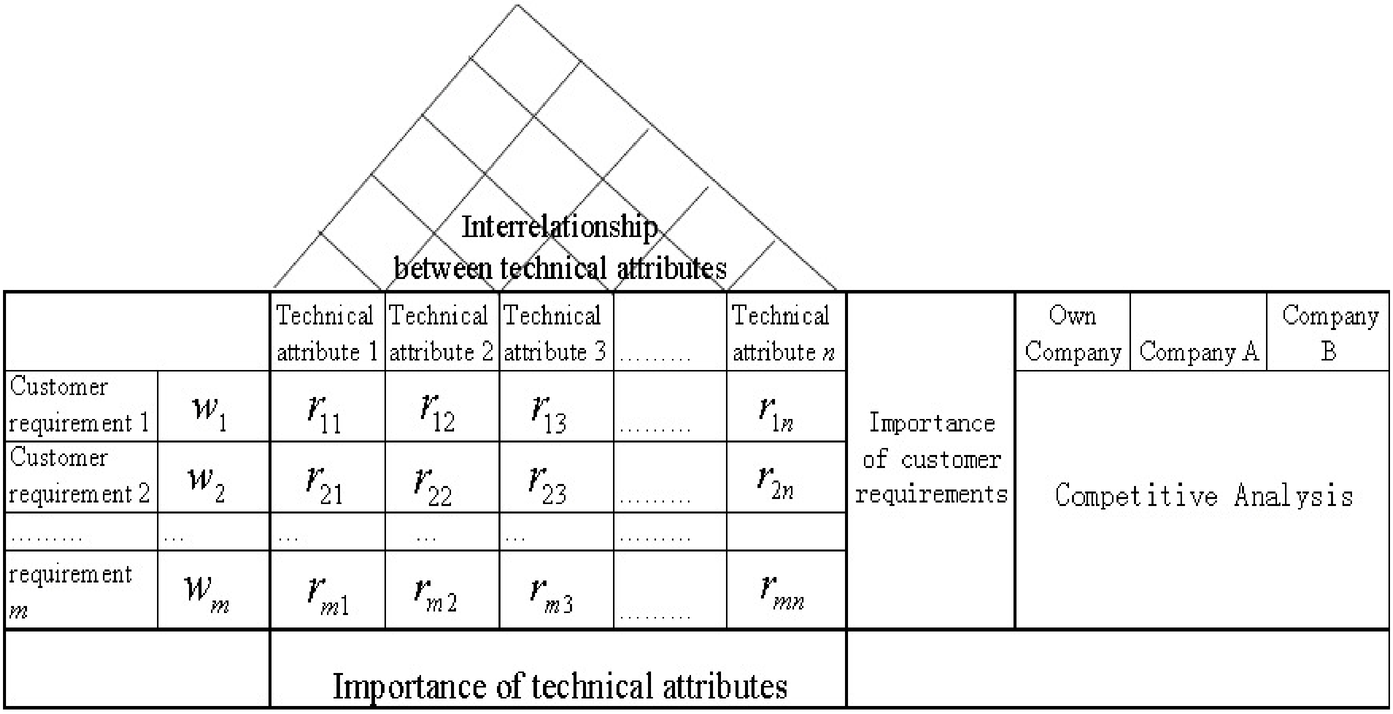


Figure 6.1 Traditional house of quality

In order to utilize dynamic programming, we need to incorporate some additional information to the traditional HOQ. After we have obtained the HOQ, this HOQ can be extended to incorporate additional information that is commonly available. Here we add alternatives of every technical attribute and corresponding customer satisfaction information to the "wall" of former "House" and then get the extended House of Quality. Figure 6.2 shows the "wall" of extended house of quality and the other parts are the same with former ones. We assume that technical attribute 1 has *a* alternatives and technical attribute 2 has b, technical attribute *i* has *p*, …… , technical attribute *n* has *q* alternatives.

		Technical attribute 1		Technical attribute 2		………	Technical attribute j		………	Technical attribute n	
Customer requirement 1	w_1	r_{11}		r_{12}			r_{1j}			r_{1n}	
		TA_{11}	Cr_{111}	TA_{21}	Cr_{121}		TA_{j1}	Cr_{1j1}		TA_{n1}	Cr_{1n1}
		…	…	…	…		…	…		…	…
		TA_{1a}	Cr_{11a}	TA_{2b}	Cr_{12b}	………	TA_{jp}	Cr_{1jp}	………	TA_{nq}	Cr_{1nq}
Customer requirement 2	w_2	r_{21}		r_{22}			r_{2j}			r_{2n}	
		TA_{11}	Cr_{211}	TA_{21}	Cr_{221}		TA_{j1}	Cr_{2j1}		TA_{n1}	Cr_{2n1}
		…	…	…	…		…	…		…	…
		TA_{1a}	Cr_{21a}	TA_{2b}	Cr_{22b}	………	TA_{jp}	Cr_{2jp}	………	TA_{nq}	Cr_{2nq}
………	…	…		…		………	…		………	…	
Customer requirement i	w_i	r_{i1}		r_{i2}			r_{ij}			r_{mn}	
		TA_{11}	Cr_{i11}	TA_{21}	Cr_{i21}		TA_{j1}	Cr_{ij1}		TA_{n1}	Cr_{in1}
		…	…	…	…		…	…		…	…
		TA_{1a}	Cr_{i1a}	TA_{2b}	Cr_{i2b}	………	TA_{jp}	Cr_{ijp}	………	TA_{nq}	Cr_{inq}
………	…	…		…		………	…		………	…	
Customer requirement m	w_m	r_{m1}		r_{m2}			r_{mj}			r_{mn}	
		TA_{11}	Cr_{m11}	TA_{21}	Cr_{m21}		TA_{j1}	Cr_{mj1}		TA_{n1}	Cr_{mn1}
		…	…	…	…		…	…		…	…
		TA_{1a}	Cr_{m1a}	TA_{2b}	Cr_{m2b}	………	TA_{jp}	Cr_{mjp}	………	TA_{nq}	Cr_{mnq}

Figure 6.2 The "Wall" of the expanded house of quality

In this HOQ, TA_{jk} (j=1,2,…,n; k=1,2,…,p) means the kth alternative of technical attributes j. Cr_{ijk} (i=1,2,…,m)means the ith customer satisfaction level (CSL) acquired by the kth alternative of technical attributes j. Cr_{ijk} can be defined in two ways: distributive mode and ideal mode. The terms Distributive Mode and Ideal Mode, originated from Analytic Hierarchy Process (AHP) literature. Normalized weights are called Distributive Mode (Saaty, 1994). It tells us how importance or priorities should be distributed among the items. All the weight adds up to exactly 1 (i.e., 0.3, 0.5, 0.2). If we divide all weights by the largest weight, we obtain another group of weights. This format is known as Ideal Mode (Saaty, 1994). It tells us how each item performs relative to the best (or ideal) item, i.e. 1.0, 0.7, 0.4.

Then, the related cost information can be summarised as in Table 6.1 which gives the cost information of each alternative of each technical attribute and the overall customer satisfaction achieved by the alternative for later computation. C_{jk} is the cost of alternative TA_{jk} and CR_{jk} means the overall customer satisfaction achieved by alternative TA_{jk}. CR_{jk} is computed from the following formula:

$$CR_{jk} = \sum_{i=1}^{m} w_i Cr_{ijk} \tag{6.3}$$

Where *m* is the number of customer requirements. Here and thereafter, we assume that the total customer satisfaction is the sum of each customer satisfaction on each customer requirement. A discussion is provided in Section 6.5.

Table 6.1 Cost information table

TA	Cost	CSL	TA	Cost	CSL	…	TA	Cost	CSL	…	TA	Cost	CSL
TA_{11}	C_{11}	CR_{11}	TA_{21}	C_{21}	CR_{21}	…	TA_{j1}	C_{j1}	CR_{j1}	…	TA_{n1}	C_{n1}	CR_{n1}
…	…	…	…	…	…	…	…	…	…	…	…	…	…
TA_{1a}	C_{1a}	CR_{1a}	TA_{2b}	C_{2b}	CR_{2b}	…	TA_{jp}	C_{jp}	CR_{jp}	…	TA_{nq}	C_{nq}	CR_{nq}

All the information needed for dynamic programming is available now. The dynamic programming is computed based on Table 6.1. The overall optimisation model is:

$$\max \ CR = \sum_{j=1}^{n} CR_j(x_j) \tag{6.4}$$

Subject to:

$$\sum_{j=1}^{n} x_j \leq B \ j = 1,2,...n \tag{6.5}$$

Where *B* is the total budget. $CR_j(x_j)$ is the overall customer satisfaction achieved when x_j budget has been allocated to a technical attribute *j*. This corresponding value of $CR_j(x_j)$ can be obtained from Table 6.1.

6.3.2. The algorithm of dynamic programming

As stated before, dynamic programming provides a systematic procedure for determining the optimal combination of a sequence of interrelated decisions. QFD application of dynamic programming is a special kind of problem called resource distribution problem. It always involves allocation one kind of resource to a number of activities and in QFD it allocates resources to a number of technical attributes respectively.

The resource distribution problem can be divided into several stages. The resources are allocated to activities one by one and each activity can be a stage. In QFD, each technical attribute is a stage. According to the dynamic programming algorithm, the number of stages is the number of technical attributes. The resource to be distributed of this product is the budget. The solution begins from full budget and ends with zero budgets.

The notations are as following.

Stage variable: n = technical attribute n (n=1,2,3,…,N)

State variable: s_n = amount of budget allocated to technical attributes 1 to n.

Decision variable: x_n = amount of budget allocated to technical attribute n and x_n^* is the optimal value of x_n (given s_n).

Return function: $f_n(s_n, x_n)$ = the total satisfaction obtained from technical attribute 1 to n.

We have that

$$f_n(s_n, x_n) = f_{n-1}^*(x_{n-1}) + CR_n(x_n) = f_{n-1}^*(s_n - x_n) + CR(x_n) \tag{6.6}$$

$$f_n^*(s_n) = \max_{x_n}\{f_n(s_n, x_n)\} \text{ or } f_n^*(s_n) = \min_{x_n}\{f_n(s_n, x_n)\} \tag{6.7}$$

If the objective is not customer satisfaction but some other things that we want to reduce, we can use minimization instead of maximization.

The function $f_n(s_n, x_n)$ depends on $f_{n-1}^*(s_{n-1})$ and $f_n^*(s_n)$ is defined in terms of $f_{n-1}^*(s_{n-1})$. Hence we have a recursive relationship. When the system starts at stage n-1 in state s_{n-1} and the choice is x_{n-1}. Then, the next stage at stage n being $s_n = s_{n-1} + x_n$. The transition is depicted below:

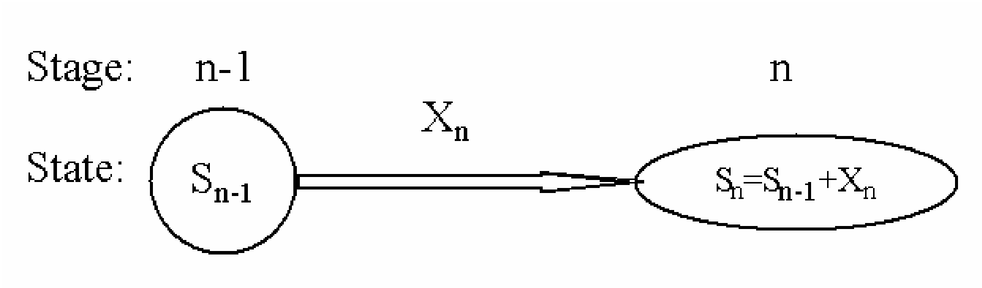


Figure 6.3 Transitions in dynamic programming

This recurring process moves from one technical attribute to another one by one. When arriving at the next stage, the new $f_n^*(s_n)$ is derived by using the $f_{n-1}^*(s_{n-1})$ function derived during the preceding iteration. This process repeats until arriving the ending of the problem (*n*=*N*).

When we use this recursive relationship, the solution procedure starts at the beginning and moves forward stage-by-stage. At the same time the optimal decision is found for that stage. When it finds the optimal decision at the final stage, this optimal policy immediately yields an optimal solution for the entire problem, i.e., x_1^* for the initial state s_1, x_2^* for the initial state s_2, x_3^* for the initial state s_3, and so forth to x_N^* for the initial state s_N. The optimal values can be obtained directly from the table constructed during the computation process.

For a clear expression of the dynamic problem, tables such as Table 6.2 are often used during computation stage and a simple example is as the following, which would be obtained for each stage (*n*= 1, 2, …, *N*-1, *N*).

Table 6.2 Stage computation table

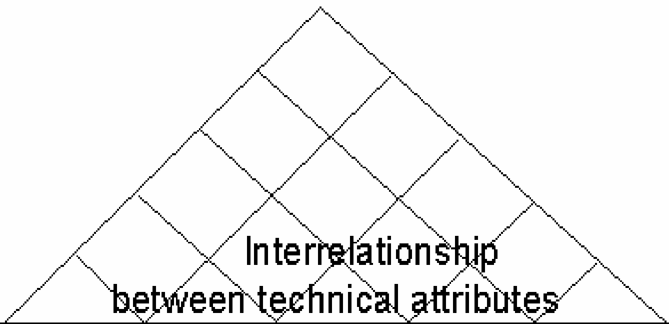
s_n \ x_n	$f_n(s_n, x_n)$			$f_n^*(s_n)$	x_n^*

When this table is finally obtained for the last stage ($n=N$), the problem is solved. Because the beginning state is known, the initial decision is specified by x_1^* in this table. The optimal values of the other decision variables are then specified by the other tables in turn according to the state of the system that results from the preceding decisions and can be found directly from the corresponding table.

When we obtained budget allocation to each technical attribute, from Table 6.1, we can find corresponding values of technical attributes. Then, all the related information, optimal value of each technical attribute, related cost and the overall customer satisfaction are clarified. The solution for Dynamic programming for resource distribution problem is structured very well and the solution is easy to find. A numerical example is provided for illustration purpose.

6.4. A numerical example

To illustrate the proposed approach, a simple example adapted from Yamashina *et al* (2002) is used. The problem is to determine the technical attributes of a washing machine according to the customer requirements. Five customer requirements are listed, namely, Thorough Washing, Quiet Washing, Thorough Rinsing, Less Damage to clothes and Short washing time. And five technical attributes are discussed, namely, Washing Quality (%), Noise level (db), Washing time (min), Rinsing quality (%), and Clothes damage rate (%). The traditional HOQ is shown in Figure 6.4.



	Washing Quality (%)	Noise level (db)	Washing time (min)	Rinsing quality (%)	Clothes damage rate (%)	Relative importance of customer requirements
Thorough Washing	0.3125	0	0.0625	0.3125	0.3125	0.3125
Quiet Washing	0.3	0.5	0.1	0.1	0	0.25
Thorough rinsing	0.3	0	0.1	0.5	0.1	0.1875
Less damage to clothes	0.231	0.077	0.077	0.231	0.384	0.125
Short washing time	0.714	0	0.143	0.143	0	0.125
Own company	Competitive Assessment					
Company A						
Company B						
Company C						

Figure 6.4 The House of quality for illustration

For the sake of simplicity, we assume that the relationship matrix has been normalized using Wasserman (1993)'s approach. Since we are not focusing on the use of competitive assessment information; the exact competitor's information is not shown here.

Both the technical attributes and customer requirements are simplified for illustration purpose. Each technical attribute has three alternatives. Then, we expand the "wall" of the original HOQ and construct the expanded house of quality. Figure 6.5 shows the expanded "wall".

We also need the cost information related to the technical attribute alternatives and the total budget. For calculation, the accumulative customer satisfaction achieved by each technical attribute alternative is also needed. All these information is listed in Table 6.3. The total budget we assume to be 13 (13 is an assumed number for illustration).

