UNIVERSITY OF CALGARY

Customer and Supplier Involved One-of-a-Kind Product Design and Manufacture

by

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A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE

DEGREE OF MASTER OF SCIENCE

DEPARTMENT OF MECHANICAL AND MANUFACTURING ENGINEERING

CALGARY, ALBERTA

JANUARY 2010

UNIVERSITY OF CALGARY

FACULTY OF GRADUATE STUDIES

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Abstract

In this research, a systematic and optimal methodology based on quality function deployment (QFD) is developed to include the voices of both customers and suppliers. This new paradigm is important for one-of-a-kind (OKP) product development to improve customer satisfaction and shorten the time-to-market. The proposed research aims at achieving the following objectives: (1) investigation of a customer and supplier involved QFD planning methodology in OKP; (2) study characteristics and quantitative formulation of customer requirements, technical attributes and part characteristics; (3) develop quantitative techniques and methods for the integration and optimization of the OKP product development process; (4) a customized product design in Gienow Windows & Doors is used as the case study to demonstrate the feasibility and effectiveness of OKP product development.

Acknowledgements

First, I would like to express my sincere gratitude to my supervisor Dr. Yiliu Tu. He provided me the opportunity to do the research I have accomplished in this thesis. The quality of this thesis would have been diminished without his brilliant ideas and financial support. I am also thankful to my co-supervisor Dr. Deyi Xue for his continuous guidance and help through my master studies. He is very generous to have shared his time, knowledge and experience with me.

I would also like to thank Dr. Van Enns, Dr. Alejandro Ramirez-Serrano and Dr. Abraham Fapojuwo, my thesis defence committee members, for their very constructive suggestions and comments on my research.

I would like to thank many people at Gienow Windows & Doors who provided much help in my research project. Special thanks are due to Dr. Paul Dean, VP of IT in Gienow, for generously providing many insights, and helping me to understand the problem and gather various data.

Many thanks to all my colleagues in this research group: Mr. Wei Li, Mr. Gang Hong, and Mr. Gang Chang for their support.

Financial support from Alberta Ingenuity Funding (AIF) of Canada through its Industrial program is also acknowledged.

Last but not least, I would like to thank my beloved family, my husband Sam Na and my daughter Sierra Na.

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CHAPTER 1: INTRODUCTION

1.1 Background and Motivation

The rapid development of communication technology is starting to allow for a greater involvement of customers and suppliers in the design and manufacture of a product. Involvement of customers and suppliers in the whole product development life cycle is a new manufacturing paradigm which has the potential of reaping substantial benefits. This new paradigm is even more important for one-of-a-kind product development due to its features such as: (1) 'once' successful development, i.e. no prototype is produced throughout the development life cycle; (2) product design, testing, and production are carried out concurrently; and (3) product requirements can be changed at any time in the product development cycle due to continuous customer involvement and uncertainties from the complex supply chain.

Early supplier involvement (ESI) in product development (PD) has been recognized as a potentially effective means of improving product quality, reducing costs, and shortening PD lead-time by many manufacturing companies (Huang and Mak 2000; Gary and Handfield 2002). In recent years, significant progress has been made in planning research using quality function deployment (QFD) to maximize overall customer satisfaction, minimizing product development lead-time and cost. Some methods used are: mathematical programming, fuzzy logic, prioritization-based heuristics and multi-criteria decision making theory (Sohn and Choi 2001; Karsak and Sozer 2002). However, most of these methods focus on product planning and simply formulate target determination problem as linear programming models. Parts deployment and process planning as well as integration with product planning are often overlooked (Tang et al. 2005).

Part deployment and process planning as well as their integration with product planning, along with the mechanism and methodologies of customer and supplier involvement in OKP, are worth being thoroughly investigated or researched.

1.2 Research Objective and Methodology

The objective of this research is to develop a systematic and optimal approach to shorten the time-to-market for one-of-a-kind production (OKP) companies which produce customized products within a certain product domain (i.e. kind in OKP). To achieve this objective, QFD-based methods are employed. Customized products from Gienow Windows & Doors are developed using the proposed method to test effectiveness and feasibility of the concepts, methods and optimization models in this research.

The proposed research program aims at achieving the following objectives: (1) investigation into a customer and supplier involved QFD (CSI-QFD) planning methodology; (2) study of the characteristics and quantitative formulation of customer requirements and suppliers evaluation; and (3) development of quantitative techniques and methods for the integration and optimization of the OKP development process. The proposed objectives and expected deliverables of this research program are original and will fill the gap between the shortage of technology and the manufacturing companies' needs for customer and supplier involved product development.

Gienow Windows & Doors is a typical OKP company in Calgary and customer requirements are diverse. Products are designed and manufactured according to small-batch-sized customer orders. This thesis will apply several operations research (OR) methods and QFD techniques to assist Gienow in developing/improving existing product development process.

1.3 Structure of the Thesis

In addition to this chapter, the thesis includes five other chapters which are briefly summarised as follows:

Chapter 2 gives a literature review on the research background and related technologies in new product development (NPD). The key issues in product development, including QFD-based product development, mathematical programming, fuzzy optimization, etc., are reviewed and discussed in this chapter.

Chapter 3 and 4 discuss the issues of customer requirement identification and design knowledge representation. Starting with the house of quality (HoQ), the analytic network process (ANP) is employed to determine the relationships between customer requirements and technical attributes. Furthermore, mathematical programming is presented to include important levels of technical attributes (TAs) derived using the ANP and cost budget to determine the TAs considered in designing the product. A case study is presented to illustrate the application of the decision approach

Chapter 5 focuses on synthesis evaluation and selection of the part design scheme in the part deployment process. The concepts of performance indicator (PI) and integrated performance indicators (IPI) are introduced to measure the performance of the part design scheme and product design scheme respectively. A two-layer fuzzy synthesis evaluation method is applied to assess the part design scheme in a supplier-involved new product development process. Combining the information of house of quality (HoQ) and evaluation results of the part design scheme and taking into account the design budget, a 0-1 integer programming model is developed for selection of the parts combinatorial scheme in supplier-involved part deployment processes.

Chapter 6 draws conclusions and outlines possible future research topics.

CHAPTER 2: LITERATURE REVIEW AND RELATED TECHNOLOGIES

2.1 Overview of One-of-a-Kind Production (OKP)

The one-of-a-kind production (OKP) phenomenon was originally found in heavy industry (e.g. ship building, power plant building, etc.). According to Wortmann et al. (1997), an OKP company is a particular type of manufacturing company which make customized products within a product domain. A comprehensive literature review of features and a clear definition of OKP are given by Tu (1996), which is summarized later in this chapter. The EEC (European Economic Community) research program, 'ESPRIT basic research action 3143 – Factory of Future (FOF) production theory' (Rolstadås 1991), envisaged that OKP would become a novel manufacturing paradigm in 21st century along with a clear market trend toward customization and responsiveness. Today, more and more general manufacturing firms are moving toward OKP to gain greater variety and rapid product development, superimposed on traditional requirements of high quality and low cost. The ability to mass produce customized products is critical for a general manufacturing company to successfully implement an OKP system.

Due to the advantages of OKP as mentioned above, the OKP mode is becoming a promising manufacturing paradigm for manufacturing companies, particularly for small and medium sized enterprises (SMEs) in developed countries like Canada. As summarized by Tu et al. (2006), a general OKP company normally demonstrates the following characteristics:

1. 'Once' (singular) successful approach on the product, i.e. no prototype or specimen will be made in OKP, and the batch size can be one.

2. Product is usually designed by modifying and combining existing products to avoid the risk of long lead time and high costs for developing a radically innovative product.

3. Frequent changes of product design, manufacturing processes, and production schedules due to changes in customer requirements, arrivals of customer orders or raw materials, and manufacturing processes, as well as machine break-downs.

4. Mix-product production.

5. Frequent changes of production systems to adapt customized product production requirements.

6. Optimal utilization of technologies and resources to continually improve production efficiency and reduce production costs.

OKP products are variations of standard configurations and are typically developed in response to specific orders by customers. Development of OKP products primarily consists of setting values of design variables such as physical dimensions, materials, functional modules, etc. When a customer order is placed, OKP manufacturers would rather modify an existing product to meet customer requirements than completely design and create a new product (Li et al. 2006) .

The success of an OKP company depends on its ability to identify the needs of customers, quickly create a product that meets customer requirements and can be produced at a low cost. To achieve both high scale of economy and customization is a dilemma in traditional manufacturing businesses. This is not solely a marketing problem, nor solely a design problem or a manufacturing problem; it is a product development problem involving all of these problems (Ulrich and Eppinger 2000). Within a given budget, quickly developing an OKP product which meets customer requirements is critical for the survival of an OKP company.

2.2 Introduction to New Product Development (NPD)

In a global market environment, how to develop a new product with short lead time, cheaper prices and better quality is becoming one of the key factors for a manufacturing enterprise to gain market competitiveness. New product development (NPD) is a complex information and business process with multiple stages, including marketing research, product planning, engineering, testing and manufacturing, and involves several factors, e.g. time, quality, cost, facilities and resources (technology, information, materials, finance and technical/manpower). It is also a complex planning and decision process, and must be managed efficiently and effectively as a planning activity not only in internal scope but also in a supply chain. Effective planning and control are key activities and means to ensure high quality, low-cost and short development time in implementing and achieving NPD successfully.

NPD can originate from new technologies or new market opportunities (Eliashberg et al. 1997). But irrespective of where opportunities originate, customers are always the ultimate judges of the success of new product development (Brown and Eisenhardt 1995). Hence, in order to develop successful new products, manufacturers need a deep understanding of "customer requirements" (CRs) and establish product target specifications based on the needs of customers to guide the whole process of new product development.

New products can be grouped into several categories. Some are new to the market, some are new to the company and some are completely novel and create totally new markets. When viewed against a different criterion, some new product concepts are merely minor modifications of existing products while some are completely innovative to the company

In general, a customer-oriented product development process consists of seven phases, which are illustrated in Figure 2.1 (Ulrich and Eppinger 2000). The process begins with identifying customer requirements. The output of this stage is a set of carefully constructed customer requirement statements with importance weight for each requirement.

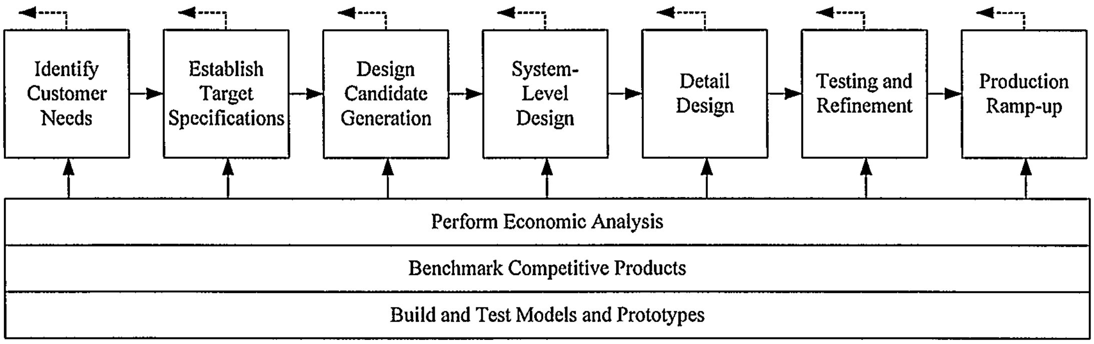


Figure 2.1 A generic process of new product development (NPD) (Ulrich and Eppinger 2000).