The problem here is to decide how much should be allocated to each technical attribute to maximize the total customer satisfaction. This problem can be expressed below:

$$\max \ CR = \sum_{i=1}^{n} CR_i(x_i) \tag{6.8}$$

Subject to

$$\sum_{i=1}^{n} x_i \leq 13 \tag{6.9}$$

		Washing Quality (%)		Noise level (db)		Washing time (min)		Rinsing quality (%)		Clothes damage rate (%)	
Thorough Washing	0.313	0.3125		0		0.0625		0.3125		0.3125	
		Value	Satisfaction level	Value	Satisfaction level	Value	Satisfaction level	Value	Satisfaction level	Value	Satisfaction level
		90%	0.65	45db	0	30min	0.8	95%	1	0.50%	0.8
		95%	0.85	50db	0	35min	0.9	90%	0.7	0.70%	0.9
		98%	1	60db	0	40min	1	80%	0.4	1%	1
Quiet Washing	0.25	0.3		0.5		0.1		0.1		0	
		Value	Satisfaction level	Value	Satisfaction level	Value	Satisfaction level	Value	Satisfaction level	Value	Satisfaction level
		90%	1	45db	1	30min	1	95%	0.85	0.50%	0
		95%	0.8	50db	0.7	35min	0.9	90%	0.9	0.70%	0
		98%	0.7	60db	0.4	40min	0.6	80%	1	1%	0
Thorough rinsing	0.188	0.3		0		0.1		0.5		0.1	
		Value	Satisfaction level	Value	Satisfaction level	Value	Satisfaction level	Value	Satisfaction level	Value	Satisfaction level
		90%	0.5	45db	0	30min	1	95%	1	0.50%	1
		95%	0.9	50db	0	35min	0.6	90%	0.8	0.70%	0.9
		98%	1	60db	0	40min	0.5	80%	0.4	1%	0.8
Less damage to clothes	0.125	0.231		0.077		0.077		0.231		0.384	
		Value	Satisfaction level	Value	Satisfaction level	Value	Satisfaction level	Value	Satisfaction level	Value	Satisfaction level
		90%	1	45db	1	30min	1	95%	1	0.50%	1
		95%	0.9	50db	0.9	35min	0.9	90%	0.6	0.70%	0.8
		98%	0.8	60db	0.9	40min	0.8	80%	0.5	1%	0.5
Short washing time	0.125	0.714		0		0.143		0.143		0	
		Value	Satisfaction level	Value	Satisfaction level	Value	Satisfaction level	Value	Satisfaction level	Value	Satisfaction level
		90%	0.7	45db	0	30min	1	95%	0.6	0.50%	0
		95%	0.9	50db	0	35min	0.8	90%	0.8	0.70%	0
		98%	1	60db	0	40min	0.6	80%	1	1%	0

Figure 6.5 The "wall" of extended HOQ

Table 6.3 Cost and customer satisfaction level

	Washing Quality (%)			Noise level (db)			Washing time (min)			Rinsing quality (%)			Clothes damage rate (%)		
decision variables	Value	Cost	Satisfaction	Value	Cost	Satisfaction	Value	Cost	Satisfaction	Value	Cost	Satisfaction	Value	Cost	Satisfaction
	90%	3	0.258	45db	5	0.135	30min	4	0.087	95%	3	0.252	0.50%	4	0.145
	95%	4	0.300	50db	3	0.096	35min	2	0.074	90%	2	0.197	0.70%	2	0.143
	98%	5	0.312	60db	2	0.059	40min	1	0.062	80%	1	0.134	1%	1	0.137

In the following, we present the computation process. The objective is to distribute the limited budget to all technical attributes and maximize the overall customer satisfaction. The mathematical formulation of this problem is as following:

Stage i = technical attribute i;

Decision variable d_i = the amount of money allocated to technical attribute i;

State variable s_i = the total budget allocated to technical attribute 1 through i

Return function $f_i(s_i)$ = the total customer satisfaction achieved from technical attribute 1 though i; it is computed as following:

$$f_i(s_i, x_i) = f_{i-1}^*(x_{i-1}) + CR_i(x_i) = f_{i-1}^*(s_i - x_i) + CR_i(x_i) \tag{6.10}$$

and

$$f_i^*(s_i) = \max_{x_i}\{f_i(s_i, x_i)\} \tag{6.11}$$

In stage 1, we deal with the first technical attribute, washing quality. The minimum budget allocated to washing quality is 3 and the maximum budget is 8. The maximum budget limit comes from total budget minus the minimum budget allocated for the rest technical attributes. The results are shown in Table 6.4. (3, 8) in the first cell indicates the possible range of state variable for stage 1. The first column shows the state variable and the second, third and fourth column shows the corresponding customer satisfaction with different state variable and decision variable. The fifth column and sixth column present the maximum $f_1(s_1)$ and corresponding decision variable.

Table 6.4 Computation table in stage 1

s1(3,8)	d1=3	d1=4	d1=5	f1*	d1*
3	0.2580			0.2580	3
4	0.2580	0.3000		0.3000	4
5	0.2580	0.3000	0.3188	0.3188	5
6	0.2580	0.3000	0.3188	0.3188	5
7	0.2580	0.3000	0.3188	0.3188	5
8	0.2580	0.3000	0.3188	0.3188	5

Stages 2, 3, 4, and 5 can be carried out in the same way as for Stage 1. The computation tables are shown in Tables 6.5-8. The highlighted cell shows the optimal solution, which is summarized in Table 6.9. The overall customer satisfaction is 0.866.

Table 6.5 Computation table in stage 2

s2(5,10)	d2=2	d2=3	d2=5	f2*	d2*
5	0.3166			0.3166	2
6	0.3586	0.3541		0.3586	2
7	0.3774	0.3961		0.3961	3
8	0.3774	0.4149	0.3926	0.4149	3
9	0.3774	0.4149	0.4346	0.4346	5
10	0.3774	0.4149	0.4534	0.4534	5

Table 6.6 Computation table in stage 3

s3(6,11)	d3=1	d3=2	d3=4	f3*	d3*
6	0.3789			0.3789	1
7	0.4209	0.3909		0.4209	1
8	0.4584	0.4329		0.4584	1
9	0.4773	0.4704	0.4035	0.4773	1
10	0.4969	0.4892	0.4455	0.4969	1
11	0.5157	0.5089	0.4830	0.5157	1

Table 6.7 Computation table in stage 4

s4(7,12)	d4=1	d4=2	d4=3	f4*	d4*
7	0.5128			0.5128	1
8	0.5548	0.5764		0.5764	2
9	0.5923	0.6184	0.6312	0.6312	3
10	0.6111	0.6559	0.6732	0.6732	3
11	0.6308	0.6747	0.7107	0.7107	3
12	0.6496	0.6944	0.7295	0.7295	3

Table 6.8 Computation table in stage 5

s5(8,13)	d5=1	d5=2	d5=4	f5*	d5*
8	0.6495			0.6495	1
9	0.7131	0.6560		0.7131	1
10	0.7679	0.7196		0.7679	1
11	0.8099	0.7744	0.6577	0.8099	1
12	0.8474	0.8164	0.7213	0.8474	1
13	0.8662	0.8539	0.7761	0.8661	1

Table 6.9 Summarization of results

Technical Attributes	Alternatives	Customer satisfaction level	Cost
Washing Quality (%)	98%	0.3188	5
Noise level (db)	50db	0.0962	3
Washing time (min)	40min	0.0623	1
Rinsing quality (%)	95%	0.2523	3
Clothes damage rate (%)	1%	0.1367	1

6.5. Discussions

In this paper, we have studied a new approach for the optimisation problem associated with QFD application. The approach integrates dynamic programming into product design process. In the dynamic programming approach, we do not require the full relationships curve between technical attributes and customer satisfaction or the relationships between technical attributes and cost. It utilizes only a group of discrete points containing information about customer satisfaction, technical attributes and cost to find the optimal product design. Therefore, comparing with other optimisation approach, it requires less time and resources. At the end of optimisation process, the value of each technical attribute, related cost and overall achieved customer satisfaction are obtained at the same time.

In the algorithm part, we assume that the total customer satisfaction is the sum of each customer satisfaction on each customer requirement. Though the addictive assumption is widely used, dynamic programming itself doesn’t have such a restriction. It means that dynamic programming can be used in more complicated situations. The total customer satisfaction can be products of each customer satisfaction on each customer requirement or a mix of sum and product. The only difference in the algorithm is the return function. Return functions will reflect the relationships between total customer satisfaction and each customer satisfaction on each customer requirement.

In the example, we assumed that all the numbers are deterministic. If there is a high degree of uncertainty, we can use probabilistic dynamic programming. In probabilistic dynamic programming, the state of next stage has a probability distribution rather than a completely determined state. Sensitivity analysis could also be carried out based on that (Xie *et al*., 1998). This is an interesting topic for further research. Furthermore, if there is more than one type of constraints, the approach can be extended to accommodate constraints.

Chapter 7 Optimizing Product Design using the Kano Model and QFD

In this chapter, an approach combining the Kano Model and Quality Function deployment (QFD) is proposed to meet customer requirements in product design. The Kano model provides an effective way to categorizing customer requirements and helps understand the nature of these requirements. By combining the two methods, we can provide a new way to optimize the product design. The proposed methods can be useful to both practitioners and researchers.

7.1. Introduction

Understanding voice of customers is the base and start point of QFD. The Kano model is a tool to help understanding customer requirements. The Kano model (Kano *et al*. 1984) suggests that there are three types of customer requirements as shown in Figure 7.1:

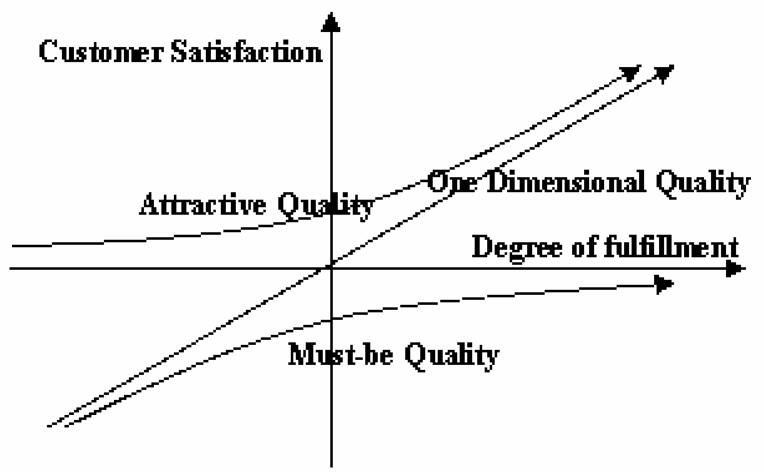


Figure 7.1 The Kano model

1. *Must-be requirements*: It is usually taken for granted by customers. Customers will not get satisfaction from fulfilment of this requirements, but will be great dissatisfied if not meet this requirement.
2. *One-dimensional requirements*: It is that the better the product meet it, the more customer satisfaction.
3. *Attractive requirements*: Typically it is not expected by customers. Sometimes customer does not know it. Therefore, when this requirement is not meet, customer will not be dissatisfied. However, if it is satisfied, customer will get great satisfaction.

This chapter is aimed to integrate the Kano model and QFD to provide a product design optimization method. This method uses the Kano model to analyze the customer requirement and uses QFD to translate customer requirement into product design. The design is optimized using a mathematical model under cost constraint. This chapter is organized as following. The second part is a short review of current QFD and the Kano model applications; the third part is the detailed analysis of the proposed method; the forth part is an example illustrating the application of proposed method, finally, the conclusion is presented.

7.2. Review of the Kano model and QFD applications

Since the introduction of the Kano model, there have been a lot of papers discussing the Kano model and its application. Saurwein (1999) provided a paper to discuss the validity and reliability of the Kano Model. Lee *et al*. (2002) did a research to construct the web-based learning environment based on students' needs and develop suitable teaching strategies for each individual. Zhang and Dran (2001) used the Kano model of Quality to conduct an investigation of quality features in the Web environment. The results of the above two papers show that the Kano model can be used as a framework to control quality in terms of three quality types and the time transition of the quality nature.

There are some works to combine the Kano model and QFD. For example, Matzler and Hinterbuber (1998) proposed a methodology based on the Kano model to explore customers' requirements and combined it with QFD. These studies suggest that the application of QFD can benefit from using the added dimension of quality in the form of types of customer requirements.

The current applications of the Kano model are mostly qualitative in nature. Most of them are focused on the benefits of using this method and the managerial implications from the model. However, the Kano model can be used in a quantitative way. It can help design team to mathematically evaluate the effect of meeting or not meeting a customer requirement. Quantitative method can better help design team to understand customer requirements and design better products.

In the following part, the chapter will propose a new method that derive quantitative information from the Kano model and combine this information into QFD optimization method.

7.3. Proposed approach

The proposed approach involves three stages. The first stage, including step 1~4, is to use Kano model to analyze customer requirements and obtain quantitative results. The second stage, including step 5, is to gather enough information for the following mathematical modelling through the traditional QFD approach and then build the HOQ. The last stage, including step 6, is to build the quantitative optimization model for the product design problem. This whole process is depicted as Figure 7.2.

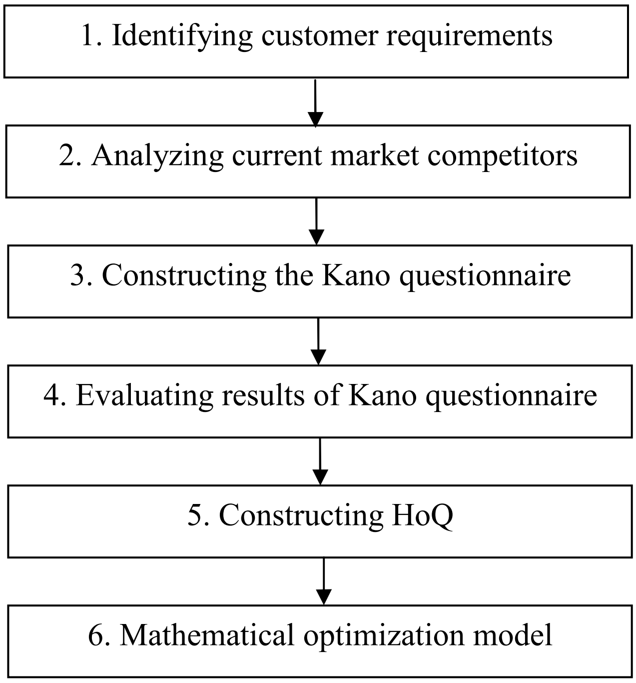


Figure 7.2 The procedure of proposed approach

7.3.1. Identifying the customer requirements

This is the start point of this Kano-QFD optimization project. There are many papers about collecting customer requirements and these papers provide a lot of methods to identify customer requirements. These methods include comment cards, surveys, focus group, direct customer contact, field intelligence, complaint analysis, and internet monitoring. Griffin and Hauser (1993) found that only 20~30 customer interviews in homogeneous segments are needed to determine approximately 90~95% of all possible customer requirements. The conclusion is very useful for the project team to design the customer requirements identification strategy. From the Kano model, we know that there are the features that customers do not expect. Therefore, we suggest that the expert must also review the result and provides their comments in it. It is especially important to reveal the "attractive requirements" when developing new and latent product. To understand customer requirements better, we use affinity or tree diagrams to construct the customer requirements structure.

7.3.2. Analyzing current market players

Usually in a niche market, there are several competitors. It is very important to analyze the market competition. The customer requirement structure provides the direction for the comparison of competitor products. Each competitor is compared on each customer requirement. And the result can be formulated as the performance rating matrix. In QFD, the performance rating matrix is listed at the right side of the House of Quality (HOQ) as shown in Figure 7.3.

$$
\begin{array}{c}
\\
CR_1 \\
CR_2 \\
\vdots \\
CR_m
\end{array}
\begin{bmatrix}
C_1 & C_2 & \cdots & C_k \\
x_{11} & x_{12} & \cdots & x_{1k} \\
x_{12} & x_{22} & \cdots & x_{2k} \\
\vdots & \vdots & \ddots & \vdots \\
x_{m1} & x_{m2} & \cdots & x_{mk}
\end{bmatrix}
$$

Figure 7.3 The performance rating matrix

After the comparison, we can choose the best one as the standard to construct the following Kano questionnaire. If it is very hard to choose the best one, we can choose the one that has the best market performance. This information can be obtained from market research institution.