These steps may be iterated as needed. Some steps may be eliminated. To reduce the time that the NPD process takes, many companies are complete several steps at the same time (referred to as concurrent engineering or time to market). Most industry leaders see new product development as a proactive process where resources are allocated to identify market changes and seize upon new product opportunities before they occur (in contrast to a reactive strategy in which nothing is done until problems occur or the competitor introduces an innovation). Many industry leaders see new product development as an ongoing process (referred to as continuous development) in which the entire organization is always looking for opportunities.

For more innovative products, great amounts of uncertainty and change may exist, which makes it difficult or impossible to plan the complete project before starting it. In this case, a more flexible approach may be advisable.

In a traditional new product development process, the product design and development is carried out by a design team, whose members are normally come from different functional departments. This process neglects the supplier's roles in part and process design, subcontracting and product. The suppliers' participation in a NPD process is limited to supplying parts and/or materials, and subsequently there exist a large gap between the requirement and specification of designed parts and that of the supplied parts (Herrmann et al. 2000). Without supplier's involvement in the NPD process, product parts design and production are separated, which results in the supplier's information on the parts, e.g. specifications and performance , time availability, and cost of parts, as well as the supplier's reputation and core design and production capability are inaccessible to the design and manufacturing enterprise. It results in higher cost, longer time-to-market and unreliable quality (Dre et al. 2000; Tang et al. 2004).

In observing the benefits of the integration of external sources of innovation into the NPD process, many firms are inviting suppliers to be part of the firm's production and design process. Innovative ties between the lead manufacturer and a nearby set of outside suppliers play a fundamental role in making flexibility possible, and they are considered a major key to a shorter development cycle and better products. The potential benefits of strategic alliances with outside firms are receiving much attention (Bonaccorsi and Lipparini 1994).

2.3 QFD-based Product Design

2.3.1 Quality Function Development

Quality function deployment (QFD), which originated in the early 1970s in Japan, is an overall concept that provides an efficient means to plan product design activities. These activities start with customer requirements, include product planning, part planning, process planning and production planning ending with the product (Akao 1990). It is a methodology that can be used during early stages of product design to make better customer-focused decisions, clearer project budgets, project quality definitions, and be responsive to customer requirements (Sharma et al. 2006). QFD focuses on delivering value by seeking out customer's real needs, translating these needs into actions, designs and communicating with the whole organization. QFD allows customers to prioritize their needs, and benchmark a manufacturer against its competitors. The customer can direct the manufacturers to optimize those aspects of their products and organization that will bring the greatest competitive advantage. Traditional quality systems aim at minimizing negative quality, such as defects, whereas the QFD method concentrates on maximizing positive qualities, for example customer satisfactions. The earliest QFD models focused on assuring quality in the factory so that production processes would deliver goods as designed. In recent years, the QFD method has been applied to place its focus on the upstream process of product design in order to improve the quality of the product design itself.

2.3.2 House of Quality (HoQ)

Hauser and Clausing (1988) presented a method that attempted to determine the values of engineering requirements using a procedure called "house of quality" (HoQ) illustrated in Figure 2.2.

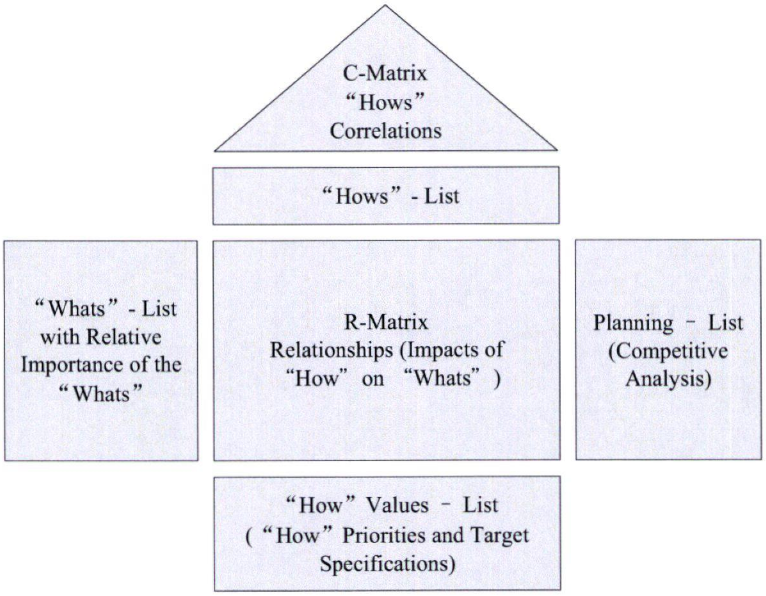


Figure 2.2 House of quality (HoQ)

With its design-oriented nature, the HoQ serves not only as a valuable resource for designers but also as a way to summarize and convert feedback from customers into information for engineers (Chen and Ko 2009). In addition, marketing research can benefit since it is based on the "voice of customer", and upper-level management can use it to develop strategic opportunities. As a result, the HoQ strengthens vertical and horizontal communications in a company. Once having identified critical TAs that demand change, these TAs will be driven to the next matrix as 'Whats' to identify the critical parts characteristics. Similarly, the manufacturing operations, and day-to-day operations and controls are defined. In this way, the company can efficiently develop a product to fulfill both customer needs and its own requirements.

With QFD, the HoQ provides an efficient tool to translate customer requirements (CRs) into technical attributes (TAs), and subsequently into parts or part characteristics, process plans and production requirements. In order to establish these relationships, the HoQ usually requires four matrices, each corresponding to a stage of the product development cycle. The stages are product planning, part deployment, process planning, and production planning matrices. The four HoQs are illustrated in Figure 2.3.

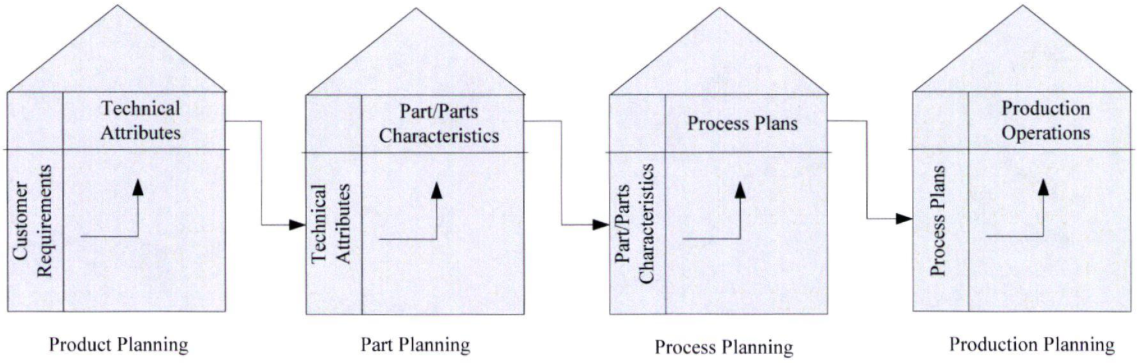


Figure 2.3 The four HoQs

In the first HoQ phase (HoQ1), customer requirements (CRs) are represented at the left side of the HoQ. The relative importance factors between CRs play an important role in identifying critical CRs and prioritizing design efforts. Technical attributes (TAs) are the design requirements that affect one or more of customer requirements. The importance ratings for TAs are calculated using CRs importance ratings and weights assigned to the relationships between CRs and TAs. The matrix in the main body of the HoQ identifies the relationships between the CRs and TAs. The "Roof" part of the HoQ establishes the correlation among the TAs. The right side of the HoQ lists a competitive benchmarking on each customer requirement for the company's and competitors' product. Target levels of technical attributes are determined using all the information in the HoQ (Han et al. 2004).

In the second HoQ (HoQ2), technical attributes (TAs) are inputs of the HoQ2 as the "what", and the parts or part characteristics are the "how" to meet the TAs. Similarly, in the third HoQ (HoQ3), parts or part characteristics are translated into process plans or manufacturing operations. These processes or manufacturing operations are then translated into day-to-day production operations and controls in the fourth HoQ (HoQ4). The four HoQs have the same structure and components. The components in each HoQ may have different meanings. In this thesis, the product development process model is developed based on the first two HoQs (also called product planning matrix and part planning matrix) to improve the design quality through understanding the customer requirements.

2.3.3 Analytic Network Process and Its Usage in Quality Function Deployment

The analytical hierarchy process (AHP) is a well-known technique that decomposes a problem into several levels in such a way that they form a hierarchy. Analytic network process (ANP) enables interrelationships among decision levels and attributes to be taken into consideration in a more general form. The ANP procedure generalizes the AHP as a widely used multi-criteria decision-making tool by replacing hierarchies with networks.

Some research work has used ANP to determine the degrees of importance of customer requirements (Park and Kim 1998). Partovi and Corredoira (2002) presented a QFD model based on ANP for prioritizing and designing rule changes for the game of soccer in order to make it more attractive to soccer enthusiasts. Partovi and Epperly (2001) presented an analytical method for quantifying Heskett's "strategic service vision". In the model, analytical hierarchy analysis is used to determine the intensity of the relationship between the row and column variables of each matrix, while the ANP is used to determine the intensity of synergy effects among column variables. Karsak et al. (2002) achieved product planning in QFD using a combined ANP and goal programming approach.

Recently, a more general form of ANP approach, which incorporates feedback and interdependent relationships among decision attributes and alternatives, has been proposed as an accurate approach for modeling complex decision environments (Karsak et al. 2002). While outer dependence implies the dependence among components allowing for the feedback circuits, inner dependence is related to the dependence within a component combined with feedback from components. Systems-with-feedback can be illustrated in a hierarchical structure. In the graphical representation, there are two-way arcs between levels. First, a looped arc is used to show the inner-dependency relationships that occur within the same level of analysis. Second, a hierarchical arc is used to show a dominance or control of one level of attributes over another set of sub-components or attributes. A linear hierarchy with no feedback and inner-dependency representation is given in Figure 2.4.

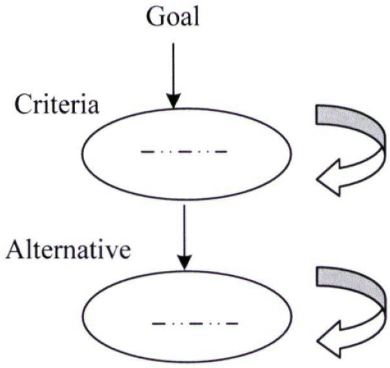
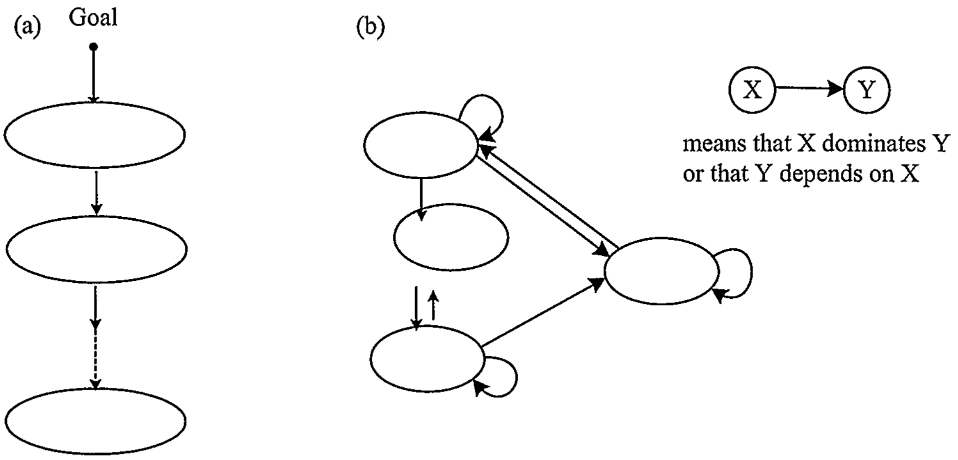


Figure 2.4 Linear hierarchy with no feedback and inner-dependence

This representation is also suitable for a general network of QFD models. After construction of the network, the calculation of priorities of elements defined by a vectors is required. In order to construct the structure of the problem, the relationships between the inner-actions and the interactions among the elements should be evaluated. These relations are evaluated by pairwise comparisons and a super-matrix (a matrix representing influence among the elements) using priority vectors. The super-matrix is proposed to limit powers to calculate overall priorities, and thus the cumulative influence of each element on every other element with which it interacts is obtained (Saaty 1996). When a network consists of only two clusters, criteria and alternatives, the matrix manipulation approach proposed by Saaty and Takizawa (1986) can be employed to deal with the dependencies of the elements of a system. This approach incorporates the dependencies inherent in QFD network processes. The super-matrix representation of QFD network processes is composed of the following three levels:

$$\mathbf{W} = \begin{array}{rccc} & G & C & A \\ \text{Goal(G)} & 0 & 0 & 0 \\ \text{Criteria(C)} & \mathbf{w}_{21} & 0 & 0 \\ \text{Alternatives(A)} & 0 & \mathbf{w}_{32} & \mathbf{I} \end{array}$$

where $\mathbf{w}_{21}$ is a vector that represents the impact of the goal on the criteria, $\mathbf{w}_{32}$ is a matrix that represents the impact of the criteria on each of the alternatives, and **I** is the identity matrix.



(a) A hierarchy. (b) A nonlinear network

Figure 2.5 Difference between hierarchy and network structures

2.3.3 Other Related Research on QFD

Many works have been produced on QFD from various aspects of theory and methodology, software systems and application engineering. QFD is now becoming a widely used customer-driven approach to ensure product quality and customer satisfaction in NPD (new production development), particularly in concurrent engineering (CE) environments. Chan and Wu (2002) conducted a comprehensive literature review and analysis of QFD's functional fields, applied industries and methodology development. The purpose of this review was to offer the researchers and practitioners an easy way to learn the state-of-the-art knowledge and applications in this research area.

Many new concepts, particularly several versions of QFD such as fuzzy QFD, extended QFD, dynamic QFD, product attribute function deployment (PAFD), and concurrent function deployment (CFD), have been developed and reported (Kim et al. 2000; Chan and Wu 2002; Sharma et al. 2006; Hoyle and Wei 2009). The recent development of methodologies, software tools and applications are summarized and reported by Chan and Wu(2002).

Of the four planning processes (product, parts, processes and production), most research is focused on product planning (Wasserman 1993; Kim et al. 2000; Shen et al. 2001; Sobrero and Roberts 2002; Fung et al. 2003), while little research has been reported on the latter three planning processes (Gui et al. 2003; Chen et al. 2005). In this aspect, Iranmanesh et al. (2005) recently developed a two-phase based QFD to craft a team that would determine an optimal design strategy to achieve higher customer satisfaction.

2.4 Supplier Involved Product Development

One of the major themes is the need to mobilize not only internal resources, but also external participants in NPD. In fact, the development process includes a set of activities that involve functions, both within and outside the firm. The increase of technological complexity and product performance makes the set of relationships with suppliers important to any firm's success.

2.4.1 Supplier Selection in Product Development

The benefits of involving suppliers in the product development process were summarized by Humphreys et al. (2007) as: 1) Enhancing information and expertise regarding new ideas and technology, allowing early identification of potential problems, improving the quality of the final product, eliminating rework and reducing costs; 2) Providing a possible route for outsourcing that can reduce the internal complexity of projects and provide for extra resources that can lead to a reduction in the critical path of the project; 3) Improving communication and information exchanges that reduce delays and ensure that the project is completed on time; 4) Improving buyer-supplier relationships; 5) Reducing development costs, providing early availability of prototypes, allowing for standardization of components, reducing engineering changes and leading to higher quality with fewer defects.

Today, companies give suppliers increasing responsibilities with regard to product design, development and engineering (Wynstra et al. 2001). Supplier selection decisions need to incorporate design criteria into the assessment process (Humphreys et al. 2007). In comparison with the traditional procurement environment, both the objectives and the constraints in supplier selection within product development are different. Maximizing customer requirements is the most important goal. Cost-related issues such as fixed and variable product costs could be either the objectives or the constraints.

2.4.2 Early Supplier Involvement in New Product Development

With the advances in information technology (IT) and emergence of supply chain management, many enterprises are changing the ways they develop new products. One apparent trend is to involve external business partners, particularly the suppliers, in their product development activities. Earlier supplier involvement (ESI) in NPD has become a popular means for improving product quality, reducing costs, and shortening delivery lead time in a highly competitive global market (Bidault and Butler 1998; Holmenand and Kristensen 1998; Wynstra and Pierick 2000; Maffin and Braiden 2001; Huang et al. 2003). For example, Bidault and Butler (1998) conducted an empirical study of ESI practices in twenty-five companies at the conceptual design stage of NPD, and suggested a model to guide ESI adoption. Holmanand and Kristensen (1998) examined supplier's role in NPD through task partitioning, and pointed out the roles of design consultation, components and parts supplying. LaBahn and Krapfel (2000) proposed some hypotheses of positive influences on suppliers with ESI. Wynstra and Pierick (2000) listed four types of possible supply involvement and developed a portfolio approach to distinguish them. Maffin and Braiden (2001) applied comparative analysis and benchmarking to investigate the roles of both manufacturers and suppliers in NPD by interviewing forty-six electrical and mechanical engineering companies in the UK. Toni and Nassimbeni (2001) established a model framework for analyzing and evaluating the supplier's co-design in buyer's NPD activities. Ragatz et al. (2002) developed a model for testing the effects of supplier integration on product quality, costs and development lead time under technical uncertainties. Sobrero and Roberts (2002) discussed the effects of conceptual and organizational relationship between suppliers and manufacturers on NPD. Caputo and

Zirpoli (2002) discussed motivations, modalities and consequences of supplier involvement in an automotive component design and presented an exploratory study on a major European car maker and two of its suppliers. Huang et al. (2003) proposed a prototype web-based framework for supporting and facilitating early supplier involvement in new product development.

Related research reveals the following three observations. First, supplier involvement including ESI is an emerging and important research area both for the research community and practitioners (Huang and Mak 2000; Wynstra and Pierick 2000; Wynstra et al. 2001). Customer-supplier interface now plays a key role in the design and development of complex new products. Significant benefits can be achieved if suppliers are involved in product development phases as early as possible (Huang and Mak 2000; Wynstra et al. 2001). Customers now require their suppliers to be more involved in product development, now shifting some design and engineering responsibilities to outside specialists. While the benefits of ESI are acknowledged, recent investigations in manufacturing industries have revealed that this approach is not widely practised in industries and its implementation has been a great challenge to researchers and practitioners (Huang and Mak 2000).

Second, while organizational aspects of ESI have received much attention, the mechanism by which suppliers are incorporated into the customer's engineering design process in practice has not been well investigated. This has been recognized by recent studies (Huang and Mark 2000; Wynstra et al. 2001). Even though the importance of ESI is acknowledged, early involvement in NPD is extremely difficult to achieve. Huang and

Mak (2000) reviewed a number of methodologies to support ESI. However, they found them of limited value because they did not "model and analyse the interfaces between customers and suppliers". According to Wynstra et al. (2001), the identification of processes and tasks that need to be carried out should pay more attention to complex issues facing manufacturers in achieving effective and efficient supplier involvement during product development.

Third, identifying where suppliers are integrated in the customer's engineering processes also facilitates quick reaction to engineering changes. While it is necessary to identify the impact of changes from customers and suppliers, recent literature discussing engineering changes only addresses changes within a single company. Efforts are lacking managing engineering changes within a customer-supplier relationship.

2.4.3 Models and Methods

In comparison with the traditional procurement environment, both the objectives and the constraints in supplier selection in the product development are different. Maximizing the customer requirements is the most important target. Cost related issues such as the fixed and variable product costs could be either the objectives or the constraints. Gupta and Krishnan (1999) proposed to solve an integrated component and supplier selection problem using an integer programming model, to minimize the sum of fixed product costs, fixed design costs and the variable costs of using components, but did not consider the customer requirements and the different engineering characteristics of the components. Fung et al. (2003) used linear programming and the quality function deployment (QFD) method to model the relationship between the customer requirements

(CRs) and the technical attributes (TAs) under the constraints of the resource allocation. Although no supplier factors are taken into consideration, the constraint in resource allocation is a good substitute for suppliers' capabilities is considered a kind of "resource". Feng et al. (2001) applied stochastic integer programming (SIP) to model the relationship between manufacturing cost, quality loss cost, assembly yield, and discrete tolerances, addressing the issue of achieving quality by concurrent tolerance design and supplier selection. Wang and Lin (2006) considered design chain partnership formation as a multi-criteria decision making problem. A genetic algorithm approach was applied to select the set of partners that maximized the total performance score of the entire design chain and satisfied the constraints of target development time and cost at the same time. Tang et al. (2005) developed a 0-1 integer programming model for selection of part combinatorial schemes in part deployment processes using a two-layer fuzzy synthesis evaluation method to assess the part design scheme in a supplier involved new product development process. Information of HoQ (house of quality) and evaluation results of the part design scheme, together with design budget, are taken into account. However, the models didn't take the multiple technical attributes of each part or component into consideration, making the model more general than specific. Erol and Ferrell (2003) utilized a fuzzy QFD and Monte Carlo simulation to analyze the relationship through which a group of specific criteria contribute to the total vendors' performance aspects, and proposed a slightly modified pre-emptive goal programming model to solve this problem with multiple and conflicting objectives considering the uncertainties of development time. Onesime et al. (2004) used QFD to relate the supplier requirements and the selection criteria, and formulated a pre-emptive goal programming (PGP) model to solve this supplier selection problem. Ni et al. (2007) proposed an extended QFD and data mining based method for supplier selection in mass customization, considering customer requirements and performance of components in a product life-cycle. The manufacturer can use data-mining techniques to find quality requirements correlated to customer categories, product usage patterns, and frequent fault patterns in order to select the proper combination of suppliers. Choy et al. (2005) developed a knowledge-based supplier intelligence retrieval system for outsource manufacturing, in which collaborative suppliers are identified quickly during the new product development process. To facilitate cooperative product development, Liang and Wei (2006) developed a conceptual design system in a Web-based virtual interactive environment for product development. The addition of modules calling for qualified suppliers' involvement to the model would satisfy needs of an OKP company.

2.5 Summary

The goal of the QFD method is to maximize overall customer satisfaction through deploying design features which have the most impact on customer requirements (Akao and Mazur 2003). Currently, this is usually accomplished in a subjective, ad hoc manner, or using a heuristic approach, such as a prioritization-based method, with the objective of producing a feasible design, rather than an optimal one (Tang et al. 2002). Particularly, when a given HoQ contains a large number of CRs and TAs, determination of the target specifications of TAs can be a very complex and time consuming process. OKP companies which mainly compete for customized and relatively small volume orders may find a traditional QFD method unsuitable because of the critical need to reduce product development lead time.

According to the comprehensive review of QFD literature by Chan et al. (2002), most QFD practitioners do not take into account manufacturing costs and issues of interdependence among technical attributes. Design engineers need to know how to make tradeoffs in the selection of design features which results in the highest level of customer satisfaction. A mathematical programming framework is shown to be useful for capturing details of the decision process (Wasserman 1993).

Finally, the inherent ambiguity in QFD also presents difficulties for setting proper target specifications for TAs using traditional methods. In practice, many design tasks take place in a fuzzy environment (Kannan 2008; Lee et al. 2008). For instance, the relationship measures between CRs and TAs may not be fully comprehended, especially when an entirely new product is developed. Owing to uncertainties in the design process, the new product design is often limited and can be inaccurate.