7.3.3. Constructing the Kano questionnaire

In the first step, we only know what kind of requirements that customers have, but we do not know which categories, i.e. must-be, one-dimensional and attractive, that these customer requirements belong to. The Kano questionnaire (Kano *et al*. 1984) can help us to classify them. For each customer requirements, a pair of questions is formulated to which the customer have five choices to answer. The first question is about the reaction that the product can satisfy this requirement and the second one is about the reaction that the product can not satisfy this requirement. Usually, the five choices are "I like it that way", "It must be that way", "I am neutral", "I can live with it that way", and "I dislike it that way". An example of Kano questionnaire is show in Figure 7.4.

Function form of the question, i.e., If the notebook has a storage capacity of 40G, how do u feel about it?	□I like it that way
	□It must be that way
	□I am neutral
	□I can live with it that way
	□I dislike it that way
Dysfunction form of the question, i.e., If the notebook has a storage capacity less than 40G, how do u feel about it?	□I like it that way
	□It must be that way
	□I am neutral

	□I can live with it that way
	□I dislike it that way

Figure 7.4 Kano questionnaire

For each customer requirement, customers will be asked to answer the above questionnaire. By combing the two answers, the customer requirements can be classified into different categories. The categorizing is shown in Table 7.1.

Table 7.1 Results of Kano questionnaire

Customer Requirements		dysfunctional form of the question				
		I like it that way	It must be that way	I am neutral	I can live with it that way	I dislike it that way
question	I like it that way	Q	A	A	A	O
	It must be that way	R	I	I	I	M
	I am neutral	R	I	I	I	M
	I can live with it that way	R	I	I	I	M
	I dislike it that way	R	R	R	R	Q

In the table, Q stands for "Questionable" because normally the customer requirement doesn't fall into that directory. A means "Attractive"; O means "One-dimension"; M means "Must-be". R stands for "Reverse". It means that the customer not only doesn't have this requirement, but also want the reverse one. This situation may happen in some areas. For example, a tour service may have the function of pre-planned event every day.

Some people would like but others not (Berger, *et al*. 1993). Sometimes, “R” is also a hint to do customer segmentation.

7.3.4. Evaluating the result of Kano questionnaire

The evaluation process consists of two parts: classifying the customer requirements and calculating the satisfying and dissatisfying coefficient. First of all, we can put the results of Kano questionnaire into a table as shown in Table 7.2. The first part, classifying the customer requirements is through the frequency analysis. For example, if the result of Kano questionnaire indicates that customer requirement 1 has 5 A, 30 O, and 60M, 4 I, 1 R and zero Q. Then, it belongs to the Must-be category because it has the highest frequency.

Table 7.2 Results of frequency

	A	O	M	I	R	Q	Category
Customer requirement 1	5	30	60	4	1	0	M
Customer requirement 2							
Customer requirement 3							
……							

However, this result is only a qualitative and rough one. We know from the example that customer requirement 1 belongs to Must-be category. And, if customer requirement 2 has the frequency of M of 50 times, it also belongs to the same category. However, customer may feel differently when the two customer requirements do not meet. To optimize the product design, it is necessary to distinguish the difference and represent this information in a quantitative way.

The customer satisfying coefficient expresses the extent that customer will feel the satisfaction when the customer requirement is meet and the customer dissatisfying coefficient indicates the other side. Berger *et al*. (1993) provide a method to quantify this kind of information as follows.

Extent of satisfaction:

$$CS = \frac{f_A + f_o}{f_A + f_o + f_M + f_I} \tag{7.1}$$

Extent of dissatisfaction:

$$DS = -\frac{f_o + f_M}{f_A + f_o + f_M + f_I} \tag{7.2}$$

CS means the customer satisfaction, *DS* means the customer dissatisfaction. f_A, f_o, f_M, f_I means the frequency of A, O, M, I respectively. The minus sign means that it is dissatisfaction. Using the above formula, we can calculate the *CS* and *DS* for each customer requirement and after that we can draw a picture to visualize the result. An example is shown in Figure 7.5. CR stands for customer requirement.

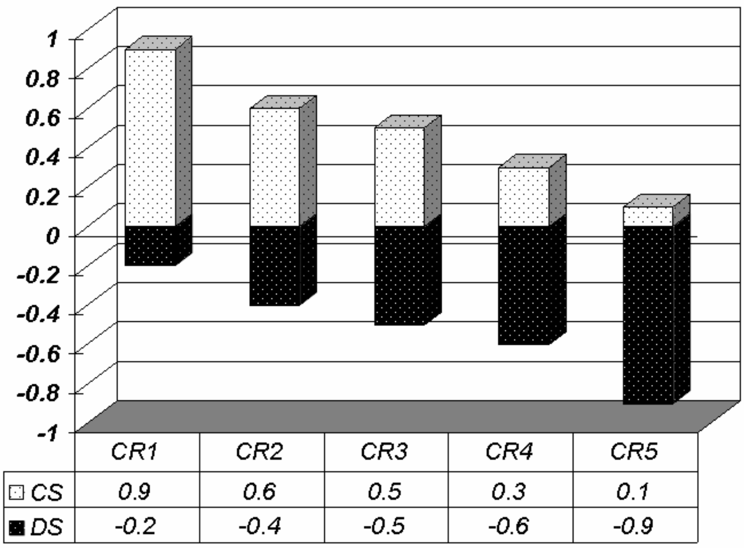


Figure 7.5 CS-DS coefficients

7.3.5. Drawing the HOQ

After we completed the above four steps, we can build the house of quality. The HOQ is shown below in Figure 7.6. The difference of Figure 7.6 from traditional HOQ is that this one contains the customer satisfaction coefficient, CS_i, and customer dissatisfaction coefficient, DS_i.

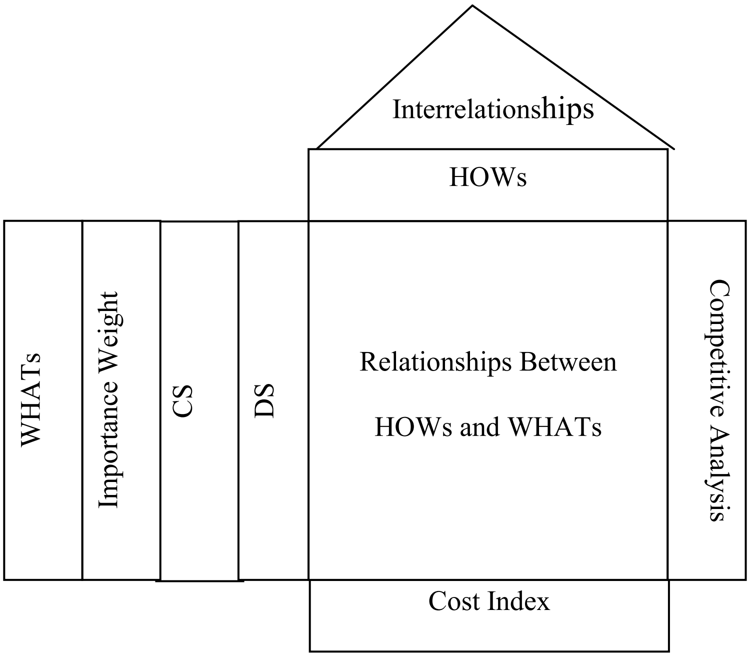


Figure 7.6 House of quality

The bottom of the HOQ is the cost index for each technical attribute. In most cases, improvements in technical attributes will increase the cost. Here, we define Ta_j as value of technical attributes *j, j*=1,2,…,*n*. Each technical attribute can choose from a set of feasible value and the maximum value is $\max\{Ta_j\}$. However, in most cases, not all technical attribute can have its highest value due to all kinds of constraints. Then, we define normalized value of technical attributes *j*

$$TA_j = Ta_j / \max\{Ta_j\},\ j=1,2,\ldots,n \tag{7.3}$$

Then, the normalized value of technical attributes is limited from 0 to 1 regardless its original value. This conversion greatly facilitates constructing the cost function.

The cost is often a combination of a fixed and variable part. The fixed part is the minimum amount of money that is needed to be invested in a technical attribute. The most important consideration in construct cost functions is the technology availability. The current available technology determined the upper and lower limit budget to each technical attribute and corresponding fulfilment level. Therefore, we formulate the cost function in a linear way as shown in Figure 7.7.

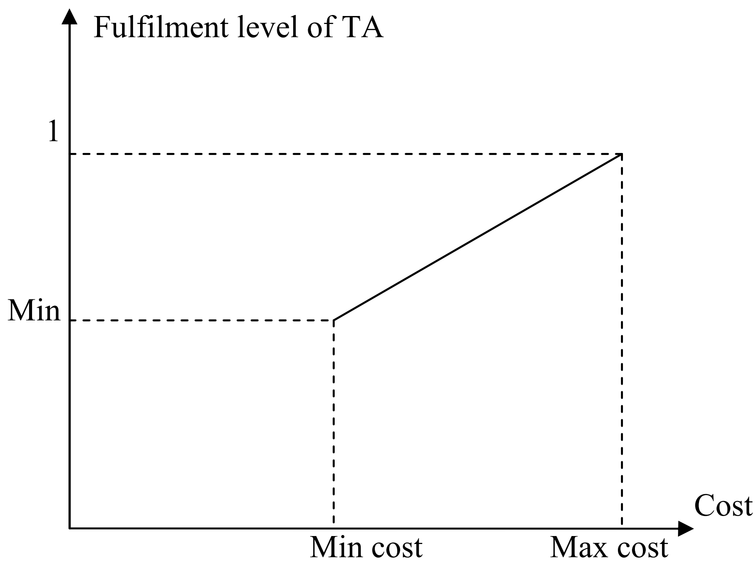


Figure 7.7 Cost function

And the mathematical expression is:

$$TA_j = f_{\min j} + (x_j - c_{\min j})(1 - f_{\min})/(c_{\max j} - c_{\min j}) \qquad (7.4)$$

$f_{\min j}$ is the minimum fulfilment level; $c_{\max j}$ and $c_{\min j}$ are the maximum and minimum cost respectively. x_j is the budget allocated to technical attribute *j*.

That is, we define cost function as a monotonically increasing linear continuous function. It is the simplest situation. There may be much more sophisticated cost functions.

7.3.6. Mathematical optimization model

To optimize the product design, we need to formulate a mathematical optimization model. Here is a summary of the notations that will be used in the mathematical optimization model.

The Kano questionnaire is carried out based on a benchmark product. Then, the objective of this optimization model is to maximize difference of customer satisfaction between the to-be-designed product and the benchmark product. Here we define a function S_i as follows. It indicate the weighted satisfaction difference of customer requirement *i*.

$$S_i = \begin{cases} w_i \times CS_i \times (y_i - t_i) & when \quad y_i \geq t_i, \mathrm{i} = 1,2,\ldots \mathrm{m}, \\ w_i \times DS_i \times (t_i - y_i) & when \quad t_i > y_i, \mathrm{i} = 1,2,\ldots \mathrm{m}, \end{cases} \qquad (7.5)$$

Then, when the to-be-designed product exceeds the benchmark product, there is a positive S_i, otherwise there is a negative S_i. The mathematical model is as following:

$$Max \quad y = \sum_{i=1}^{m} S_i \tag{7.6}$$

Subject to:

$$y_i = \sum_{j=1}^{n} R_{ij}^{norm} TA_j \tag{7.7}$$

$$TA_j = f_{\min j} + (x_j - c_{\min j})(1 - f_{\min})/(c_{\max j} - c_{\min j}) \tag{7.8}$$

$$B \geq \sum_{j=1}^{n} x_j \tag{7.9}$$

$$c_{\min j} \leq x_j \leq c_{\max j}, \; j = 1, 2, ..., n; \tag{7.10}$$

$$S_i = \begin{cases} w_i \times CS_i \times (y_i - t_i) & when \quad y_i \geq t_i, \mathrm{i} = 1,2,\ldots\mathrm{m}, \\ w_i \times DS_i \times (t_i - y_i) & when \quad t_i > y_i, \mathrm{i} = 1,2,\ldots\mathrm{m}, \end{cases} \tag{7.11}$$

The above mathematical model is not easy to solve directly. We have to use if-else to discuss the different situations. However, as the number of customer requirements goes up, the number of different situations goes up exponentially. For example, if there are 4 customer requirements, there are 16 different situations; 5 customer requirements, 32 different situations; 8 customer requirements, 256 different situations, 10 customer requirements, 1024 different situations. It becomes very time-consuming to solve it. We need to find a smart way to solve this problem.

First, we define two variables, w_{1i} and w_{2i}, as follows:

$$w_{1i} = -DS_i - CS_i \tag{7.12}$$

$$w_{2i} = CS_i \tag{7.13}$$

And, we define d_{1i}, d_{2i} as the difference between y_i and t_i, y_i and 1(ideal situation) respectively. Then, the objective function can be minimizing the weighted difference to-be-designed product and the ideal situations. This model is much easier to solve and its result can be converted to be the same as the first one. The optimization model is:

$$Min\ \ D = \sum_{i=1}^{m} (d_{1i} \times w_{1i} \times w_i + d_{2i} \times w_{2i} \times w_i) \tag{7.14}$$

Subject to:

$$y_i = \sum_{j=1}^{n} R_{ij}^{norm} TA_j \tag{7.15}$$

$$TA_j = f_{\min j} + (x_j - c_{\min j})(1 - f_{\min}) / (c_{\max j} - c_{\min j}) \tag{7.16}$$

$$y_i + d_{1i} \geq t_i \tag{7.17}$$

$$y_i + d_{2i} \geq 1 \tag{7.18}$$

$$B \geq \sum_{j=1}^{n} x_j \tag{7.19}$$

$$c_{\min\ j} \leq x_j \leq c_{\max\ j},\ j = 1, 2, \ldots, n; \tag{7.20}$$

$$0 \leq d_{1i}, d_{2i} \leq 1, i = 1, 2, \ldots, m; \tag{7.21}$$

7.4. A case study

In this part, a snow ski design project is used to demonstrate how the proposed Kano Model and QFD approach can be used to solve product design problems. This example is modified from MatzlerHans and Hinterhuber's work (1998). The whole problem solving process follows the proposed procedure as shown in Figure 7.8.

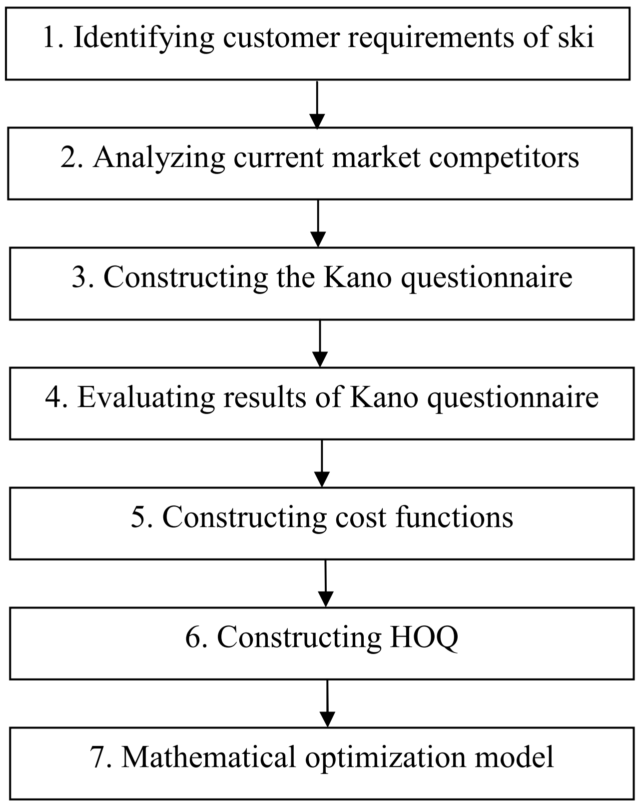


Figure 7.8 Procedure of solving ski design problem

First, an explorative investigation on customer requirements has been carried out to identifying the customer requirements of snow ski. This investigation included customer interview, focus group and survey. The identified customer requirements are: good edge grip on hard piste, great ease of turn, good powder snow features, very light skis and stable gliding when skiing fast.

After that, the performance of current competitors has been compared and the best one for each customer requirements is chosen to construct following Kano questionnaire. The Kano questionnaire is constructed in the standard way as described before. Then, the survey of Kano questionnaire was carried out. After the evaluation of Kano questionnaire, good edge grip on hard piste, great ease of turn, and stable gliding when skiing fast were classified as must-be requirements, good powder snow features and very light skis were classified as one-dimensional requirements.