In order to improve the traditional QFD methodology, developing optimization methods and software tools for new or improved product development have received extensive attention. Wassermann (1993) incorporated the cost or resource consideration into the QFD planning process and formulated a linear programming model for TAs prioritization in order to yield a high level of customer satisfaction. Park and Kim (1998) proposed an integrated decision model for selecting an optimal set of TAs using a modified HoQ model. Tang et al. (2002) proposed the concepts of planned attainment and actual achieved attainment in order to take into account the correlation among TAs. Fung et al. (2003) formulated QFD planning with resource allocation as a linear programming model. This model can bridge the gap and resolve the conflicts between the design targets at the strategic level, and resource allocations in the part development and process planning level. Tu et al. (2003) reported a collaboratively developed computer-aided customer interface for rapid product development using a mathematical programming-based QFD method.

In addition, a number of researchers have focused on fuzzy modeling approaches. Xue and Dong (1997) developed a fuzzy-based design-function coding system to identify design candidates from design functions. Sun et al. (2000) presented a method for design candidate evaluation and identification using neural network-based fuzzy reasoning. Kim et al. (2000) proposed a fuzzy multi-criteria modeling approach for QFD planning, in which fuzzy linear regression with symmetric triangular fuzzy numbers was used to investigate the functional relationships between CRs and TAs as well as the correlations among TAs. Shen et al. (2001) employed fuzzy sets to address complex and imprecise problems in customer requirement management. Vangegas and Labib (2000) proposed a fuzzy approach to determine the target specifications of TAs. Karsak et al. (2002) presented a fuzzy multiple objective programming approach that incorporated imprecise and subjective information inherent in the QFD process to determine the level of fulfillment of design requirements. Chen et al. (2005) considered a fuzzy expected value operator approach to model the QFD process in a fuzzy environment. In this paper, the idea of a fuzzy expected value operator proposed by Liu and Liu (2002) is extended to model the QFD process in a fuzzy environment.

The literature review in previous sections shows there is a lack of a systematic development procedure for OKP (one-of-a-kind production) product development. The research projects mentioned only focus on the first house of quality (HoQ1) which is also called product planning, and seldom address the downstream product development processes, i.e. part planning, process planning, and production planning. However, the downstream processes, particularly part planning, are very critical for a new or improved product design in OKP product development. Finally, various optimization methods are used to aid designers to set design targets at the product planning stage.

In summary, the problem of supplier selection under the product development environment not only involves the commercial factors such as the price, quality, lead time, warranty service, etc., of the suppliers, but also involves the product development objective. Product development includes the design scheme, parameter selection, functional trade-off, and so on. However, the models discussed assume that the product mix is known, i.e., they assume that the product design task has been completed. However, the designers are frequently resolving part and supplier selection problems during the product design stages. Including rapid evaluation and selection of suppliers under the continuously changing customer requirements and product configurations in the model will be of great help for OKP companies.

CHAPTER 3: INDENTIFICATION OF THE PRIORITIES OF TECHNICAL ATTRIBUTES USING ANALYTICAL NETWORK PROCESS METHOD

Quality function deployment (QFD) starts with the house of quality (HoQ), which is a planning matrix which translating the customer requirements (CRs) into measurable product technical attributes (TAs). A robust evaluation method should consider the interrelationships among customer requirements and TAs while determining the importance levels of TAs in the HoQ. This chapter employs the analytic network process (ANP) to fulfill this requirement.

3.1 Identifying Customer Requirements (CRs)

In this thesis work, customer requirements are classified into two categories. The first category is called the basic and direct requirements of a product such as size, material, color, and basic configuration of the product. All design candidates (which are the products made by an OKP company in the past with similar customer requirements) selected and final products developed must meet these basic customer requirements. Failure to do so will result in dissatisfaction of customers. Normally, these basic and direct requirements must be fulfilled and cannot be adjusted or planned by methods presented in this chapter.

The second category of customer requirements is called indirect requirements, e.g., “energy saving”, “clear view of the outdoors”, and “easy to open/close” windows. These requirements are normally not clearly defined by customers. They are adjustable or can be planned to certain degrees (or levels) of fulfillment under consideration of a given budget and manufacturing constraints. To optimally or rationally plan the degrees or levels of fulfillment of the second category of customer requirements under a given budget and manufacturing constraints is critical in achieving overall customer satisfaction. Through this research work, it is also recognized that various customer requirements have different impacts on overall customer satisfaction. Impacts can be described by the importance weights of customer requirements.

Customer requirements in the first category must be fulfilled completely (or 100%) in order to avoid customer dissatisfaction. They are basic customer requirements and cannot be planned or adjusted. In the remainder of this thesis, for simplicity, customer requirements will refer to those in the second category, i.e., indirect requirements. A linear (or proportional) relationship between the fulfillment of customer requirements and overall customer satisfaction is also assumed.

Among the second category of customer requirements, some are considered more important or weighted with higher values than others. Paying attention to these higher weighted requirements has a great impact on product competitiveness since the product will contain the most essential functions when customer expectations are high, lead time is short, and resources are limited. To determine the priorities of requirements, some quantitative ranking techniques, such as Saaty's pairwise comparisons (Saaty and Takizawa 1986), spanning tree matrix and bubble sort are used to get more accurate and reliable ranking results than the ones obtained using the rough prioritization techniques which are heavily dependent on experts' subjective judgments. So far, it has been found that Saaty's pairwise comparison method is often used in product design to prioritize CRs. The fundamental inputs required in Saaty's pairwise comparison technique are customer's answers to a series of general questions, e.g., "How important is customer requirement '*A*' relative to customer requirement '*B*'?" Responses to these questions are gathered in verbal form and subsequently codified on a nine-point intensity scale. For instance, '1' denotes 'equally important', '3' denotes 'moderately more important', '5' denotes 'strongly more important', etc. If the judgment is that *B* is more important than *A*, then the reciprocal of the relevant index value is assigned. For example, if *B* is felt to be moderately more important than *A*, then the value 1/3 would be assigned to *A* relative to *B*.

If m customer requirements (denoted by CR_i, $i = 1, 2, \ldots, m$) are associated with m importance weights, $w_1, w_2, \ldots, w_m$, the relative importance, a_{ij}, considering the i-th customer requirement compared with the j-th customer requirement can be described as

$$a_{ij} = \frac{w_i}{w_j} \tag{3.1}$$

The pairwise ratios satisfy

$$\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1m} \\ a_{21} & a_{22} & \cdots & a_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mm} \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_m \end{bmatrix} = \lambda \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_m \end{bmatrix} \tag{3.2}$$

For ease of explanation, this formula is described as

$$\mathbf{Aw} = \lambda \mathbf{w} \text{ or } (\mathbf{A} - \lambda \mathbf{I})\mathbf{w} = 0 \tag{3.3}$$

where, **I** is a $m \times m$ identity matrix. From this equation, it is apparent that λ is an eigenvalue of the pairwise ratio matrix **A**, and **w** is an eigenvector for eigenvalue λ. Saaty asserts that the importance weights implied by the $m \times m$ pairwise ratio matrix can be estimated by the eigenvector which corresponds to the maximum eigenvalue $\lambda_{\max}$. The corresponding maximum eigenvector can be calculated using the geometric mean of each row. That is, the elements in each row are multiplied with each other and then the m-th root is taken (where m is the number of elements in the row), such as $w_1 = \sqrt[n]{a_{11}.a_{12}...a_{1m}}$. The normalized elements of the eigenvector represent the relative importance weights of CRs.

3.2 Identification of the Priorities of TAs based on ANP Method

The super-matrix representation of the QFD model used in this chapter is given below:

$$\mathbf{W} = \begin{array}{r c} & \begin{array}{ccc} \text{G} & \text{CRs} & \text{TAs} \end{array} \\ \begin{array}{r} \text{Goal(G)} \\ \text{CRs} \\ \text{TAs} \end{array} & \begin{pmatrix} 0 & 0 & 0 \\ \mathbf{w}_1 & \mathbf{W}_3 & 0 \\ 0 & \mathbf{W}_2 & \mathbf{W}_4 \end{pmatrix} \end{array}$$

where $\mathbf{w}_1$ is a vector that represents the impact of the goal, i.e., manufacturing a product that satisfies the customer's requirements; $\mathbf{W}_2$ is a matrix that denotes the impact of the customer requirements on each of the TAs; $\mathbf{W}_3$ and $\mathbf{W}_4$ are the matrices that represent the inner dependence of the customer requirements and the inner dependence of the TAs, respectively. Here, "impact" denotes the potential of the TAs to satisfy the requirements implicit in each of the customer requirements in accordance with the goal.

The network representation of the QFD model is the same as depicted in Figure 2.4. This is the case of a hierarchy with inner dependence within components and no feedback. The Customer requirements correspond to criteria whereas the TAs correspond to alternatives in standard ANP terms, both of which have inner dependence within themselves; however, there is no feedback, i.e. customer requirements do not depend on the TAs.

Using the notation given above, the interdependent priorities of customer requirements ($\mathbf{w}_C$) are computed by multiplying $\mathbf{W}_3$ by $\mathbf{w}_1$, and similarly interdependent priorities of TAs ($\mathbf{W}_A$) are obtained by multiplying $\mathbf{W}_4$ by $\mathbf{W}_2$. Then, the overall priorities of TAs ($\mathbf{w}_{ANP}$), which reflect the interrelationships within the HoQ, are calculated by multiplying $\mathbf{W}_A$ and $\mathbf{w}_C$.

3.3 Overall Procedure for Calculating Technical Attributes

The evaluation algorithm steps for determining the overall priorities of the TAs can be summarized by the following procedure:

Step 1. Identifying customer requirements (CRs) and determining the technical attributes (TAs) matching the CRs.

Step 2. Determining the importance degrees of CRs with linguistic data by assuming that there is no dependence among the CRs: Calculation of $\mathbf{w}_1$

Step 3. Determining the importance degrees of TAs with respect to each CR with linguistic data by assuming that there is no dependence among the TAs: Calculation of $\mathbf{W}_2$.

Step 4. Determining the inner dependency matrix of CRs with respect to each CR with linguistic data by utilizing the schematic representation of inner dependence among CRs: Calculation of $\mathbf{W}_3$.

Step 5: Determining the inner dependency matrix of TAs with respect to each TA with linguistic data by utilizing the schematic representation of inner dependence among TAs: Calculation of $\mathbf{W}_4$.

Step 6: Determining the interdependent priorities of CRs: Calculation of $\mathbf{w}_c = \mathbf{W}_3 * \mathbf{w}_1$.

Step 7: Determining the interdependent priorities of TAs: Calculation of $\mathbf{W}_A = \mathbf{W}_4 * \mathbf{w}_2$.

Step 8: Determining the overall priorities of TAs: Calculation of $\mathbf{w}_{ANP} = \mathbf{W}_A * \mathbf{w}_c$.

CHAPTER 4: OPTIMZATION OF PRODUCT PLANNING WITH COST BUDGET

This chapter presents mathematical programming that includes importance levels of TAs derived using the ANP and cost budget to determine the TAs to be considered in designing the product. An example is presented to illustrate the application of the decision approach.

4.1 Calculation of the Overall Customer Satisfaction

The overall customer satisfaction, *S*, of a given product can be considered as a mathematical aggregation of the degrees of customer satisfaction s_i with individual CRs, so, $S = f(s_1, s_2, ..., s_m)$, where $f(s_1, s_2, ..., s_m)$ is an aggregation function reflecting the customer overall perceptions of the product. In general, the aggregate function can be expressed in an additive, multiplicative or multi-linear fashion depending on customer preference. Using the weighted linear additive operator, overall customer satisfaction can be expressed as:

$$\mathrm{S} = \sum_{i=1}^{\mathrm{m}} w_{1i} s_i \tag{4.1}$$

The degree of customer satisfaction s_i with a given CR is calculated from the actual target attainment denoted by x_j for TA through considering the relationship matrix between CRs and TAs, i.e., $s_i = \sum_{j=1}^{n} W_{2ij}^{*} x_j$. Moreover, let $x_j = y_j + \sum_{k \neq j}^{n} W_{4kj} y_k = \sum_{k=1}^{n} W_{4kj} y_k$, where

y_k denotes planned target attainment for the kth TA, $k = 1,2,\ldots,n$. Thus, the equation (4.4) can be expressed as (Tang et al. 2002):

$$\mathrm{S} = \sum_{i=1}^{\mathrm{m}} w_{1i} \sum_{j=1}^{n} W_{2ij}^{*} x_j = \sum_{j=1}^{n}\sum_{i=1}^{\mathrm{m}} w_{1i} W_{2ij}^{*} \sum_{k=1}^{n} W_{4kj}^{*} y_k = \sum_{k=1}^{n}\sum_{j=1}^{n}\sum_{i=1}^{m} w_{1i} W_{2ij}^{*} W_{4kj}^{*} y_k = \sum_{k=1}^{n} w_k y_k \qquad (4.2)$$

4.2 Formulation for Costs and Budgets Constraints

Assume that there are multiple resources required to support the design of a required product, including technical expertise, and advanced equipment, tools and other facilities. At the level of strategic planning, these resources can be aggregated in financial terms (Tang et al. 2002; Fung et al. 2003). The development cost B only depends on the levels of actual attainment of TAs x_j, and can be obtained as the sum of costs required for achieving the level of individual TA, i.e., $B = \sum_{j=1}^{n} C_j$, where, C_j is the cost incurred for improving TA_j. For simplicity, suppose that C_j is linearly proportional to the level of attainment x_j, hence, $C_j = c_j x_j$, where, the cost coefficient c_j is defined as the cost committed for attaining the upper bound of the jth TA while nothing has been committed to other TAs. In other words, c_j is the cost committed to reach the highest target for the jth TA without relying on the contribution from other TAs. Here, c_j is called the primary cost, and can be determined according to the knowledge of the design team or by estimation. For instance, based on the linear assumption between the cost c_j and the actual attainment x_j, c_j can be estimated from the costs of two existing similar products for which only one TA_j is different and the rest of the TAs are all the same, i.e.,

$c_j = C_d/(x_1 - x_2)$, where, C_d is the cost difference of the two existing similar products, x_1 and x_2 are two different attainments of the two similar products with respect to TA_j.

However, practical cases are seldom as simple as this owing to the complex correlations among the TAs. The actual cost c_j^* can be defined as the necessary cost to achieve the highest target for the *j*th TA subject to the influence from other TAs. c_j^* can be formulated as (Fung et al. 2003):

$$c_j^* = c_j(1 - \sum_{k \neq j} W_{4kj} y_k) \tag{4.3}$$

The actual attainment for the *j*th TA, x_j, consists of two components. The first one is achieved directly from the costs committed to the *j*th TA. The second component is acquired indirectly using the correlation of the *j*th TA with other TAs. The actual costs $C_j(x_j)$ for achieving a given planned attainment, y_j, is called the planned cost, and it can be calculated by (Fung et al. 2003):

$$C_j(x_j) = c_j^* x_j = c_j(1 - \sum_{k \neq j} W_{4kj} y_k)(y_j + \sum_{k \neq j}^{n} W_{4kj} y_k) \tag{4.4}$$

$W_{4kj} = 0$ $(k \neq j)$ when the *j*th TA is independent of other TAs. In this case, $c_j^* = c_j$ and $C_j(x_j) = c_j y_j = c_j x_j$. As indicated above, when $1 - \sum_{k \neq j} W_{4kj} y_k = 0$, it implies that the target for the *j*th TA is achieved solely based on its correlation with other TAs, i.e., the planned attainment for the *j*th TA is zero. This means that no planned costs are needed for achieving the *j*th TA. Finally, the cost constraint can be formulated as (Fung et al. 2003):

$$C(y)=\sum_{j=1}^{n}C_j(x_j)=\sum_{j=1}^{n}c_j^{*}x_j=\sum_{j=1}^{n}c_j(1-\sum_{k\neq j}W_{4kj}y_k)\sum_{k=1}^{n}W_{4kj}y_k \leq B \tag{4.5}$$

4.3 Product Planning Model based on QFD

Taking into account the technical and budget limitations, a mathematical programming based QFD planning model can be formulated as follows:

$$\text{Max } \mathrm{S}=\sum_{k=1}^{n}w_k y_k \tag{4.6}$$

$$\text{s.t.} \qquad 0\leq y_k \leq 1, \quad k=1,2,\ldots,n \tag{4.7}$$

$$\theta \leq \sum_{k=1}^{n}W_{2kj}y_k \leq 1, \quad j=1,2,\ldots,n; \tag{4.8}$$

$$C(y)=\sum_{j=1}^{n}c_j(1-\sum_{k\neq j}W_{4kj}y_k)\sum_{k=1}^{n}W_{4kj}y_k \leq B \tag{4.9}$$

Where $\theta \in (0, 1)$ is the preferred acceptable attainment for the *i*th TA, it reflects the designer's subjectivity, preference, and technical requirements for the product or knowledge of competitors. Different and/or common values of θ may be assigned to different TAs. B is the budget limit, while y_j is a decision variable in this model representing the planned attainment for the *j*th TA.

In this model, the objective of Formula (4.6) maximizes overall customer satisfaction, which is assumed linearly proportional to the weighted sum of actual attainments for various TAs. The constraint of Equation (4.7) reflects requirements of practical design, and so it is more acceptable by designers. Equation (4.8) gives the threshold of actual attainment θ, for a given TA. Equation (4.9) restricts the total design costs not to exceed the available budget.

4.4 Illustrative Example

A window manufactured by Gienow Windows and Doors (Calgary, Canada) is used here as a case study to demonstrate the feasibility and effectiveness of the introduced methodology. The application is demonstrated in stepwise form as follows.

Step 1. As mentioned in Section 4.3, the QFD product planning process begins with the determination of customer requirements and then the TAs. Collected and organized customer phrases are placed in the upper left part of the HoQ. In our example, the six ambiguous customer requirements, i.e., "Energy saving" (CR1), "Less frost on interior of glass and frame" (CR2), "Clear view of the outdoors" (CR3) , "Strong structure" (CR4), "Quiet inside" (CR5), and "Brightness" (CR6) are recorded.

Step 2. In this step, the relative importance of customer requirements is determined by asking the following question: "Which customer requirement should be emphasized more in designing a window, and how much more?" Assuming that there is no dependence among customer requirements, the following eigenvector for customer requirements is obtained by performing pairwise comparisons with respect to the goal of achieving the best design. Based on Saaty's method, their relative importance weights are calculated as follows

$$\mathbf{w}_1 = (0.34, 0.05, 0.30, 0.10, 0.03, 0.18)$$

Assuming that there is no dependence among the TAs, they are compared with respect to each customer requirement yielding the column eigenvectors. Seven TAs, i.e., "Air leakage" (TA1), "Water tightness" (TA2), "Wind resistance" (TA3), "Condensation resistance" (TA4), "Visible transmittance" (TA5), "Energy rating" (TA6), and "Sound transmission" (TA7) are identified according to the CRs. According to designers' experiences, the relationships between TAs and CRs, correlations among CRs and TAs (denoted using crisp scale such as 1-3-9, representing weak, medium and strong relationships respectively) are obtained and normalized as illustrated in Table 4.1. The transposition of the data shown in Table 4.1 will be placed in the body of the HoQ.

Table 4.1 The relationships between TAs and CRs

	TA1	TA2	TA3	TA4	TA5	TA6	TA7
CR1	0.278	0.167	0	0.056	0	0.5	0.8
CR2	0.238	0.333	0	0.429	0	0.067	0
CR3	0	0	0	0.333	0.6	0	0
CR4	0.1	0	0.9	0	0	0	0
CR5	0.357	0	0	0	0	0	0.643
CR6	0	0	0	0	0.9	0.1	0

Following that, inner dependence among customer requirements is determined through analyzing the impact of each customer requirements on other customer requirements using pairwise comparisons.

Table 4.2 Pairwise comparison of customer requirements

	CR1	CR2	CR3	CR4	CR5	CR6
CR1	1	6	1	3	9	3
CR2	1/6	1	1/5	1/2	2	1/4
CR3	1	5	1	3	8	2
CR4	1/3	2	1/3	1	3	1/2
CR5	1/9	1/2	1/8	1/3	1	1/7
CR6	1/3	4	1/2	2	7	1

Following this, inner dependencies are determined and the required pairwise comparisons are performed. Dependencies among the TAs are depicted in Table 4.3.

Table 4.3 The correlations among TAs

	TA1	TA2	TA3	TA4	TA5	TA6	TA7
TA1	1	0.5	0.167	0.278	0	0.5	0.278
TA2	0.5	1	0.056	0.5	0.056	0.167	0.056
TA3	0.167	0.056	1	0	0	0	0
TA4	0.278	0.5	0	1	0.167	0	0.056
TA5	0	0.056	0	0.167	1	0.056	0
TA6	0.5	0.167	0	0	0.056	1	0
TA7	0.278	0.056	0	0.056	0	0	1

Interdependent priorities of the customer requirements ($\mathbf{w}_C$) can be obtained as

$$\mathbf{w}_C^T = (\mathbf{W}_3 \times \mathbf{w}_1)^T = (0.358, 0.447, 0.36, 0.55, 0.62, 0.19, 0.114)$$

Then, interdependent priorities of the TAs, $\mathbf{W}_A$ are calculated as follows:

$$\mathbf{W}_A = \mathbf{W}_4 * \mathbf{W}_2 = \begin{pmatrix} 0.528 & 0.447 & 0.546 & 0.7267 & 0.325 & 0.4 & 0 \\ 0.3216 & 0.0894 & 0.272 & 0.3 & 0.02 & 0.08 & 0 \\ 0.06802 & 0.08493 & 0.2684 & 0.2945 & 0.919 & 0.076 & 0 \\ 0.1158 & 0.0447 & 0.1 & 0.1158 & 0.01 & 0.04 & 0.8 \end{pmatrix}$$

Following that, overall priorities of TAs ($\mathbf{w}_{ANP}$), reflecting the interrelationships within the HoQ, are obtained by multiplying $\mathbf{W}_A$ and $\mathbf{w}_C$.

$$\mathbf{w}_{ANP} = \mathbf{W}_A \times \mathbf{w}_C = (0.209, 0.168, 0.062, 0.175, 0.199, 0.160, 0.027)$$

ANP analysis results indicate that the most important design feature is visible transmittance with a relative importance value of 0.227, which is slightly more important than air leakage. Condensation resistance with a relative weight of 0.172, and water tightness with a relative weight of 0.158 follow the most important TAs. Energy rating, wind resistance and sound transmission, are the least important design features according to the ANP analysis.

Step 3. Construct the model using the data as follows: Costs committed for attaining the highest target for TAs are collected from Gienow as 300, 400, 500, 1000, 1000, 1000 and 500 cost units, respectively. Assuming that the budget, B, is limited to 1,000 cost units, and the primary cost for each TA is expressed as:

$$\mathbf{c} = (300, 400, 500, 200, 50, 700, 500)$$

The planned attainment, actual attainment, primary costs, actual costs and planned costs for achieving various technical design targets can be compared as shown in Table 4.4. The table is divided into two sections, i.e. the top and bottom sections, which shows within the allowed budgets of 1000 cost units and 1200 cost units. The prioritization-based method gives a 89.29% and a 94.19% satisfaction level, respectively.