The next important step is to determine the cost for each technical attributes. In this example, the cost function was formulated as a linear one. Three parameter to determine the cost function is the minimum fulfilment level, $f_{\min j}$, the maximum, $c_{\max j}$, and minimum cost, $c_{\min j}$. Figure 7.8 shows the whole house of quality. In Figure 7.9, the relationship between customer requirements and technical attributes were normalized using Wasserman's method (1993). In this example, the budget is set to 43.

	Importance	DS	CS	Catetory	Technical attributes	Total Weight	Shape carving	Torsion-stiffness	Lengthways stiffness	Target
Customer requirements										
Good edge grip on hard pistes	0.32	-0.83	0.40	M		0.26	0.14	0.30	0.30	0.75
Great ease of turn	0.18	-0.78	0.57	M		0.30	0.25	0.23	0.23	0.70
Good powder snow features	0.07	-0.44	0.53	O		0.28	0.24	0.24	0.24	0.85
Very light skis	0.26	-0.51	0.53	O		0.27	0.18	0.27	0.27	0.65
Stable gliding, when skiing fast	0.13	-0.75	0.35	M		0.26	0.14	0.30	0.30	0.90
Cost information										
Min fulfilment						0.65	0.4	0.5	0.7	Total
Min investment						8	5	9	6	28
Max investment						20	10	25	9	64

Figure 7.9 HOQ of snow ski

After all these data were obtained, we can construct the mathematical model using formula 12 to 21. What we need to do is just replacing the parameters with numbers from the above house of quality. Table 7.3 shows the optimal results of budget allocated to each technical attribute and corresponding fulfilment level. Table 7.4 shows the fulfilment level of each customer requirement. As we can see from Table 7.4, the fulfilment level of three customer requirements, “Good edge grip on hard pistes, Great ease of turn, and Very light skis” are well above their target value respectively. The remaining two are below their target values. The budget is 43, far from 68 that can achieve highest customer requirement fulfilment level because it makes every technical attribute to best. Therefore, some customer requirements must get some priority to be satisfied first. This situation is very normal in the real world. Thus, the proposed model can help designers to allocate the budget to achieve optimal customer satisfaction.

Table 7.3 Optimal results of technical attributes

Technical Attributes	Budget allocation	Fulfillment level
Total Weight	8	0.65
Shape carving	10	1
Torsion-stiffness	16	0.7187
Lengthways stiffness	9	1

Table 7.4 Optimal results of customer requirements

Customer requirements	Fulfillment level
Good edge grip on hard pistes	0.8246
Great ease of turn	0.8403
Good powder snow features	0.8345
Very light skis	0.8196
Stable gliding, when skiing fast	0.8246

7.5. Conclusions

In this chapter, we have proposed a new approach to optimize the product design by integrating the Kano model and QFD. This approach obtains the quantitative information from the Kano model and uses it to evaluate the extent of customer satisfaction and dissatisfaction. Finally it provides an optimal product design using the QFD optimization method under the cost constraint.

Compared with previous works, this method provides a way to use the quantitative information of the Kano model other than managerial implications. Traditional QFD optimization methods usually assume that the satisfaction that customers will get when a requirement is meet is the same as the dissatisfaction that customers will feel when the requirement is not meet. It is contradictory with the Kano model and conceals the properties of Must-be requirements and attractive requirements. Our proposed method overcomes this problem by integrating the Kano model into its optimization process. This chapter presented a case study on snow ski. The findings indicate that quantitative QFD may be successfully implemented in product design.

Chapter 8 QFD Optimization Using Linear Physical Programming

8.1. Introduction

The goal of the product design team is to formulate a design that meets a number of customer requirements. This is a multi-objective optimization problem. The fact is that many multi-objective optimization methods can be and have been applied to QFD optimization (Fung *et al*. 2004, Reich and Levy 2004). They include linear programming, mix-integer programming, and dynamic programming. This chapter proposes a new approach that incorporates linear physical programming (LPP) in QFD optimization in order to find the optimal set of technical attributes (see Messac *et al*. (1996) for a discussion of LPP).

This chapter is organized as follows. Section 2 contains a discussion of the traditional multi-objective optimization methods and their pros and cons. Section 3 includes a brief introduction to LPP in QFD. Section 3 also presents the proposed LPP approach that can help resolve the QFD optimization problem. In Section 4, a numerical example is used to illustrate the application of the new approach. Section 5 discusses a sensitivity analysis done on the case study.

8.2. Literature review and motivation for study

8.2.1. Traditional multi-objective optimization methods

In using QFD, a product design team will usually surface the following issues. First, the product to be designed needs to meet several customer requirements. Second, these customer requirements are sometimes conflicting, and they may have different importance weights. The problem is to look for the best possible design that can satisfy different objectives. Thus, the optimal solution must simultaneously meet and satisfy several customer requirements and constraints.

The previous methods usually convert a multi-objective problem into a single objective problem, and then solve the single objective problem for a compromise solution. For this process to work, the design team has to specify, in advance, a weight for each objective. The weights are important and need to be adequate in terms of capturing the nature of the optimization problem. In addition, the aggregate objective function, the constraints, and the bounds on the decision variable constraints, need to be clearly expressed in mathematical terms. These mathematical presentations are difficult to express clearly and accurately.

8.2.2. Advantages of linear physical programming

Linear physical programming (LPP) is a new and effective multi-objective optimization method. All multi-objective optimization problems involve determining numerical weights either directly or indirectly. The challenge is how to determine the correct weights during the optimization process because the weights that are valid in a certain design space may not remain valid in a different neighbourhood. The design team needs a way to determine correct weights in the objective space both locally and globally. And this needs to be in a flexible and simple way. In most traditional methods, the weights are constant. This may lead to bias in some cases. LPP proposes a different and systematic approach to obtain the weights both locally and globally. Furthermore, it integrates the approach of obtaining the weights to the optimization process in order to obtain optimal results.

As mentioned above, it is difficult for both customers and the design team to decide how important the customer requirements are. However, is it relatively easier to identify at what satisfaction level a certain customer requirement would be ideal, desirable, tolerable, undesirable, highly undesirable, or unacceptable. With this kind of information, LPP can derive the importance weights and obtain the optimal results.

Another source of information for differentiating the customer needs can come from the competition analysis within QFD. At the right side of the HOQ, information on the performance of both competitors and the company's own product are shown. LPP can make use of the competition information in a deliberate and systematic way.

Compared to other approaches, LPP uses data that are relatively easier to obtain. An example is the use of linguistic data for expressing customer preferences in a general and deliberately imprecise manner to compute the weights. Using the LPP approach, a design team need not specify the weight of each objective in advance. The arithmetic is a little complicated, but it can be handled easily by a computer program. LPP can be viewed as an extension of goal programming (Messac *et al*. 1996).

Messac *et al*. (2001) discussed the mathematical and pragmatic aspects of physical programming. Their results showed that all solutions obtained from LPP are indeed Pareto optimal. In this chapter, a design solution can be called 'Pareto optimal' if there exists no other design solution that will yield an improvement in the satisfaction level of one customer requirement without causing a degradation in the satisfaction level of at least one other customer requirement. In addition, concerning the sensitivity of optimal solutions to changes in user parameters, LPP performs better than the weighted sum method, the weighted square sum method, and compromise programming. Many papers have discussed the application of LPP (e.g. Messac *et al*. 2002, Maria *et al*. 2003, Melachrinoudis *et al*. 2004).

8.3. Applying LPP to QFD optimization

Applying LPP to QFD optimization involves two steps. The first step is to gather enough information for LPP through the traditional QFD approach and then build the HOQ. This step will also help the design team to complete a qualitative analysis of the design problem. The second step is the mathematical modelling using LPP. Some necessary adjustments to LPP have to be carried out in order to use it for QFD optimization. This whole process is depicted as Figure 8.1. Table 8.1 shows the notations that will be used in the following sections.

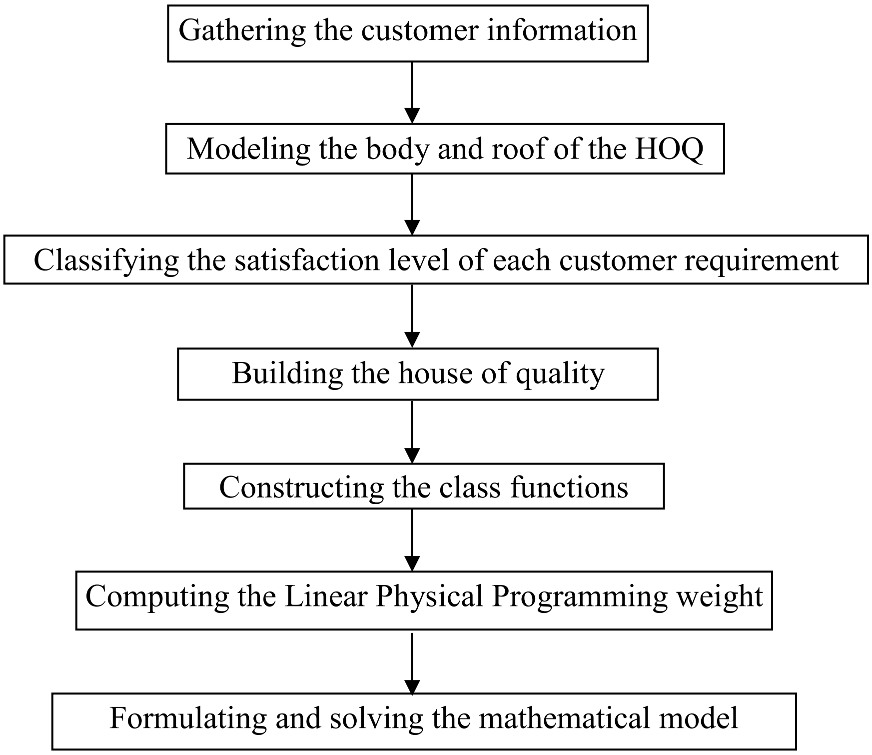


Figure 8.1 The process of applying LPP to QFD optimization

Table 8.1 Notations

B	**Cost limit**
β	**A convexity parameter**
c_j	**The cost of unit improvement of the technical attribute**
d_{is}^{-}	**The deviation from target**

m	**The number of customer requirements**
n	**The number of technical attributes**
γ_{jk}	**The relationship between the j_{th} and k_{th} technical attributes**
R_{ij}	**The relationship between the i_{th} customer requirement and the j_{th} technical attribute, i=1,2,…,m, and j=1,2,…,n**
R_{ij}^{norm}	**The normalized relationship between the i_{th} customer requirement and the j_{th} technical attribute, i=1,2,…,m, and j=1,2,…,n**
t_{is}	**The classification of satisfaction level of the i_{th} customer requirement, i=1,2,…,m, s=1,2…,5**
$\tilde{t}_{is}$	**The difference between $t_{i(s-1)}$ and t_{is}**
w_{is}	**The importance weight of customer satisfaction level s of the i_{th} customer requirement**
$\tilde{w}_{is}$	**The difference between w_{is} and $w_{i(s-1)}$**
Ta_j	**The value of the j_{th} technical attributes, j=1,2,…,n**
TA_j	**The normalized value of the j_{th} technical attributes, j=1,2,…,n**
y_i	**The satisfaction level of the i_{th} customer requirement, i=1,2,…,m**
z_i	**The loss function defined in LPP**
z^s	**The value of the class function at ranges-intersection s, s=1,2,…,5**
$\tilde{z}^s$	**The difference between z^s and z^{s-1}**

8.3.1. Building the HOQ

In this step, customer information is first gathered. The body and roof of the HOQ are then mathematically modelled. Next the classification of each customer requirement's fulfilment level is defined. Finally, the HOQ is built.

8.3.1.1. Gathering customer information

Several methods can be used to obtain the customer requirements, e.g. comment cards, formal surveys, focus group, direct customer contact, field intelligence, etc. To better understand the customer requirements, design teams usually classify them using affinity or tree diagrams (Evans and Lindsay 2002). This step is nearly the same as that of previous QFD optimization model.

8.3.1.2. Modeling the body and roof of the HOQ

Some technical attributes are inter-related. Changing the value of one technical attribute may alter its impact on the customer requirements or on other technical attributes. The roof of the HOQ shows the relationships among the technical attributes. Usually these relationships are obtained from the knowledge and experience of the design team. To represent dependencies between technical attributes, the notation, γ_{jk} , denoting elements of the correlation matrix is introduced to describe the correlation between the j_{th} and k_{th} technical attributes. The body of the HOQ shows the relationships between the technical attributes and the customer requirements. R_{ij} is used to denote the relationship between the i_{th} customer requirement and j_{th} technical attribute.

Traditionally, these two kinds of relationship are evaluated using a weak, strong, and very strong, or 1-3-5, scale. In this chapter, a more sophisticated scale (1-9 scale) is used, where 1 denotes the weakest relationship and 9 denotes the strongest relationship.

The impact of the dependencies between the technical attributes on the relationship between the customer requirements and the technical attributes, needs to be quantified. The most commonly used method is the one proposed by Wasserman (1993).

8.3.1.3. Classifying the satisfaction level of each customer requirement

The purpose of this step is to prepare for the LPP algorithm. Using LPP, the satisfaction level of each customer requirement is classified into one of six different ranges. There are many ways to construct the ranges. One way is from the competitor performance ratings. The design team can list the competitors' performance regarding each customer requirement. The best rating can be used as the limit for the ideal, and the worst rating can be used as the limit for the intolerable.

Another way to construct the ranges is to specify the values using the designers' experience. Customer linguistic data regarding their preferences is also a widely used source to acquire the importance weights of the customer requirements (Chen *et al*. 2004, Shen *et al*. 2001). If there is some kind of past data or reference, the design team can use that also. Usually this process will contain the design team's judgments. There is no rigid rule on how to construct the ranges.

In the LPP algorithm, the desired behaviour of an objective is described by one of eight sub-classes, four soft and four hard (Messac *et al*. 1996). In this chapter, only class 2-S is used. The following Figure 8.2 presents both the qualitative and quantitative depiction of class 2-S. y_i is the value of the performance rating of customer requirement i under consideration. t_{is} is the limit of different ranges and s denotes a range. The best is t_{i1} and the worst is t_{i5}. z_i is the class function. In addition, z_i can be viewed as a loss of customer satisfaction and then, a lower z_i is better than a higher one. The ideal value is zero. z_i will be discussed in detail later. The classes are defined as follows:

- Ideal range ($y_i \geq t_{i1}$)
- Desirable range ($t_{i1} \geq y_i \geq t_{i2}$)
- Tolerable range ($t_{i2} \geq y_i \geq t_{i3}$)
- Undesirable range ($t_{i3} \geq y_i \geq t_{i4}$)
- Highly undesirable range ($t_{i4} \geq y_i \geq t_{i5}$)
- Unacceptable range ($y_i \leq t_{i5}$)

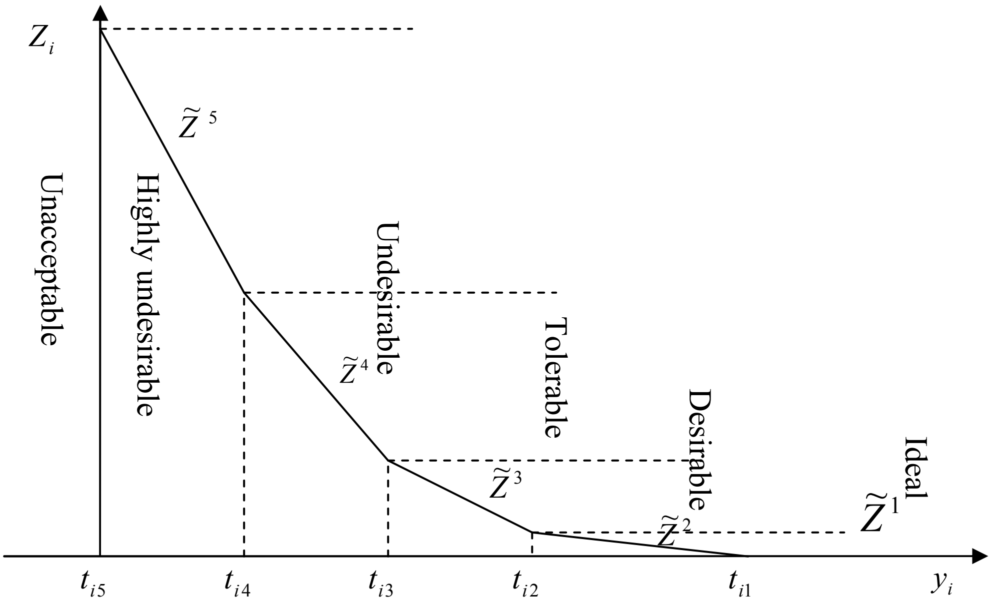


Figure 8.2 Classification of satisfaction level of customer requirement *i*

8.3.1.4. Building the HOQ

The HOQ is constructed as traditionally done. However, the right side is little different from a traditional HOQ that lists the competitors' performance at the right side. The competitors' performance may not be used to construct the customer requirements' satisfaction level. In this situation, the design team needs to revise it to choose other criteria to formulate the customer requirements' satisfaction level. The aim of this change is to be consistent with LPP.