Table 4.4 Various costs and degrees of target attainments for TA

Technical attributes (TA)	Planned attainment	Actual attainment	Primary cost (*1000)	Actual cost (*1000)	Planned cost (*1000)	Overall customer satisfaction
TA1+	0.29	1.0	86.2	86.2	300	
TA2+	0.44	1.0	175.3	175.3	400	
TA3+	0.42	0.5	463.7	231.9	500	
TA4+	0.54	1.0	107.2	107.2	200	
TA5+	0.87	0.6	43.3	43.3	50	
TA6+	0.34	0.5	512.2	312.9	700	
TA7+	0.36	1.0	86.5	43.3	100	
Total			1474.4	1000	1000	0.8929
TA1*	0.29	1	0.89	0.89	300	
TA2*	0.46	1	187.3	187.3	400	
TA3*	0.47	0.5	486.6	243.3	500	
TA4*	0.6	1	120.4	120.4	200	
TA5*	0.83	1	41.5	41.5	50	
TA6*	0.79	0.9	611.7	559.7	700	
TA7*	0.44	0.5	93.9	46.9	100	
Total*			1542.29	1199.99	1200	0.9419

+ Optimal solution under the budget limit of 1000 cost units.

* Optimal solution under the budget limit of 1200 cost units.

4.5 Summary

In this chapter, a planning approach supported by mathematical programming based QFD and an ANP method have been developed. With reference to the attribute relationship and correlation in a HoQ, the costs for achieving certain degrees of design targets are formulated mathematically. The concepts of actual attainments and planned attainments for TAs, primary costs, actual costs, and planned costs for various TAs are adopted in the solving resource allocation problems in product development and improvement. Decision-makers can make use of a set of feasible solutions obtained from the proposed optimization model at various desired levels to create product design strategies which will support more practical and cost-effective QFD planning under resource constraints.

CHAPTER 5: FUZZY SYNTHESIS EVALUATION OF PARTS DESIGN SCHEME WITH SUPPLIER INVOLVEMENT

Focusing on supplier involvement in the new product development (NPD), this chapter discusses synthesis evaluation and selection of part design schemes in the part deployment process. The concepts of a performance indicator (PI) and integrated performance indicators (IPI) are introduced to measure the performance of part design schemes and product design schemes. A two-layer fuzzy synthesis evaluation method is applied to assess part design scheme in a supplier-involved new product development process. Combining the information of house of quality (HoQ) and evaluation results of part design scheme and taking into account design budgets, a 0-1 integer programming model is developed for selection of the parts combinatorial scheme (PCS) in supplier-involved part deployment process. A case study with a type of door produced at Gienow is also illustrated in this chapter.

5.1 Framework of Evaluation of Part Design Scheme

In the part deployment phase, designers not only need to determine the composed components or parts (simply referred to as parts hereafter) of the product, but also need to design technical solutions for all individual parts to meet functional requirements. In general, during part deployment, more than one alternative technical solution is provided. These alternatives are evaluated and balanced from several aspects before a preferable one is determined. With suppliers involved in the NPD environment, parts suppliers can utilize their core design ability and participate in the part deployment process, rather than the manufacturing process, and participate in the part's performance requirements.

Design and manufacturing enterprises may decide to subcontract the parts design tasks to suppliers. Evaluation and selection of the product design scheme becomes a very important task for manufacturing enterprises when there is supplier involvement in NPD.

The formulation of the HoQ in part deployment can be conducted in a similar way. Assuming a product has h parts (each denoted by PA), let **E** be the relationship matrix between TAs and PAs (parts characteristics). The element E_{jk} ($j=1,2,\cdots,n$; $k=1,2,\cdots,h$) indicates the relative strength of the kth PA towards fulfilling the jth TA, and it can be quantified with a rating scale, such as 1-3-9 or 1-9-15 to denote weak, medium, and strong relationships, respectively. Let **P** be the correlation matrix among PAs; each element P_{ks} denotes the degree of dependence of the kth PA on the sth PA. If there is no dependence between them, $P_{ks}=0$. When P is normalized, $P_{ks} \in [-1, 1]$, it can be interpreted as incremental changes of the degree of the attainment of the sth part when the degree of attainment of the kth PA is increased by one unit. Taking into account the correlation among PAs, the absolute weight vector **V** of parts is expressed as follows (Tang et al. 2002):

$$\mathbf{V} = \mathbf{P}\mathbf{E}^{*T}\mathbf{U}^{*}, \; E_{jk}^{*} = \frac{E_{jk}}{\sum_{l=1}^{h} E_{jl}} \tag{5.1}$$

After normalization, the relative weight of the kth part can be given as:

$$v_k^{*} = \frac{v_k}{\sum_{l=1}^{h} v_l}, \quad k = 1,2,\cdots,h \tag{5.2}$$

When suppliers are involved in the part deployment process, there may be multiple suppliers bidding for an individual part design. Each may provide one or more options. Relationships among products, parts, suppliers, and technical solutions or schemes are sketched in a hierarchical model as shown in Figure 5.1. In the hierarchical model (Figure 5.1), the first layer is the product layer which consists of multiple components/parts given in the second layer, followed by the supplier layer, and finally, the solution layer at the bottom. To formulate a synthesis and evaluation process, the concepts of alternative solutions, design schemes, and selected schemes for a part and parts combinatorial scheme (PCS) are introduced. Without consideration of a supplier, an alternative solution is a technical solution for a part design, while a design scheme is an alternative solution with supplier involvement. Evaluation of an alternative solution is just made from the technical solution of a part design itself, while evaluation of a design scheme is made from the perspective of the alternative solution and its supplier. A selected scheme for a part is the preferable method, that is, a part selected from many design schemes provided by many suppliers. The formulation method is presented in the following subsections.

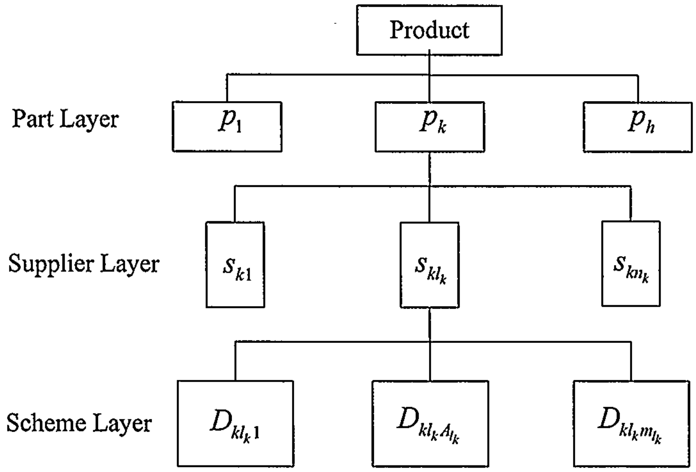


Figure 5.1 Hierarchical model of part, supplier, and alternative solution

A PCS is a product design scheme by which each part has a selected scheme. As indicated in Figure 5.1, the product is composed by h parts; each is denoted by p_k, $k = 1, 2, \cdots, h$. For the kth part p_k, there are n_k suppliers bidding for the part design, each is denoted by s_{l_k} , $l_k = 1, 2, \cdots, n_k$. For the kth part p_k, each of the alternative solutions of the part design are given as $A_{l_k} = 1, 2, \cdots, m_{l_k}$, and the corresponding design scheme from the supplier l_k is denoted by $D_{kl_kA_{l_k}}$.

During part deployment, the overall process of evaluation and selection of a part design scheme is summarized in the following five steps:

Step 1: Announcing the information for calling bids for part designs.

Step 2: Evaluating the candidate suppliers separately and giving an evaluation grade to each supplier.

Step 3: All of the alternative solutions for parts provided by suppliers are evaluated and scaled in different grades, each with a unique grade.

Step 4: Based on the grades of the evaluation and their alternative solutions, the synthesis evaluation of each design scheme for a part is conducted and an aggregated grade is obtained with a mathematical operation.

Step 5: Based on the these results, a selected scheme for a part design is determined to be the design scheme with the best grade, and consequently the supplier and its solution are selected.

In order to formulate the evaluation of alternative solution and design schemes for parts in a quantitative way, the concept of a performance indicator (PI) is introduced in this chapter. The PI of an alternative solution of a part is obtained using a fuzzy synthesis evaluation with multiple attributes and is denoted mathematically by PI_1. While the PI of a design scheme is quantified using fuzzy synthesis evaluation, using the technical aspects of the part design, and the evaluation grade of the part supplier. The fuzzy synthesis evaluation is achieved by aggregating the evaluation grade of the supplier and PI of the alternative solution. The PI of the alternative solution, the PI of a design scheme is symbolically denoted by PI_2.

Let $g(l_k)$ and $PI_1(A_{l_k})$ denote the evaluation grade of the supplier l_k and the PI of its alternation solution A_{lk} respectively in the fuzzy synthesis evaluation process, and $PI_2(D_{kl_k A_{lk}})$ denote the PI of the corresponding design scheme of the *k*th part. The PI of a design scheme can be interpreted as the contribution level of the design scheme to overall customer satisfaction level of a certain product. In the following sub-sections, fuzzy synthesis evaluation procedures for obtaining evaluation grades of suppliers and performance indicators of the alternative solution and part design schemes are discussed.

5.2 Fuzzy Synthesis Evaluation of Suppliers

As a method of multiple attribute decision analysis, fuzzy synthesis evaluation is based on a fuzzy set theory to give an object an overall evaluation by taking into account multiple influencing factors. It is categorized into a single-level or multi-level fuzzy synthesis evaluation according to the complexity of evaluated objects.

There are four pivotal facets in fuzzy synthesis evaluation, i.e., (1) factor set, which is a set of attributes or factors that influence the object being evaluated; (2) weight set, an element which indicates the relative importance of influencing factors; (3) opinion set, that is a set of linguistic levels to scale the grade of the evaluated object; and (4) single-level evaluation, indicating the degree of membership of each attribute to each linguistic level in the opinion set.

Single-level synthesis evaluation is adopted in this section to conduct the fuzzy synthesis evaluation of suppliers. The procedure is illustrated as follows with the example of the l_k th supplier of the *k*th part.

Step 1: Determine the influencing factor set $\Omega = \{\pi_{k1}, \pi_{k2}, \cdots, \pi_{kf_k}\}$ 。 Each element represents a criterion or attribute for assessing the supplier, e.g., part quality, part cost, core design ability, supply capacity, credit standing level, response time, financial stability, and reputation. As a result,

Ω = (cost, quality, response time, core design ability, supply capacity, reputation, financial stability, credit standing level)

Step 2: Determine the opinion set of suppliers $\Theta = \{\varepsilon_{k1}, \varepsilon_{k2}, \cdots, \varepsilon_{kg_k}\}$ to give evaluation classification. For instance, the supplier can be classified into five classes, such as world class (ideal), award winners (reliable), improvers (potential), drifters (unfavorable), and uncommitted (unqualified). To quantify the assessment of suppliers, a numerical value is given using a scaling method. For example, the scale values 1.0, 0.8, 0.6, 0.4, 0.2 are assigned to the assessment of suppliers with world class, award winner, improver, drifters and uncommitted respectively. Let α_i, $i = 1, 2, \cdots, g_k$ be the numerical value of the evaluation class of suppliers by using a scaling method.

Step 3: Determine the weight vector $\mathbf{W} = \{w_{k1}, w_{k2}, \cdots, w_{kf_k}\}$ of attributes so that $w_{ki} \geq 0, \sum_{i=1}^{f_k} w_{ki} = 1$.

Step 4: Establish the assessment matrix. Each element of the matrix indicates the degree of membership of an attribute of the supplier to an evaluation class in an opinion set. The assessment matrix is expressed in terms of a $f_k \times g_k$ matrix $\mathbf{O} = \{O_{k1}, O_{k2}, \cdots, O_{kg_k}\}$, where O_{ki} is a vector of a number of f_k elements, each representing the degree of membership of the supplier in the *i*th class from the aspect of a specified attribute.

Step 5: Determine the fuzzy synthesis evaluation vector in terms of $\mathbf{B} = \mathbf{W} \times \mathbf{O}$. The vector **B** denotes the degree of membership of the supplier in each evaluation class with consideration of multiple attributes.

Step 6: Determine the evaluation class of the supplier using the maximum degree of membership method or other methods. If the maximum membership degree method is accepted, the supplier is positioned at the evaluation grade with $b_i = \max(b_j)$ and assigned with a numerical value

$$g_k(l_k) = \alpha_i \tag{5.3}$$

5.3 Fuzzy Synthesis Evaluation of Alternative Solutions

When evaluating an alternative solution of a part design by means of fuzzy synthesis evaluation, a large number of attributes should be considered. These attribute show different aspects of part characteristics, and can be further divided into several subclasses. The multi-level fuzzy synthesis evaluation is demonstrated in this subsection. It is illustrated with the example of an alternative solution A_{l_k} from the supplier l_k.

Step 1: Determine the factors that influence the assessment of the alternative solution and denote the factors set by Ω. These factors are further divided into s subclasses. Each is denoted by $\Omega_i = \{\sigma_{i1}, \sigma_{i2}, \cdots, \sigma_{in_i}\}$ ($i = 1, 2, \cdots, s$) such that $\sum_{i=1}^{s} n_i = n \cup_{i=1}^{s} \Omega_i = \Omega$; $\Omega_i \cap \Omega_j = \varnothing$, $i \neq j$. The factors subclass Ω_i reflects certain engineering characteristics of part p_k, so their relative importance can be obtained by engineers. Let w_i denote the weight of subclass $\Omega_i (i = 1, 2, \cdots, s)$ and $\mathbf{W} = \{w_1, w_2, \cdots, w_i, \cdots, w_s\}$ be the weight vector of factor subclasses in the factor set Ω. For a factor subclass Ω_i, let

$\mathbf{W}_i = \{w_{i1}, w_{i2}, \cdots, w_{in_j}\}$ be the weight vector of the attributes in the subclass Ω_i such that $\sum_{i=1}^{n_i} w_{it} = 1$.

Step 2: Establish the opinion set $\Theta = \{\varepsilon_1, \varepsilon_2, \cdots, \varepsilon_m\}$ of the alternative solution. Each element is assigned with a numerical value i.

Step 3: Assess each factor subclass $\Omega_i (i = 1, 2, \cdots, s)$ through using the single-level fuzzy synthesis evaluation method. Let the assessment matrix be O_i and hence the fuzzy synthesis evaluation vector B_i is given as:

$$B_i = W_i \times O_i = (b_{i1}, b_{i2}, \cdots, b_{im}) \tag{5.4}$$

Step 4: Calculate the assessment matrix $\mathbf{R}$ in the factor set $\Omega = \{\Omega_1, \Omega_2, \cdots, \Omega_s\}$ as follows:

$$\mathbf{R} = \begin{pmatrix} \mathbf{B}_1 \\ \mathbf{B}_2 \\ \vdots \\ \mathbf{B}_s \end{pmatrix} = \begin{pmatrix} b_{11} & b_{12} & \cdots & b_{1m} \\ b_{21} & b_{22} & \cdots & b_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ b_{s1} & b_{s2} & \cdots & b_{sm} \end{pmatrix} \tag{5.5}$$

Step 5: Calculate the fuzzy synthesis evaluation vector in terms of

$$\mathbf{B} = \mathbf{W} \times \mathbf{R} = (b_1, b_2, \cdots, b_m) \tag{5.6}$$

Step 6: Determine the performance indicator of the alternative solution using a maximum degree of membership method or other methods. If the maximum membership degree method is accepted, the performance indicator of the alternative solution is assigned with a numerical value α_i, so that $b_i = \max(b_j)$

$$PI_1(A_{l_k}) = \alpha_i \tag{5.7}$$

where the alternative solution is positioned at the *i*th evaluation grade.

5.4 Calculation of Performance Indicator of a Design Scheme

As indicated previously, the PI of a design scheme is quantified by using fuzzy synthesis evaluation not only from technical aspects of the part design but also taking into account the evaluation grade of the part supplier. It is achieved by aggregating the evaluation grade of the supplier and PI of the alternative solution. Under a given evaluation grade of a supplier and the PI of its alternative solution, the PI of its design scheme is calculated in a weighted sum as given below:

$$PI_2(D_{kl_k A_{l_k}}) = W_s \cdot g(l_k) + W_A \cdot PI_1(A_{l_k}) \tag{5.8}$$

where W_S and W_A are weights of importance of the supplier and the alternative solution in the design scheme. Of course, some other mathematical operators, e.g., max operator, min operator, addition operator, and multiplication operator, also can be used to obtain the performance indicator.

5.5 Optimization Model for Selection of Parts Combinatorial Schemes

During the QFD based product development process, the part deployment process determines the product design scheme, in order to meet product functional requirement specified in the product conceptual design phase. The purpose of the product design scheme is to determine what the composed parts are, and in which way these parts are needed to fulfill the functional requirements of the product. This implies that there are two tasks in the product design scheme, i.e., evaluation of design schemes for parts and selection of part combinatorial schemes (PCS).

The evaluation of design scheme is to assess the part design scheme from different aspects with the measure of PI and then choose a favorable one from several competing design schemes. From the viewpoint of the part, the selected scheme is the design scheme with the highest performance indicator. However, from the product point of view, the selected scheme of a part design may not be the best design scheme of the part.

A product design scheme is a combination of selected schemes of composed parts. The selection of PCS is a process of combining optimal design schemes of each part. On one hand, manufacturing enterprise will select the design scheme based on the PI. The higher the PI of a design scheme is, the more possibility that the design scheme is selected. On the other hand, some other considerations, e.g., design budget, resources, as well as some special technical requirements, should be considered during the selection process. The selection of PCS is a decision problem with the goal being to determine the selected scheme of each part in the developed product in order to optimize an objective, e.g., to maximize overall customer satisfaction or a performance measure of the designed product under technical, resource, and financial constraints. To solve this optimization problem, a 0-1 integer programming model has been developed through this thesis work.

After a design scheme of a part is determined, the performance characteristic of the part related to the design scheme is determined in terms of PI. The performance of a part in a product depends completely on the design scheme selected, and is measured in PI. In this section, the concept of an integrated performance indicator (IPI) is introduced to measure the performance of a PCS, and the performance characteristic of the product depends completely on the PCS. The IPI of a PCS is defined as a weighted sum of the PI of the selected scheme for each part in the PCS.

Given a PCS $D=(D_{1l_1A_{l_1}},D_{2l_2A_{l_2}},\cdots,D_{hl_kA_{l_k}})$, the product design scheme is given as: part p_1 selects the A_{l_1} th test design scheme provided by the l_1 th supplier, part p_2 selects the A_{l_2} th design scheme provided by the l_2 th supplier, etc., and the part p_h selects the A_{l_h} th design scheme provided by the l_h th supplier. In this case, the integrated performance indicator $IPI(D)$ of the parts combinatorial scheme D is formulated as:

$$IPI(D)=\sum_{k=1}^{h}v_kPI_2(D_{kl_kA_{l_k}}) \tag{5.9}$$

where v_k is the weight of the kth part in the product, as given in formula (5.2) and it indicates the relative importance of the parts in the product.

Corresponding to each design scheme of a part, a cost for designing and manufacturing of the part needs to be determined. Let $c(D_{kl_kA_{l_k}})$ be the cost for designing and manufacturing the part made from design scheme $D_{kl_kA_{l_k}}$. The cost of a part design scheme is provided from the supplier together with its technical solution when the supplier bids for the part design. However, the PI is given by the tenders through evaluation. There are complex and nonlinear relationships between the PI and the cost of a design scheme of a part. Their relationships can be obtained by using some mathematical statistic tools, e.g., two variable regression analysis and dependency analysis.

Let *C*(*D*) be the cost for a PCS. Assume that *C*(*D*) is the sum of the costs of the design scheme selected in the PCS. Given the cost vector of selected schemes for parts, $c(D_{1l_1A_{l1}})$, $c(D_{2l_2A_{l_2}})$, . . . , $c(D_{kl_kA_{l_k}})$, the cost of the PCS D is given below:

$$C(D)=\sum_{k=1}^{h}c(D_{kl_kA_{l_k}}) \tag{5.10}$$

Let the decision variables $x_{kl_kA_{l_k}}$ be binary variable, and satisfy $x_{kl_kA_{l_k}}=1$ when the part p_k selects the A_{l_k} th design scheme provided by the l_k th supplier, otherwise $x_{kl_kA_{l_k}}=0$.

Taking into account financial consideration in supplier involved product development, the selection of PCS with the objective of maximizing PI can be formulated as a 0-1 integer programming model (PCS):

$$\max IPI(x)=\sum_{k=1}^{h}\sum_{l_k=1}^{n_k}\sum_{A_{l_k}}^{m_{l_k}}v_k\cdot PI_2(D_{kl_kA_{l_k}})x_{kl_kA_{l_k}} \tag{5.11}$$

$$\text{s.t. } \sum_{l_k=1}^{n_k}\sum_{A_{l_k}}^{m_{l_k}}x_{kl_kA_{l_k}}=1,\ \forall k=1,2,\cdots,h \tag{5.12}$$

$$\sum_{k=1}^{h}\sum_{l_k=1}^{n_k}\sum_{A_{l_k}}^{m_{l_k}}c(D_{kl_kA_{l_k}})x_{kl_kA_{l_k}}\le C \tag{5.13}$$

$$x_{kl_kA_{l_k}}\in\{0,1\}\quad 1\le k\le h\quad 1\le l_k\le n_k\quad 1\le D_{l_k}\le m_{l_k} \tag{5.14}$$

where *C* is the design budget of the product pre-specified by design teams. In the PCS model, equation (5.11) is the objective function to maximize integrated performance indicator; Equation (5.12) implies that for each part of the product, only one design scheme is selected; Equation (5.13) is the design budget constraint in the product design scheme.

The PCS model is a 0-1 integer linear programming model which can be solved by conventional algorithms, e.g., Branch and Bound. It can be observed from Section 5.2 that the weight vector of parts is obtained by mapping weighs of customer requirements, and the objective function of the model PCS reflects the customer requirements and equates to the idea of QFD.

5.6 An Illustrative Example

5.6.1 Background of the Illustrated Example

A practical door design in Gienow is introduced in this section to illustrate the application of the proposed method. During the development of a new product or product improvements in the enterprise, supplier involvement has been considered for several years. Now the enterprise is developing a new type of door. The parts of this new door are supplied from several sources. From Gienow, the four ambiguous customer requirements, i.e., "Energy saving" (CR1), "Less frost on interior of glass and frame" (CR2), "Strong structure" (CR3), "Quiet inside" (CR4), and pairwise comparison data have been obtained through a computer-aided survey system. Based on Saaty's method, their relative importance weights are calculated as (0.1, 0.2, 0.1, 0.6). Six TAs, i.e., "Air leakage" (TA1), "Watertightness" (TA2), "Wind resistance" (TA3), "Condensation resistance" (TA4), "Visible transmittance" (TA5), "Energy rating" (TA6), the customer requirements and their weights are illustrated in Table 5.1.