The roof shows the interrelationships between technical attributes. The bottom of the HOQ is the cost index for each technical attribute. The value of technical attribute j is normalized using:

$$TA_j = Ta_j / \max\{Ta_j\},\ j=1,2,\ldots,n \tag{8.2}$$

8.3.2. LPP model formulation in QFD optimization

The calculation involving LPP contains three steps. First, the class function is constructed according to the classification of each customer requirement's fulfilment level. Then, an algorithm is used to obtain the weight. Finally, the mathematical model is developed.

8.3.2.1. Constructing the class function

In the LPP algorithm, the one versus others criteria rule (OVO rule) expresses the preference regarding inter-criteria relationships, i.e., the importance weights. The pre-emptive nature in the OVO rule is to minimize the worst performance. In the OVO rule, the following two options are considered:

Option 1: Full improvement of y_i across a given range (e.g. range 3).

Option 2: Full improvement of all other customer requirements across the next better range (e.g. range 2).

Option 1 is preferred over Option 2. That is, the worst performance should be improved first. The worst performance has the highest rank to be improved. For example, it is preferable for a single customer satisfaction to improve to the *tolerable* range, than it is for other customer requirements to be improved to the *desirable* range.

The class function is shown in Figure 8.3. The following are important properties of class functions:

1. z_i represents a loss, and a lower value of a class function the better
2. Class functions are positive
3. The value of a class function, z_i, is the same for all customer requirements
4. Class functions must satisfy the OVO rule

The value of a class function, z_i, at a given ranges-intersection is the same for any customer requirement. z^s is defined as the value of class function at ranges-intersection *s*. It can be mathematically expressed as:

$$z^s \equiv z_i(\mathrm{t_{is}}) \qquad (8.3)$$

Then, z^s is a constant for all *i*. $\tilde{z}^s$ is defined as:

$$\tilde{z}^s \equiv z^s - z^{s-1}, \ (2 \le \mathrm{s} \le 5); \qquad (8.4)$$

$$z^1 \equiv 0 \qquad (8.5)$$

Mathematically, the OVO rule can be expressed as:

$$\tilde{z}^{s} = \beta\,(m\text{-}1)\,\tilde{z}^{s-1} \quad (3 \leq s \leq 5); \tag{8.6}$$

where m donates the number of customer requirements, and β is the convexity parameter.

$\tilde{t}_{is}$ is defined as follows:

$$\tilde{t}_{is} = t_{i(s-1)} - t_{is}\,,\ (2 \leq s \leq 5); \tag{8.7}$$

And the importance weight of each customer satisfaction level is defined as:

$$w_{is} = \tilde{z}^{s} / \tilde{t}_{is}\,,\ (2 \leq s \leq 5); \tag{8.8}$$

$$w_{i1} = 0, \tag{8.9}$$

8.3.2.2. Computing the linear physical programming weights

After the class function is defined, the algorithm can be used to calculate the weight algorithm using the following steps.

Step a. Initialize. Suppose β=1.1; w_{i1}=0, $\tilde{z}^{1}$=0, $\tilde{z}^{2}$=small positive number (e.g. 0.1), m = the number of customer requirements

Step b. Calculate $\tilde{z}^{s}$ using equation (6), ($3 \leq s \leq 5$)

Step c. Evaluate $\tilde{t}_{is}$ using equation (7), ($1 \leq i \leq m$, $2 \leq s \leq 5$)

Step d. Evaluate w_{is} using equation (8), ($1 \leq i \leq m$, $2 \leq s \leq 5$)

The importance weight of an ideal range is set to zero and the importance weight of an unacceptable range is defined as a very large number. After the calculation, the importance weight of each range for every customer requirement can be obtained.

8.3.2.3. Formulating and solving the mathematical model

The goal of the design team is to attain the highest customer satisfaction level while meeting budget limitation. Now the linear programming (LP) mathematical expressions can be formulated. This kind of expressions must be in a piecewise form according to the classification of the fulfilment level of each customer requirement. However, the 'if-else' statement cannot be used in the LP model. To overcome this problem, a deviational variable is used to formulate it as a GP model. The deviational variable, denoted by d_{is}^{-}, can be viewed as the distance of y_i to $t_{i(s-1)}$ from the left side.

To use the GP model, the new weight of customer requirement $\tilde{w}_{is}$ is defined as follows:

$$\tilde{w}_{is} = w_{is} - w_{i(s-1)}, \ (2 \leq s \leq 5) \tag{8.10}$$

After the weights are obtained successfully, it is possible to present the piecewise linear class function of each customer requirement. Then, the LP model is used to solve the problem. The LP problem can be formulated as follows:

$$\min_{d_{is}^{-}, x} \sum_{i=1}^{m} \sum_{s=2}^{5} (\tilde{w}_{is} d_{is}^{-}) \tag{8.11}$$

Subject to

$$y_i + d_{is}^- \geq t_{i(s-1)}\text{, } i\text{=1,2,…, } m\text{; } s\text{=2,…,5;} \tag{8.12}$$

$$d_{is}^- \geq 0\text{, } i\text{=1,2,…, } m\text{; } s\text{=2,…,5;} \tag{8.13}$$

$$y_i \geq t_{i5}\text{,} \tag{8.14}$$

$$y_i = \sum_{j=1}^{n} R_{ij}^{norm} TA_j \text{ ;} \tag{8.15}$$

$$B \geq \sum_{j=1}^{n} c_j TA_j \text{ ;} \tag{8.16}$$

$$0 \leq TA_j \leq 1, j = 1,2,...,n; \tag{8.17}$$

This model can be further written in a concise way by replacing y_i in equations (8.13) and (15) using equation (16). That is,

$$\min_{d_{is}^-, x} \sum_{i=1}^{m} \sum_{s=2}^{5} (\tilde{w}_{is} d_{is}^-) \tag{8.18}$$

Subject to

$$\sum_{j=1}^{n} R_{ij}^{norm} x_j + d_{is}^- \geq t_{i(s-1)}\text{, } i\text{=1,2,…, } m\text{; } s\text{=2,…,5} \tag{8.19}$$

$$\sum_{j=1}^{n} R_{ij}^{norm} TA_j \geq t_{i5} \tag{8.20}$$

$$B \geq \sum_{j=1}^{n} c_j TA_j \tag{8.21}$$

$$d_{is}^- \geq 0\text{, } i\text{=1,2,…, } m\text{; } s\text{=2,…,5} \tag{8.22}$$

$$0 \leq TA_j \leq 1, j = 1,2,...,n \tag{8.23}$$

At this point, common mathematical softwares, e.g. Matlab, can be used to solve this type of problem. Note that in the above formulas, the only constraint is the budget. However, in the actual situation, there may be other constraints. For example, there might be a minimum satisfaction level, CRL_i ($0 \leq CRL_i \leq 1$), for the i_{th} customer requirement. In that case, a new constraint formula can be added as follows:

$$\sum_{j=1}^{n} R_{ij}^{norm} TA_j \geq CRL_i \tag{8.24}$$

If there is a technical constraint, the k_{th} technical attribute has a cap, TAH_k ($0 \leq ECH_k \leq 1$), then a new constraint formula is added:

$$TA_k \leq TAH_k \tag{8.25}$$

The above two constraints are the most common ones, which may be numerous in real situations. What the design team needs to do is to include the additional constraints to the model.

8.4. An illustration

A fictitious software design is used as an illustration. Suppose that Company A wants to develop a type of software for its customers. There are six customer requirements for this software: i) quality of the software, ii) performance of the software as per specifications, iii) user friendliness of the software, iv) deviations from requirements changed during design, v) standards followed in all activities/phases, and vi) the extent delivered software enhanced to meet business requirements. In addition, there are eight technical attributes: i) defect density, ii) experience of the project team, iii) peer review, iv) training provided, v) business knowledge of team, vi) documentation available, vii) technical skills of the team, and viii) long-term relationship with client. Figure 8.3 shows the HOQ of the software design.

Engineering Characteristics / **Customer Requirements**	Defect density	Experience of the project team	Peer reviews	Training provided	Business knowledge of team	Documentation available	Technical skill of the team	Long term relationship with client	t_1	t_2	t_3	t_4	t_5
Quality of the software	17.20%	16.42%	15.65%	6.80%	11.95%	9.52%	14.24%	8.21%	1.00	0.85	0.75	0.50	0
Performance of the software as per specifications	13.78%	21.75%	12.20%	4.92%	12.89%	7.97%	13.78%	12.70%	1.00	0.80	0.70	0.40	0
User friendliness of the software	11.81%	17.33%	8.74%	6.75%	16.72%	10.43%	10.43%	17.79%	1.00	0.90	0.85	0.70	0
Deviations from requirements changed during design	17.41%	14.43%	15.75%	8.29%	12.77%	10.28%	13.68%	7.38%	1.00	0.70	0.50	0.30	0
Standards followed in all Activities/Phases	16.46%	11.52%	15.43%	10.43%	13.72%	12.62%	11.52%	8.29%	1.00	0.80	0.60	0.50	0
The extent delivered software enhanced to meet business requirements	15.37%	17.37%	16.97%	8.38%	9.78%	10.38%	12.87%	8.88%	1.00	0.75	0.60	0.45	0
Cost Index	9.50	14.00	8.50	5.50	12.00	7.50	9.00	6.50					

Figure 8.3 HOQ of the software design

The relationships between the technical attributes and the customer requirements are assumed to have been normalized. In addition, the roof has been removed after the normalization process in order to simplify the illustration. The classification of satisfaction level of each customer requirement is listed at the right side of the HOQ. The bottom part shows the cost index.

Due to current technological constraints, the maximum achievement of defect density can only be 0.9. In addition, due to human resource limitation in the company, the maximum training provided can only be 0.85. From communication with customers, the design team found that customers had minimum requirements on 'user friendliness of the software' and 'the extent delivered software enhanced to meet business requirements'. Thus, the design team used the minimum values of 0.7 and 0.6 for these two customer requirements, respectively. The overall budget limitation is 65.

To simplify the mathematical expressions of the model, the following matrices are defined:

$$R = \begin{bmatrix} 0.1720 & 0.1642 & 0.1565 & 0.0680 & 0.1195 & 0.0952 & 0.1424 & 0.0821 \\ 0.1378 & 0.2175 & 0.1220 & 0.0492 & 0.1289 & 0.0797 & 0.1378 & 0.1270 \\ 0.1181 & 0.1733 & 0.0874 & 0.0675 & 0.1672 & 0.1043 & 0.1043 & 0.1779 \\ 0.1741 & 0.1443 & 0.1575 & 0.0829 & 0.1277 & 0.1028 & 0.1368 & 0.0738 \\ 0.1646 & 0.1152 & 0.1543 & 0.1043 & 0.1372 & 0.1262 & 0.1152 & 0.0829 \\ 0.1537 & 0.1737 & 0.1697 & 0.0838 & 0.0978 & 0.1038 & 0.1287 & 0.0888 \end{bmatrix}$$

$$T = \begin{bmatrix} 1 & 0.85 & 0.75 & 0.50 \\ 1 & 0.80 & 0.70 & 0.40 \\ 1 & 0.90 & 0.85 & 0.70 \\ 1 & 0.70 & 0.50 & 0.30 \\ 1 & 0.80 & 0.60 & 0.50 \\ 1 & 0.75 & 0.60 & 0.45 \end{bmatrix} \qquad D = \begin{bmatrix} d_{12}^- & d_{13}^- & d_{14}^- & d_{15}^- \\ d_{22}^- & d_{23}^- & d_{24}^- & d_{25}^- \\ d_{32}^- & d_{33}^- & d_{34}^- & d_{35}^- \\ d_{42}^- & d_{43}^- & d_{44}^- & d_{45}^- \\ d_{52}^- & d_{53}^- & d_{54}^- & d_{55}^- \\ d_{62}^- & d_{63}^- & d_{64}^- & d_{65}^- \end{bmatrix}$$

$$X = [x_1 \quad x_2 \quad x_3 \quad x_4 \quad x_5 \quad x_6 \quad x_7 \quad x_8]^T$$

Then the mathematical model can be formulated as follows:

Minimize

j=3.57 d_{12}^{-} +26.58 d_{13}^{-} +36.30 d_{14}^{-} +116.46 d_{15}^{-} +2.65 d_{22}^{-} +27.50 d_{23}^{-} +25.21 d_{24}^{-} +173.31 d_{25}^{-} +5.40 d_{32}^{-} +55.00 d_{33}^{-} +50.42 d_{34}^{-} +19.81 d_{35}^{-} +1.73 d_{42}^{-} +13.29 d_{43}^{-} +68.06 d_{44}^{-} +221.83 d_{45}^{-} +2.65 d_{52}^{-} +12.38 d_{53}^{-} +151.25 d_{54}^{-} +16.64 d_{55}^{-} +2.10 d_{62}^{-} +17.97 d_{63}^{-} +90.75 d_{64}^{-} +92.43 d_{65}^{-} (8.26)

Subject to

$$\mathrm{R} \times [\,\mathrm{X\ X\ X\ X}\,] + \mathrm{D} \geq \mathrm{T} \tag{8.27}$$

$$9.5x_1 + 14x_2 + 8.5x_3 + 5.5x_4 + 12x_5 + 7.5x_6 + 9x_7 + 6.5x_8 \leq 65 \tag{8.28}$$

$$d_{is}^{-} \geq 0,\ i=1,2,\ldots,6;\ s=2,\ldots,5; \tag{8.29}$$

$$0 \leq x_j \leq 1,\ j=1,2,\ldots,8; \tag{8.30}$$

$$x_1 \leq 0.9; \tag{8.31}$$

$$x_4 \leq 0.85 \tag{8.32}$$

$$0.1181\,x_1 + 0.1733\,x_2 + 0.0874\,x_3 + 0.0675\,x_4 + 0.1672\,x_5 + 0.1043\,x_6 + 0.1043\,x_7 + 0.1779x_8 \geq 0.7 \tag{8.33}$$

$$0.1537\,x_1 + 0.1737\,x_2 + 0.1697\,x_3 + 0.0838\,x_4 + 0.0978\,x_5 + 0.1038x_6 + 0.1287\,x_7 + 0.0888\,x_8 \geq 0.6 \tag{8.34}$$

Matlab was used to solve this problem. The results are the achievement level of each technical attribute, the cost allocated to each technical attribute, and the customer satisfaction level of each customer requirement. They are shown in Tables 8.2 and 8.3 respectively.

Table 8.2 Results of budget allocation and achievement level of ECs

	Defect density	Experience of the project team	Peer reviews	Training provided	Business knowledge of team	Documentation available	Technical skill of the team	Long term relationship with client	Total Budget
Budget Allocation	8.55	12.88	8.50	4.68	7.32	7.50	9.00	6.50	64.93
Achievement Level	0.90	0.92	1.00	0.85	0.61	1.00	1.00	1.00	

Table 8.3 Results of customer satisfaction level

Customer Requirements	**Satisfaction Level**
Quality of the software	91.35%
Performance of the software as per specifications	91.20%
User friendliness of the software	90.00%
Deviations from requirements changed during design	90.95%
Standards followed in all Activities/Phases	90.59%
The extent delivered software enhanced to meet business requirements	92.07%

As can be seen from Table 8.3, the satisfaction level of each customer requirement is nearly the same. It is coordinated with the preference of LPP which always puts more effort on the aspects that lag behind. This makes the satisfaction level of each customer requirement similar.

8.5. Sensitivity analysis

In the LPP algorithm, some coefficients (e.g. β, z_1) are manually determined. It is important to investigate the sensitivity of the results upon changing these coefficients.

In the above example, β was set to 1.1. In the algorithm, β is the convexity parameter that should be larger than 1.0. In the sensitivity analysis, β is increased from 1.1 to 6.0. The results do not change much with this change in β. The parameter z_1 is the loss of the first class. It can be set as a small positive number. In the example, it was set to 0.1. When it increases from 0.1 to 1, only a negligible difference is produced. These are two important characteristics. It shows that the results are not affected by these two pre-determined values. The effect here is to decrease the possibility of error in the final result.

In the sensitivity analysis on the budget allocation, the budget grows from 46 to 70. Figure 8.4 shows the results. EC1 to EC8 respectively, represent the eight technical attributes: defect density, experience of the project team, peer reviews, training provided, business knowledge of team, documentation available, technical skill of the team, and long-term relationship with client.

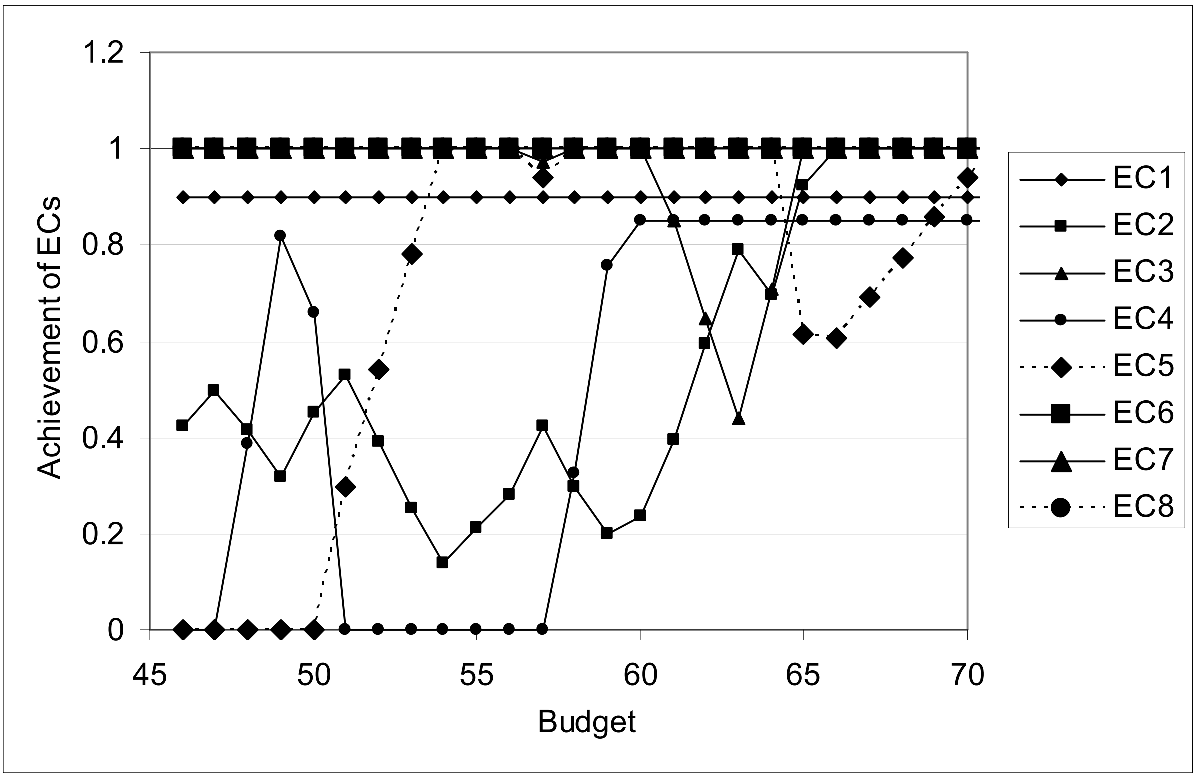


Figure 8.4 Sensitivity analysis of budget on achievement of technical attributes

Figure 8.4 shows that the achievements of the technical attributes vary greatly when the budget grows. This is a unique feature of LPP. When the achievement of each technical attribute grows, the customer satisfaction level grows also. When it enters a classification level, the importance of the customer requirement will change greatly. This change makes some technical attributes fluctuate greatly. However, the satisfaction level of each customer requirement increases as the budget grows. The ‘loss’ defined in the LPP also decreases as the budget grows. These results are shown in Figures 8.5 and 8.6, respectively. CR1 to CR6 are the six customer requirements. This pattern is consistent with common sense in that when more money is put into designing a product, the customer should get more (not less) satisfaction.

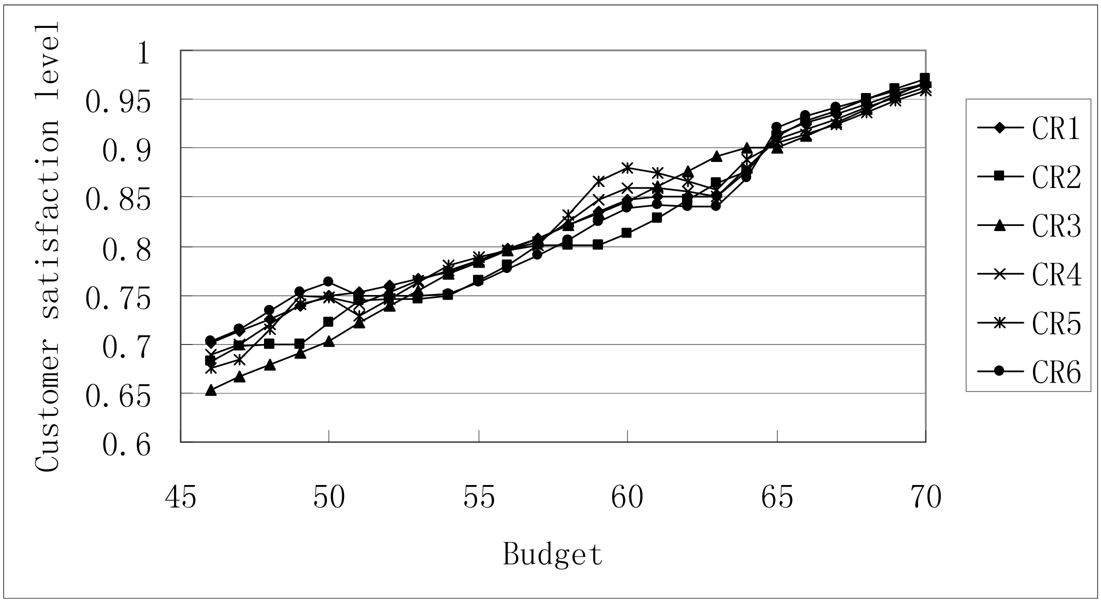


Figure 8.5 Relationship between customer satisfaction level and budget

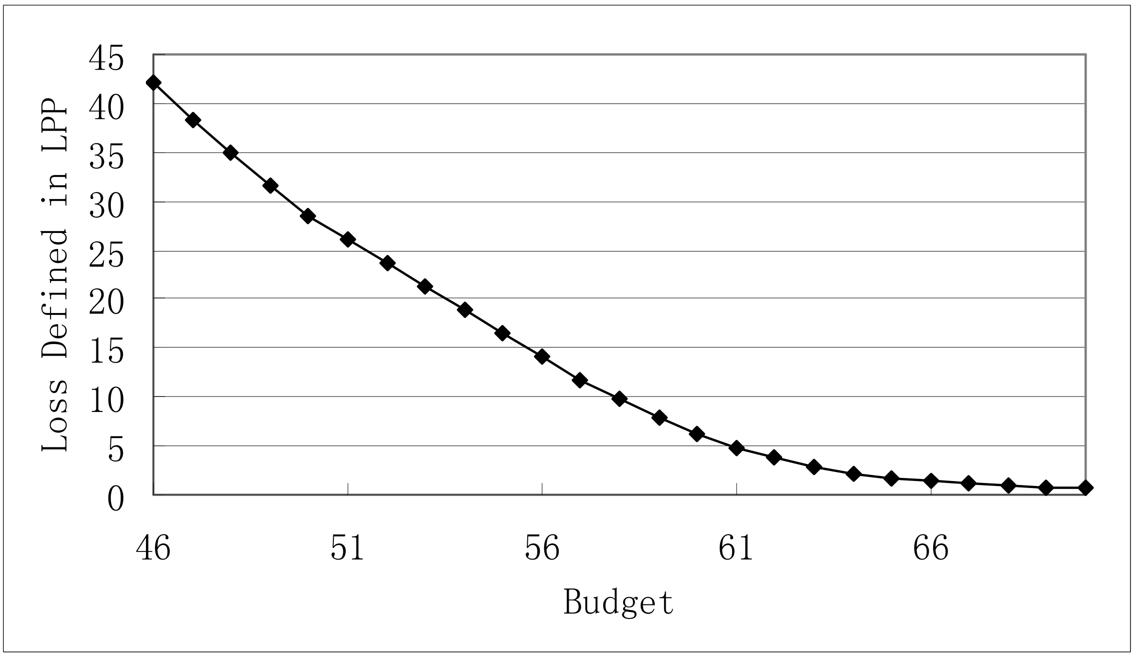


Figure 8.6 Relationship between the budget and loss in customer satisfaction

8.6. Conclusions

This chapter introduces a new method to deal with optimization problems in QFD analysis. Linear physical programming has a unique feature that gives a different priority to each customer requirement when the requirements are at different stages. The weight algorithm used in this method can also provide a way to use information concerning one's competitors. With keen competition, taking into consideration such information in product design is very important.

Following the illustration of the numerical example, a sensitivity analysis of two pre-determined coefficients was carried out. It shows that the results do not depend on the two predetermined coefficients of β and z_1. The sensitivity of budgeting shows that the customer satisfaction level is positively related to budget, but the achievement of each technical attribute does not relate positively or negatively to total budget.

Chapter 9 Optimizing Product Design using Quantitative Quality Function Deployment: A Case Study

In this chapter, an attempt is made to examine the applicability of quality function deployment (QFD) in optimizing product design. In recent years, many quantitative QFD methods have been developed. However, there have been few case studies reported on their use. A case study on personal computer design was conducted. The case study findings demonstrate that quantitative QFD can be successfully implemented in product design. Some limitations are highlighted. Practical suggestions on implementing quantitative QFD are discussed also.

9.1. Introduction

In recent years, many quantitative QFD methods have been developed, e.g., Liu (2005), Lai *et al*. (2004), Yoram and Eyal (2004), Vanegas and Labib (2001), Persson *et al*. (2000), Dawson and Askin (1999). However, there have been few case studies reported on their use.

Currently the personal computer (PC) industry is in the midst of change. In the past, PC makers could achieve competence by producing faster PCs. However the performance of computer hardware is hundreds of time what they were several years ago. Faster hardware is no longer the only concern of both customers and providers. There is an increasing demand for other attributes such as appearance, usability, more entertaining functions, etc.

The case study in this research covers a QFD application by a personal computer manufacturer. The management of the company realized that they needed to improve their product design in order to achieve competitive advantage. A new project using quantitative QFD to improve their product design was, thus, carried out.

The implementation process was divided into two stages. The first stage was to construct the house of quality (HOQ). The second stage was to optimize the product design using mathematical programming.

9.2. Constructing the house of quality

The HOQ is the main representation for information gathered from customers. It shows the interconnectedness between the customer requirements (CRs) and technical attributes (TAs) of the product.

9.2.1. Analyzing the customer requirements

The analysis of the CRs in this case study included two major tasks: i) identifying the customer requirements, and ii) determining their importance weights. There are several internal and external sources of the information regarding the customer requirements. In this case study, the sources of information were discussions with sales and production staff, discussions with customers, previous market surveys, specialized computer websites, internet discussion forums, and customer surveys conducted by the company.

The task of identifying the customer requirements involved three steps as shown in Figure 9.1. First, a review was conducted on the current literature using computer websites, previous market surveys, and from internet discussion forums. From the literature, a list of customer requirements was generated. A tree-diagram was constructed to classify the CRs into several groups. Second, sales and production staff opinions were incorporated into the research findings. After which the CRs were finally classified into four groups, namely: appearance, performance, functionality, and usability. In the third and last step, a customer survey was carried out to determine future customer requirements, if any. This step was accomplished together with determining the importance weights. The tree-diagram for the final list of customer requirements is shown in Figure 9.2.

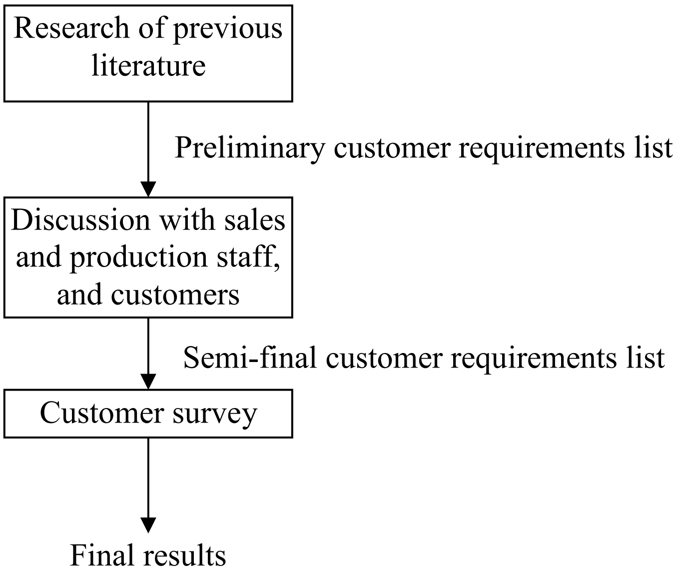


Figure 9.1 Steps in identifying the customer requirements

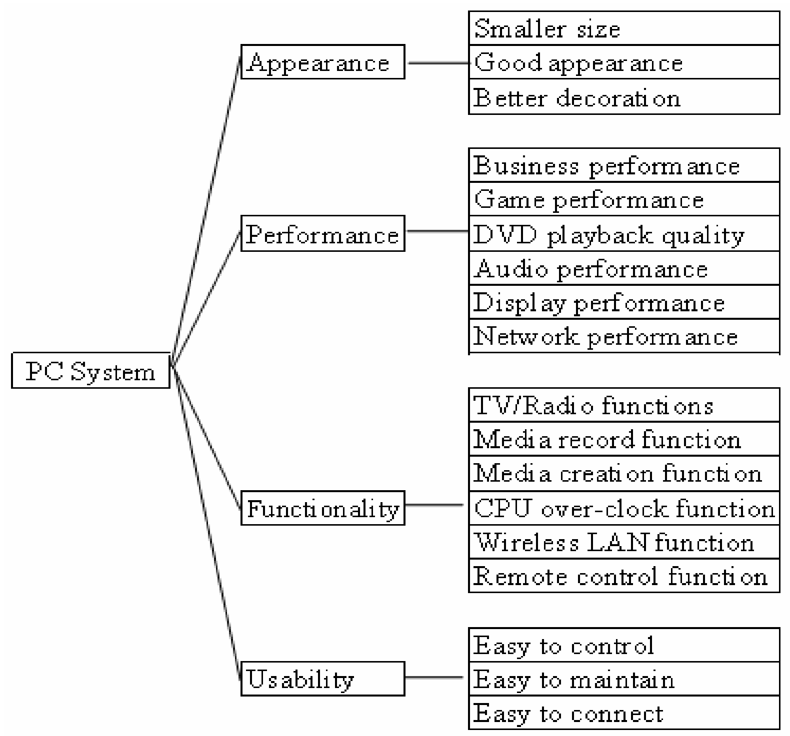
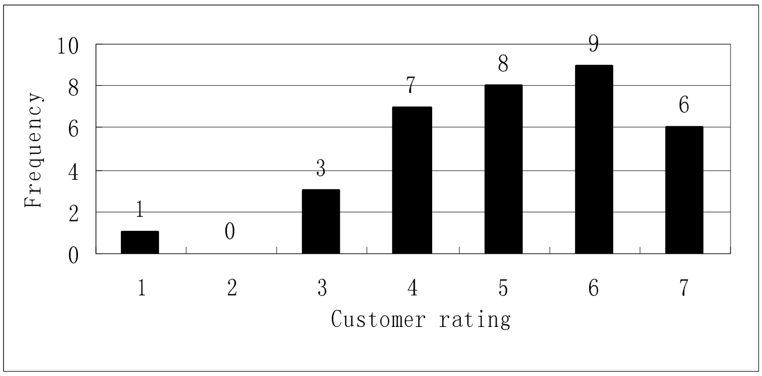


Figure 9.2 Tree-diagram of customer requirements

To determine the importance weights of the customer requirements, a customer survey was carried out. Thirty-four customers were surveyed through internet. All of them were between 20-29 years old and have monthly incomes under S$3000. Males comprised 53.1%, while females comprised 46.9%. 85.3% of them own a personal computer. 76.0% of them demonstrated good and above computer skills. On average, each respondent had 2.8 other information technology gadgets.

In the survey, respondents were asked to give each of these customer requirements a rating using a 1-7 scale. 1 denotes the least important, while 7 denotes the most important. A sample of the result is shown in Figure 9.3.



Average	5.12
Median	5
Mode	6
Std	1.43
Average	5.12

Figure 9.3 Survey result of the 'smaller size' requirement

The survey found that customers were more concerned with performance and usability. The average scores for the four groups of CRs were: appearance (4.7), performance (5.3), functionality (4.4), and usability (5.7). We normalized the importance of each customer requirement in order to obtain their relative importance. This result is shown in the second column of Table 9.1.

Table 9.1 Information concerning the customer requirements

Customer requirement	Relative importance	CS	DS	Target
Smaller size	5.70%	0.80	0.30	0.85
Good appearance	5.47%	0.80	0.30	0.80
Better decoration	4.59%	0.80	0.30	0.60
Business performance	6.29%	0.40	0.80	0.90
Game performance	6.22%	0.40	0.80	0.90
DVD playback quality	6.09%	0.40	0.80	0.60
Audio performance	6.16%	0.40	0.80	0.75
Display performance	6.32%	0.40	0.80	0.60
Network performance	4.62%	0.40	0.80	0.60
TV/Radio function	5.01%	0.30	0.80	0.80
Media record function	4.91%	0.30	0.80	0.80
Media creation function	5.63%	0.30	0.80	0.80
CPU over-clock function	4.65%	0.30	0.80	0.80
Wireless LAN function	4.72%	0.30	0.80	0.80
Remote control function	4.45%	0.30	0.80	0.80
Easy to control	6.65%	0.65	0.30	0.95
Easy to maintain	6.29%	0.65	0.30	0.85
Easy to connect	6.22%	0.65	0.30	0.80

9.2.2. Determining the relationships between the CRs and the TAs

Because the production of PCs in the company involves only assembling the components, the discussion of technical attributes is focused at the component level. A personal computer typically has 17 components (we call these technical attributes). They are listed in Figure 9.4. In order to obtain a more accurate picture of the relationship between the TAs and the CRs, it is necessary to go deeper into the sub-attributes of each component. Because each component has several sub-attributes, this would make the HOQ very large.

Several small HOQs were constructed instead. A preliminary study was carried out to determine the approximate relationship between the TAs and the CRs. Then, the preliminary result was used to split the matrix to several smaller ones. Each will be discussed in detail, but the overall results are summarized in one matrix as shown in Figure 9.4.

Table 9.2 shows the matrix used to perform the preliminary study. "▲" denotes a weak relationship, "○" denotes a normal relationship, and "●" denotes a strong relationship. After the preliminary study, the customer requirements and technical attributes that have a normal or a strong relationship were analyzed together. For example, the usability requirement and 6 technical attributes were analyzed together. To get a better understanding of the relationship between the customer requirements and the technical attributes, the sub-characteristics of each technical attribute were also analyzed as shown in Table 9.3. All the other customer requirements also went through the same process of analysis. In this way, the relationship between the customer requirements and the technical attributes are much clearer to see.

An analysis of the sub-attributes of the technical attributes was carried out to help understanding the customer requirements at the component level. Together with previous analyses, a matrix was constructed as shown in Figure 9.4. In Figure 9.4, a 1-9 scale was used where a larger number denotes a stronger relationship.

Table 9.2 Rough relationships between the customer requirements and the technical attributes

Customer requirements	CPU	Motherboard	Ram	Hard disk	Sound card	Graphics card	Network card	Optical drive	Keyboard	Mouse	Case	Decoration	Power supply	TV/Radio tuner	Speaker	Monitor	Card reader
Appearance requirements	▲	▲	▲	▲	▲	▲	▲	○	○	●	●	●	▲	●	●	●	▲
Business performance	●	●	●	○	▲	○	○	●	▲	▲	▲	▲	▲	▲	▲	▲	▲
Game performance	●	●	●	●	○	●	▲	○	▲	▲	▲	▲	▲	▲	○	○	▲
Multimedia performance	●	○	○	○	●	●	▲	●	▲	▲	▲	▲	▲	●	●	●	▲
Network performance	○	●	●	●	▲	○	●	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲
Usability requirements	▲	▲	▲	▲	▲	▲	▲	○	●	●	●	●	▲	▲	▲	▲	●
Functional requirements	▲	●	▲	▲	▲	▲	●	●	▲	▲	●	▲	▲	●	▲	▲	▲

Table 9.3 Relationship between usability and the technical attributes

		Technical attributes													
		Optical drive	**Keyboard**				**Mouse**				**Case**			**Mon--itor**	**Card reader**
Customer Requirements	**Usability**	Front panel	Functions	Shape	Comfort	Wireless	Color	Shape	Comfort	Wireless	Front connectors	Status indicators	Remote control	Control panel	Additional I/O ports
	Easy to control	6	7	9	9	9	1	9	9	9	9	9	9	9	9
	Easy to maintain	6	5	1	5	5	1	5	5	5	9	9	5	5	5
	Easy to connect	8	1	1	3	9	1	3	3	9	6	5	1	1	9

9.2.3. Analyzing the relationships among the TAs

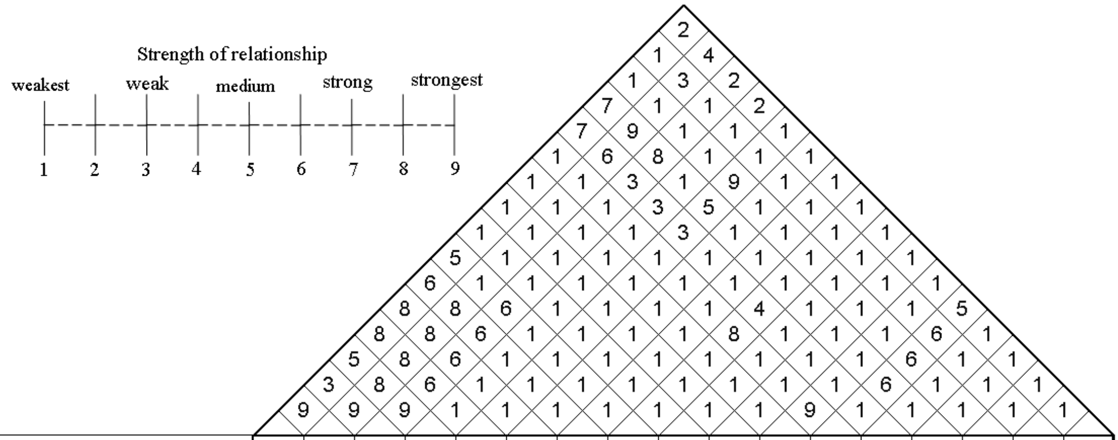
In this case study, the technical attributes were also analyzed at the component level as shown in Figure 9.4. The relationships among the technical attributes were normalized using Wasserman's (1993) model. The results are shown in Table 9.4. From Table 9.1 and 9.4, the normalized importance weight of each technical attribute was derived using the following formula:

$$Taw_j = \sum_{i=1}^{m} w_i R_{ij}^{norm} \Bigg/ \sum_{j=1}^{n} \sum_{i=1}^{m} w_i R_{ij}^{norm} \tag{9.1}$$

where Taw_j is the importance weight of technical attribute j. The results are shown in the last row of Table 9.4.

9.3. Optimizing product design using Kano's model and goal programming

The importance weights of the customer requirements and the technical attributes give only a general impression of the issues faced by the product designer. It does not provide guidance in terms of solving the design issues. Kano's model and goal programming are useful in this regard. Kano's model provides an effective way to categorize customer requirements. This helps to understand the nature of customer requirements by categorizing them as "must be", "attractive", and "exciting". In this case study, an approach combining Kano's model and goal programming (Lai *et al.*, 2004) is used to achieve optimal product design. To implement the optimization method, additional information was added to the HOQ.



Customer requirements \ Technical attributes	CPU	Motherboard	Ram	Hard disk	Sound card	Graphic card	Network card	Optical drive	Keyboard	Mouse	Case	Decorations	Power supply	TV/Radio tuner	Speaker	Monitor	Card Reader
Smaller size	1	1	1	1	1	1	1	5	7	5	9	5	1	1	6	9	1
Good appearance	1	1	1	1	1	1	1	6	7	5	9	5	1	6	8	9	1
Better decoration	1	1	1	1	1	1	1	1	1	1	4	9	1	1	1	1	1
Business performance	9	9	9	9	6	7	3	5	2	2	1	1	1	2	1	5	3
Game performance	9	9	9	9	7	9	6	8	2	3	1	1	1	2	9	7	1
DVD playback quality	9	9	8	5	8	6	5	8	1	1	1	1	1	2	7	6	1
Audio performance	7	9	7	3	9	1	3	5	1	1	1	1	1	2	9	1	1
Display performance	6	7	7	3	1	7	5	2	1	1	1	1	1	2	1	9	1
Network performance	6	9	6	3	3	3	9	2	1	1	1	1	1	2	1	1	1
TV/Radio function	5	6	6	3	7	6	1	1	1	1	1	1	1	9	5	5	1
Media record function	9	7	9	9	9	7	6	1	1	1	1	1	1	1	9	1	1
Media creation function	6	7	5	4	4	2	1	9	1	1	1	1	1	1	1	1	1
CPU over-clock function	3	9	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Wireless LAN function	3	3	2	1	1	1	9	1	1	1	1	1	1	1	1	1	1
Remote control function	3	3	1	1	1	1	5	1	9	9	1	1	1	9	1	1	1
Easy to control	1	1	1	1	1	1	1	6	9	9	5	1	1	1	1	7	6
Easy to maintain	1	6	1	1	1	1	1	2	3	3	9	1	1	1	1	7	1
Easy to connect	1	6	1	1	1	1	9	7	6	7	9	1	1	6	1	5	9

Figure 9.4 Body and roof of the HOQ

Table 9.4 The normalized relationship matrix

Customer requirements \ Technical Attributes	CPU	Motherboard	Ram	Hard disk	Sound card	Graphic card	Network card	Optical drive	Keyboard	Mouse	Case	Decoration	Power supply	TV/Radio tuner	Speakers	Monitor	Card reader
Smaller size	0.06	0.06	0.06	0.04	0.06	0.04	0.04	0.07	0.05	0.04	0.08	0.13	0.04	0.05	0.06	0.07	0.04
Good appearance	0.07	0.07	0.07	0.04	0.07	0.04	0.03	0.06	0.05	0.04	0.07	0.13	0.04	0.06	0.06	0.06	0.04
Better decoration	0.06	0.07	0.06	0.04	0.05	0.04	0.04	0.08	0.03	0.03	0.10	0.11	0.04	0.08	0.06	0.06	0.06
Business performance	0.10	0.12	0.10	0.08	0.07	0.07	0.06	0.05	0.02	0.02	0.02	0.04	0.06	0.07	0.03	0.03	0.04
Game performance	0.10	0.11	0.10	0.07	0.08	0.07	0.06	0.05	0.02	0.02	0.02	0.05	0.06	0.07	0.05	0.04	0.03
DVD playback quality	0.10	0.11	0.10	0.07	0.09	0.07	0.06	0.05	0.02	0.02	0.02	0.05	0.06	0.07	0.05	0.03	0.03
Audio performance	0.10	0.11	0.09	0.07	0.10	0.06	0.06	0.05	0.02	0.02	0.02	0.05	0.06	0.08	0.06	0.03	0.03
Display performance	0.10	0.12	0.10	0.07	0.07	0.08	0.07	0.05	0.02	0.02	0.02	0.05	0.05	0.07	0.03	0.05	0.03
Network performance	0.10	0.12	0.10	0.07	0.08	0.07	0.08	0.04	0.02	0.02	0.02	0.04	0.06	0.08	0.03	0.03	0.04
TV/Radio function	0.10	0.12	0.10	0.06	0.09	0.07	0.05	0.04	0.02	0.02	0.02	0.06	0.05	0.09	0.05	0.04	0.03
Media record function	0.10	0.12	0.10	0.07	0.09	0.07	0.06	0.04	0.02	0.02	0.02	0.04	0.06	0.07	0.05	0.02	0.03
Media creation function	0.10	0.11	0.10	0.07	0.08	0.07	0.06	0.07	0.02	0.02	0.02	0.05	0.07	0.07	0.03	0.03	0.04
CPU over-clock function	0.10	0.11	0.09	0.07	0.08	0.07	0.07	0.04	0.02	0.02	0.03	0.04	0.06	0.09	0.03	0.03	0.04
Wireless LAN function	0.10	0.13	0.10	0.06	0.07	0.06	0.10	0.05	0.02	0.02	0.03	0.05	0.05	0.07	0.03	0.03	0.04
Remote control function	0.10	0.11	0.09	0.05	0.07	0.05	0.06	0.04	0.06	0.06	0.03	0.06	0.05	0.08	0.03	0.03	0.03
Easy to control	0.07	0.08	0.07	0.05	0.05	0.04	0.04	0.06	0.06	0.06	0.05	0.11	0.05	0.05	0.04	0.06	0.06
Easy to maintain	0.08	0.09	0.08	0.06	0.06	0.06	0.05	0.04	0.04	0.04	0.07	0.10	0.05	0.06	0.03	0.06	0.04
Easy to connect	0.09	0.10	0.09	0.05	0.05	0.04	0.06	0.05	0.04	0.04	0.05	0.10	0.05	0.06	0.03	0.04	0.06
Importance Weight	**0.09**	**0.10**	**0.09**	**0.06**	**0.07**	**0.06**	**0.06**	**0.05**	**0.03**	**0.03**	**0.04**	**0.07**	**0.05**	**0.07**	**0.04**	**0.04**	**0.04**

After analyzing the current market players, we set the target value (i.e., benchmark value) for each customer requirement as shown in the last column of Table 9.1. These values range from 0.0 to 1.0 representing the target customer satisfaction level. A higher value implies a higher target customer satisfaction level.

Cost is one of the most important constraints in PC design. The cost model in this case study was modelled the same as that in chapter 7. The minimum and maximum costs for each component are determined according to the experience of the design staff. At the same time, the minimum fulfilment level for each component was also determined. The same scale of 0.0 to 1.0 was used. Because there was a large pool of components available in the market, the fulfilment level was assumed to have a linear relationship with cost. The mathematical expression is:

$$TA_j = f_{\min j} + (x_j - c_{\min j})(1 - f_{\min j})/(c_{\max j} - c_{\min j}) \tag{9.2}$$

The detailed cost information is listed in Table 9.5. This information was used to construct the cost function for each technical attribute. In this case study, the cost limit is S$1503.

Table 9.5 Cost information and optimal results for the technical attributes

Technical attributes	Minimum fulfilment	Minimum cost (S$)	Maximum cost (S$)	Budget allocation (S$)	Optimized fulfilment
Card reader	0.85	20	30	30	1.00
Monitor	0.75	365	799	365	0.75
Speaker	0.65	20	160	130	0.93
TV/Radio tuner	0.65	66	119	119	1.00
Power supply	0.90	60	100	60	0.90
Decoration	0.50	10	100	100	1.00
Case	0.80	100	200	100	0.80
Mouse	0.75	8	45	45	1.00
Keyboard	0.75	8	60	8	0.75
Optical drive	0.80	70	169	70	0.80
Wireless network card	0.95	80	120	80	0.95
Graphic card	0.75	0	336	0	0.75
Sound card	0.85	0	119	0	0.85
Hard disk	0.70	110	228	110	0.70
Ram	0.65	67	200	67	0.65
Motherboard	0.80	120	220	120	0.80
CPU	0.50	99	285	99	0.50

The last step is to formulate the optimization model using the approach proposed by Lai *et al.* (2004). First, the customer satisfaction coefficient (CS) and the customer dissatisfaction coefficient (DS) of each customer requirement were determined. These were based on the experience of staff in the company. CS and DS are displayed in the third and forth columns of Table 9.1. Then, a goal programming model was established for this PC design problem. Matlab was used to solve the optimization problem.

The optimization model is:

$$Min \quad D = \sum_{i=1}^{18} (d_{1i} \times w_{1i} \times w_i + d_{2i} \times w_{2i} \times w_i) \tag{9.3}$$

Subject to:

$$w_{1i} = -DS_i - CS_i \tag{9.4}$$

$$w_{2i} = CS_i \tag{9.5}$$

$$y_i = \sum_{j=1}^{17} R_{ij}^{norm} TA_j \tag{9.6}$$

$$TA_j = f_{\min j} + (x_j - c_{\min j})(1 - f_{\min}) / (c_{\max j} - c_{\min j}) \tag{9.7}$$

$$y_i + d_{1i} \geq t_i \tag{9.8}$$

$$y_i + d_{2i} \geq 1 \tag{9.9}$$

$$B \geq \sum_{j=1}^{17} x_j \tag{9.10}$$

$$c_{\min j} \leq x_j \leq c_{\max j} \tag{9.11}$$

$$0 \leq d_{1i}, d_{2i} \leq 1 \tag{9.13}$$

Where t_i is the benchmark value of the classification of satisfaction level of the i^{th} customer requirement $i = 1, 2, \ldots 18$, x_j is the budget allocated to technical attribute *j and* B is the cost limit

Table 9.5 shows the optimized budget allocation for each technical attribute, and Table 9.6 shows the optimized fulfilment level for each customer requirement. The overall customer requirement satisfaction level is 0.84.

In the above discussion, we obtained the optimal value when the budget is S$1503. Then, we carried out a sensitivity analysis of the overall customer satisfaction level and the budget. Figure 9.5 shows the results. The overall customer satisfaction level increases steadily as the budget increases.

Table 9.6 Optimal results of customer requirements

Customer requirement	Relative importance weight	Fulfilment level	Target
Smaller size	5.70%	0.82	0.85
Good appearance	5.47%	0.83	0.80
Better decoration	4.59%	0.84	0.60
Business performance	6.29%	0.84	0.90
Game performance	6.22%	0.85	0.90
DVD playback quality	6.09%	0.85	0.60
Audio performance	6.16%	0.86	0.75
Display performance	6.32%	0.86	0.60
Network performance	4.62%	0.85	0.60
TV/Radio function	5.01%	0.85	0.80

Media record function	4.91%	0.84	0.80
Media creation function	5.63%	0.86	0.80
CPU over-clock function	4.65%	0.84	0.80
Wireless LAN function	4.72%	0.86	0.80
Remote control function	4.45%	0.84	0.80
Easy to control	6.65%	0.83	0.95
Easy to maintain	6.29%	0.85	0.85
Easy to connect	6.22%	0.83	0.80

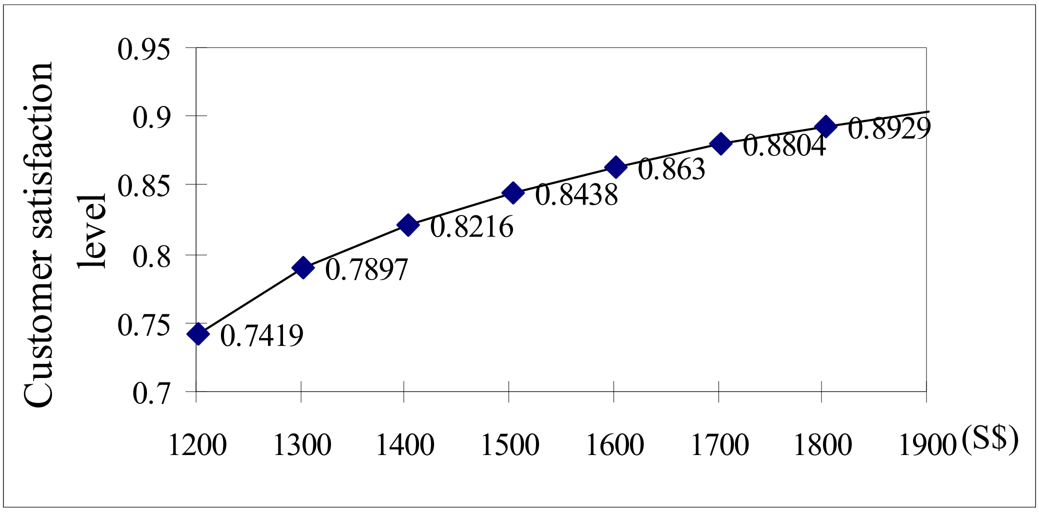


Figure 9.5 Relationship between customer satisfaction level and available budget

9.4. Findings of the case study

The results from the survey are important to emphasize the most important customer requirements. From the customers' perspective, *Easy to control*, *Display performance*, *Business performance*, *Easy to maintain*, *Game performance*, and *Easy to connect*, are the six most important requirements. As we can see from the results, the usability factor plays a critical role in customer requirements. *Business performance* and *Display performance* are also important to customers. This phenomenon is consistent with what we thought. Performance is no longer the most important requirement. Other aspects, e.g., usability, are getting more attention.

The six most important technical attributes are *CPU*, *Motherboard*, *Ram*, *Sound card*, *TV/Radio tuner*, and *Decorations*. It is not surprise that *CPU*, *Motherboard*, and *Ram* have the highest importance weights. This is because they determine most of a computer's performance and have a great impact on the other technical attributes. High importance weights on *Sound card*, *TV/Radio tuner*, and *Decorations* show customer requirements on entertainment, function, and appearance.

In Table 9.5, we can find the optimal budget allocation using Kano's model and goal programming. As can be seen, among the six most important technical attributes, only *Decorations* and *TV/Radio tuner* received 100% fulfilment. Other than these attributes, *Card reader* and *Mouse* also got 100% fulfilment. This is followed by *Wireless network card* (95%), *Speaker* (92.5%), and *Power supply* (90%). From a traditional perspective, it is not a customer-focused design. However, the optimized results are not surprising when considering the cost aspect. Although some technical attributes are important, their fulfilment levels are too costly to improve. Similarly, some technical attributes are important, but they are very costly to improve on. It may be more cost-effective to improve the less expensive technical attributes.

From Table 9.6, we can see the optimal results of the customer requirements fulfilment levels. Among the six most important customer requirements, only *Display performance* and *Easy to connect* exceeded the target. It seems that both the most important customer requirement and the most important technical attribute were not given enough attention in the optimized results. From the traditional perspective, this is not a customer-focused design. However, the optimized results are not surprising when considering the cost aspect. In the same way, although some customer requirements are important, they are too expensive to fulfil. Some other customer requirements, though not so important, are relatively inexpensive to fulfil. The dissatisfaction from unfulfilled customer requirements can be compensated by the satisfaction from fulfilled customer requirements. At the same time, the overall customer satisfaction was maximized, under the budget constraint.

9.5. Limitations of the case study

As well as its contributions, this case study on QFD methodology has some limitations. Some are due to the QFD methodology itself. Other limitations are of a more practical nature.

First, from an organizational point of view, QFD does little to consider the strategic requirement of an enterprise. In this case study, QFD was implemented at the product level. The ultimate goal would be to maximize the customer requirements and the strategic objectives of an enterprise. The QFD methodology itself lacks a systematic means to incorporate an organization's strategic objectives into product design.

Second, in this case study, the suppliers were not actively involved. The enterprise in this case essentially assembles the various parts of the PC. Therefore, the final product is largely restricted by the parts that are available. This enterprise is new and small. It has yet to establish long-term relationships with its suppliers. Therefore, this case study did not get much support from its suppliers, where technical and cost information are time-consuming to acquire.

Third, the marketing involvement in this case study was not sufficient. Marketing strategy can affect product design. Although the implemented QFD method provided an optimized product design under cost constraint, this advantage may not be immediately perceived by customers. Additional sales may be needed to promote the product.

The fourth limitation is on the brand of the product. Branding is a very important factor affecting customer purchase decision. However, this is inherited from the enterprise and is not a factor that can be controlled in this case study.

9.6. Recommendations on QFD implementation

A wider framework of the QFD methodology is needed. Usually in product design, customer requirements and cost are not the only considerations. Other requirements, e.g., schedule, technology availability, market strategy, supplier ability, etc, also need to be considered. An expanded QFD methodology is essential in order to improve the current practice of QFD implementation.

Quantitative methods can be used to improve the reliability of the QFD process. Subjective decisions made in the use of QFD are often accused by practitioners and researchers as being imprecise and vague. This greatly reduces the face validity of QFD. In this case study, a quantitative approach using goal programming and Kano's model was used to obtain an optimal product design.

Management support is essential in implementing QFD, especially when introducing it for the first time. Cristiano *et al.* (2001) concluded that management support is one key factor in the successful application of QFD. Much information is not readily available when implementing QFD for the first time. Moreover, QFD is a multi-department activity that requires the cooperation of people from different departments. Without management support, it is difficult for QFD practitioners to obtain the necessary resources, e.g., people, information, etc.

This chapter presents a case study on personal computer design. The findings demonstrate that quantitative QFD can be successfully implemented in product design. A wider framework of the QFD methodology and quantitative methods can improve the usefulness of QFD. Other non-technical aspects, e.g., management support, are essential to successful QFD implementation.

Chapter 10 Conclusions

As mentioned in Chapter 1, this dissertation is mainly concerned with quantitative optimization issues involved in QFD. In the previous nine chapters, these issues were introduced, analyzed, and discussed in detail.

The background of this study and the literature review on QFD were presented in Chapter 1 and Chapter 2 respectively. Chapter 3 and Chapter 4 dealt with two major components involved in QFD, i.e., the voice of the customer and the relationship measurement among technical attributes. The following 4 chapters focused on the QFD optimization model. A case study on the application of QFD in personal computer design was provided in Chapter 9.

In this concluding chapter, discussions and conclusions on this dissertation are given. Specifically, some major contributions of the current study to the QFD optimization methodology development will be highlighted. In the end of this chapter, due to the shortcomings and limitations involved in this research, some suggestions and recommendations for future work are also covered.

10.1. Major findings and contributions

Various topics have been discussed in this dissertation, with the ultimate aim of improving the QFD quantitative optimization methodology. Based on the detailed discussions in the previous chapters, the major findings and contributions of this dissertation are summarized as follows.

As the main input of house of quality, the voice of the customer plays an important role in the use of this methodology. In this dissertation, the discussion was focused on ranking the customer requirements from a competitive point of view. The managerial implication of this method is explicit: QFD can direct companies to win the competition in the market. Although some customer requirements are very important from the customer perspective, if one's own product performs very well in these customer requirements, the design teams should not spend too much time and incur too much cost on these customer requirements. Consequently, these customer requirements should be given lower rankings. Compared with previous method, the proposed method puts more emphasis on those aspects where one's own product performs worse than products of competitors. More emphasis on these aspects indicates that the proposed method can provide a strategy to succeed in the market competition.

Another important contribution relating to the input of house of quality is on the new approach to analyze the interrelationship among technical attributes. After Wasserman (1993) proposed his model, little advancement in this field was reported. According to our understanding, this is the first chapter that focuses solely on the roof of HOQ. In Chapter 4, the properties of a good method were first summarized. And based on these properties, the previous research results in this field were reviewed. All the previous methods have some kinds of deficiencies. The proposed approach in Chapter 4 overcomes all the deficiencies in the previous methods. The interdependency among technical attributes is very important and widely used in quantitative QFD methodology development; the proposed method can greatly improve the accurateness of QFD.

The above topics discussed in this dissertation are basically concerned with the input of the HOQ to ensure the completeness and accuracy. Yet it is the output of the HOQ that is beneficial to companies. The quality, accuracy and effectiveness of the output of QFD are essential. In view of this need, research effort has been put into the development of QFD quantitative optimization method.

The generalized QFD optimization framework proposed in Chapter 5 did not introduce any fancy and complicated mathematical formulas. However, it is very useful to learners, researchers and practitioners of QFD because most current and further research of QFD optimization method can also be identified based on this framework. It can be used as a guide to QFD optimization method by learners and practitioners and a foundation of QFD optimization research by researchers. It is the first published generalized QFD quantitative optimization framework.

Three difference QFD optimization methods were discussed in Chapters 6, 7 and 8 respectively. Each method has its own distinctive contributions. The "Dynamic Programming for QFD Optimization" deals with the discrete feasible values of technical attributes while most other published methods with only continuous situations. This method are most suitable to the products that using modular design. Compared with previous method mentioned in Chapter 6, this one is easier to implement in terms of the complexity of input data and the feasibility of final results is guarantied.

In Chapter 7, an approach combining the Kano Model and Quality Function deployment (QFD) is proposed to meet customer requirements in product design. The Kano model provides an effective way to categorizing customer requirements and helps understand the nature of these requirements. By combining the two methods, we can provide a new way to optimize the product design. The proposed methods can be useful to both practitioners and researchers.

The approach introduced in Chapter 8 utilized linear physical programming. This makes this method have a unique feature that gives a different priority to each customer requirement when the requirements are at different stages. The weight algorithm used in this method can also provide a way to use information concerning one's competitors. With keen competition, taking into consideration such information in product design is very important.

A case study utilizing QFD in personal computer design was presented in Chapter 9. In recent years, many quantitative QFD methods have been developed. However, there have been few case studies reported on their use. The case study findings demonstrate that quantitative QFD can be successfully implemented in product design. Some limitations are highlighted. Practical suggestions on implementing quantitative QFD are discussed also.

10.2. Limitations and recommendations for future research

Advancements of QFD quantitative methodology have been made in this dissertation. Major findings and contributions were summarized as above. Nevertheless, due to the limitations involved in the current study, much more research needs to be carried out for QFD's further improvement.

As stated in Chapter 2, this thesis focused on the first phase of QFD, house of quality, because all other three phases are similar. However, it would be beneficial to extend it into the whole QFD process since enterprises may not only use the HoQ. Extension to the whole QFD process may make the QFD implementation easier.

Similarly, this thesis did not touch the "Matrix of Matrices" QFD process models because most current QFD papers focus on the four-phase model that is developed by Hauser and Clausing (1988). Howver, Akao's model is worthwhile to do some research, for example, a survey on the comparative study of the application of the two process models.

Another limitation of this research is that it has only one case study. As most of the research effort has been put into the development of new methodologies and the further improvements of the QFD quantitative optimization methodology, limited attention could have been devoted to the applications and case studies. Some more case studies for these approaches proposed in this thesis are desirable because more case studies and applications can improve the robustness of the proposed approaches and methodologies. However, all the methodologies proposed in this research are theoretically feasible, valid and illustrated using examples.

Computerization of proposed methods will be very useful although it may not have any theoretical contribution. All the newly developed methods presented in this thesis involve various kinds of analyses and computational work. In this research Matlab is used to solve this problem, but these programs were developed case by case only. Software with graphic user interface can make these methods much easier for companies to user.

The above points of further research are based on the limitations in current dissertation. From a broader perspective, some important and interesting research topics, which may or may not have close relationship with this dissertation, are recommended below for future research.

The first one is comparative study of quantitative QFD methods. Comparison of different methods exists at the literature part of most papers. However, these comparisons are theoretical in nature and the comparison standard varies according to the focuses of different papers. Therefore, a comparative study of existing quantitative QFD methods may propose a set of criteria to compare different quantitative QFD methods. And in this way, it can also serve a guide for enterprises to choose the most suitable methods.

The second one is empirical study of implementation of quantitative QFD method. There are a lot of papers on the study of implementation of QFD, but none of them focuses on quantitative QFD method. As a lot of quantitative methods have been published, it is worthwhile to investigate the application of them. This study can explore various factors of successful and efficient implementation of quantitative QFD methods. It may result in tremendous contribution if those successful and unsuccessful factors could be identified.

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