Table 5.1 HoQ1 of product planning

	TAs	TA1	TA2	TA3	TA4	TA5	TA6
	TA1	1	0.33	0	0	0	0
	TA2	0.33	1	0.56	0	0	0
	TA3	0	0.56	1	0	0	0
	TA4	0	0	0	1	0.33	0.33
	TA5	0	0	0	0.33	1	0.33
	TA6	0	0	0	0.33	0.33	1
CRs	Weights	0.04	0.101	0.124	0.229	0.222	0.287
CR1	0.1	5	9	1	0	0	0
CR2	0.2	1	0	0	5	5	0
CR3	0.1	0	0	9	0	0	0
CR4	0.6	0	0	3	5	3	9

To meet functional requirements, the engineers determine three major parts, i.e., film coating (PA1), weather strip (PA2) and frame (PA3). After quantification in terms of the information provided by the engineers, the first and second HoQs are established and illustrated in Tables 5.1 and 5.2, where the CR_i and TA_j denote the CRs and TAs respectively. In Table 5.1, the relationships between CRs and TAs are quantified by scale 1-3-5-9 and the correlations among TAs are quantified in a normalized way. The relationship matrix between TAs and PCs and the correlations among PAs in Table 5.2 are explained in a similar way.

Table 5.2 HoQ2 of parts product planning

	PAs	PA1	PA2	PA3
	PA1	1	0.33	0.33
	PA2	0.33	1	0.56
	PA3	0.33	0.56	1
TAs	Weights	0.457	0.270	0.273
TA1	0.040	9	3	9
TA2	0.101	0	3	9
TA3	0.124	0	9	3
TA4	0.229	9	0	0
TA5	0.222	9	0	0
TA6	0.287	9	0	0

The weights of the TAs indicated in Table 5.1 and the weights of the parts shown in Table 5.2 are obtained by the formulae (5.1) and (5.2), respectively.

$$U^* = (0.04, 0.101, 0.124, 0.229, 0.222, 0.287)$$

$$V^* = (0.457, 0.270, 0.273)$$

During the design of film coating, weather stripping and door framing, there are several suppliers. Each provides more than one design scheme. For simplicity, assume that three suppliers of film coating denoted by S11, S12, S13 provide one, two and three design schemes. There is only one supplier for the weather strip S21 and it provides five alternative design solutions.

Two suppliers of the door frame are denoted by S31, S32, and each provides two alternative design solutions for the frame of door. The relationships between parts, suppliers, and alternative solutions, as well as the costs of design schemes provided by suppliers, are presented in the first four columns in Table 5.3.

Table 5.3 Evaluation results of the supplier, alternative solution, and design scheme

Parts	Suppliers	Alternative Solution (AS)	Cost of design Scheme (*100)	Evaluation of supplier g_k (S_k)	PI of AS (PI_1)	PI of design Scheme (PI_2)
Film coating	S_{11}	D_{111}	18.9	0.7	0.7	0.7
	S_{12}	D_{121}	19.2	0.9	0.9	0.9
		D_{122}	19.0		0.7	0.76
	S_{13}	D_{131}	19.8	0.7	0.9	0.84
		D_{132}	19.2		0.7	0.70
		D_{133}	18.7		0.5	0.56
Weather stripping	S_{21}	D_{211}	2.4	0.9	0.9	0.90
		D_{212}	1.9		0.7	0.76
		D_{213}	1.6		0.5	0.62
		D_{214}	1.5		0.5	0.62
		D_{215}	1.9		0.7	0.76
Frame	S_{31}	D_{311}	0.8	0.7	0.9	0.84
		D_{312}	0.6		0.7	0.70
	S_{32}	D_{321}	0.9	0.7	0.9	0.84
		D_{322}	0.5		0.7	0.70

5.6.2 Evaluation of the Supplier and Design Scheme

During the assessment of suppliers, the first supplier of film coating, S_{11}, is illustrated as an example. Four evaluation classes, excellent, good, normal, and poor are selected; their corresponding numerical values are given as 0.9, 0.7, 0.5, and 0.3, respectively. Five influencing factors including price, quality, core design ability, credit standing level, and supply capacity are selected and their weights are given as 0.2, 0.4, 0.2, 0.1, and 0.1, respectively. During the assessment, members from the engineering department and procurement department evaluate suppliers from each attribute (e.g., price) separately. From this evaluation, the assessment vector (e.g., 0.3, 0.8, 0.4, and 0.1) and subsequently the assessment matrix can be obtained. Let the assessment matrix of the supplier obtained in this way be:

$$\mathbf{O} = \begin{pmatrix} 0.3 & 0.8 & 0.4 & 0.1 \\ 0.2 & 0.7 & 0.4 & 0.1 \\ 0.7 & 0.5 & 0.3 & 0.1 \\ 0.2 & 0.8 & 0.4 & 0.1 \\ 0.3 & 0.4 & 0.6 & 0.4 \end{pmatrix}$$

where the second row to the last row denote the assessment vectors of the quality, core design ability, credit standing level, and supply capacity.

Using the formula $\mathbf{B} = \mathbf{W} \times \mathbf{O}$, the fuzzy synthesis evaluation vector $\mathbf{B}$ = (0.27, 0.56, 0.48, 0.19) can be obtained. Because max (b_j) = b_2 = 0.56, the evaluation class of the supplier S_{11} is a second class, i.e., good, using the maximum degree of membership method and its numerical value 0.56. As a result, the numerical value of the fuzzy synthesis evaluation of the supplier S_{11} is given as $g_1(s_{11}) = 0.56$.

During the assessment of alternative solutions of the design for film coating, the following 11 attributes are considered: meet the frames u_1, easy to replace u_2, flexible u_3, moveable u_4, the scope of temperature u_5, work condition u_6, drafty u_7, display size u_8, resolution ratio u_9, refurbish rate u_{10}, and space u_{11}. These attributes are categorized into subclasses, i.e., Customer (CT), Examiner (EX), and Expert (EP) from the perspective of the evaluator. The first two attributes belong to the CT subclass. The attributes numbered from 3-5 are in EX subclass, and the others are in EP subclass. For example, an alternative solution is evaluated from the customer's perspective under consideration of the attributes of u_1, u_2, and u_3. Weights for these subclasses are given as 0.3, 0.25, and 0.45. The weight vectors of these attributes in the CT, EX, and EP subclasses are given as $\mathbf{W}_1$, $\mathbf{W}_2$ and $\mathbf{W}_3$ respectively, which are:

$$\mathbf{W}_1 = (0.3, 0.25, 0.45) \qquad \mathbf{W}_2 = (0.25, 0.25, 0.25, 0.25) \quad \mathbf{W}_3 = (0.3, 0.3, 0.20, 0.20)$$

The set of evaluation grades of an alternative solution is given in four classes: ε_1 (first-class), ε_2 (second-class), ε_3 (inferior) and ε_4 (waster), i.e., $\Theta = \{\varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_4\}$.

For the alternative solution D_{111}, the assessment matrixes of Customers, Examiners and Experts denoted by $\mathbf{R}_1$, $\mathbf{R}_2$ and $\mathbf{R}_3$ are given as follows:

$$\mathbf{R}_1 = \begin{pmatrix} 0.36 & 0.24 & 0.13 & 0.27 \\ 0.20 & 0.32 & 0.25 & 0.23 \\ 0.60 & 0.30 & 0.10 & 0 \end{pmatrix}$$

$$\mathbf{R}_2 = \begin{pmatrix} 0.30 & 0.28 & 0.24 & 0.18 \\ 0.26 & 0.36 & 0.12 & 0.20 \\ 0.35 & 0.30 & 0.20 & 0.15 \\ 0.22 & 0.42 & 0.16 & 0.10 \end{pmatrix}$$

$$\mathbf{R}_3 = \begin{pmatrix} 0.24 & 0.56 & 0.10 & 0.10 \\ 0.34 & 0.48 & 0.15 & 0.03 \\ 0.38 & 0.24 & 0.08 & 0.20 \\ 0.24 & 0.28 & 0.30 & 0.18 \end{pmatrix}$$

By multiplying the weight vector and assessment matrix, corresponding assessment vectors under subclasses CT, ET, and EP denoted by $\mathbf{B}_1$, $\mathbf{B}_2$, and $\mathbf{B}_3$ are obtained as follows:

$\mathbf{B}_1 = (0.43, 0.29, 0.14, 0.14)$ $\mathbf{B}_2 = (0.28, 0.34, 0.18, 0.16)$ $\mathbf{B}_3 = (0.30, 0.42, 0.15, 0.12)$

The assessment vector of multi-class fuzzy synthesis evaluation is finally given by

$$\mathbf{B} = \mathbf{W} \times \begin{pmatrix} \mathbf{B}_1 \\ \mathbf{B}_2 \\ \mathbf{B}_3 \end{pmatrix} = (0.30, 0.25, 0.45) \begin{pmatrix} 0.43 & 0.29 & 0.14 & 0.14 \\ 0.28 & 0.34 & 0.18 & 0.16 \\ 0.30 & 0.42 & 0.15 & 0.12 \end{pmatrix} = (0.33, 0.36, 0.15, 0.14)$$

The alternative solution, D_{111}, is evaluated as second class (good), and the performance indicator of the alternative solution is PI_1 $(D_{111}) = 0.7$. Aggregating the evaluation grade of the supplier and the alternative solution using a Weight Sum Operator, the PI of the first design scheme for file coating provided by the first supplier is,

$$PI_2(D_{111}) = 0.3 \times g_1(s_{11}) + 0.7 \times PI_1(D_{111}) = 0.3 \times 0.7 + 0.7 \times 0.7 = 0.70$$

The supplier and the alternative solution are given weights 0.3 and 0.7 respectively, when evaluating a design scheme.

Likewise, the other suppliers, alternative solution, and design schemes are evaluated and the results are shown in the last three columns in Table 5.3

5.6.3 Selection of Parts Combinatorial Scheme (PCS)

As indicated in Table 5.4, there are six design schemes from three suppliers for film coating, five design schemes for weather stripping, and four design schemes for frame from two suppliers. In total, there are 120 alternatives for PCS for a door. Given a design cost budget of 22 (*100) Dollars, using the tool software LINGO, one can obtain the optimal part combination design as shown in Table 5.4.

Table 5.4 Part combinatorial schemes vary with design budget and comparison with competitive companies.

Design budget	Part Combinatorial Scheme (PCS)	Costs for the PCS (*100$)	Integrated performance indicator of PCS
21.0	(D_{122}, D_{214} , D_{322})	21.0	0.7088667
22.0	(D_{111}, D_{212} , D_{311})	22.0	0.84582
23.0	(D_{121}, D_{211} , D_{311})	23.0	0.88362
24.0	(D_{121}, D_{211} , D_{311})	23.0	0.88362
24.5	(D_{121}, D_{211} , D_{311})	23.0	0.88362
25.5	(D_{121}, D_{211} , D_{311})	23.0	0.88362
Competitive Company Door		Costs for the door (*100 $)	Integrated Performance Indicator of the door
Company 1	N/A	24.5	0.70516
Company 2	N/A	25.5	0.75442
Company 3	N/A	22.0	0.54878

Table 5.5. The part combinatorial scheme of the example using the proposed model

Max S	X_{111}	X_{121}	X_{122}	X_{131}	X_{132}	X_{133}	X_{211}	X_{212}	X_{213}	X_{214}	X_{215}	X_{311}	X_{312}	X_{321}	X_{322}
0.84582	1	0	0	0	0	0	0	1	0	0	0	1	0	0	0

From Table 5.4, it is illustrated that the parts combinatorial scheme is (D_{111}, D_{212}, D_{311}) with the IPI being 0.84582. The PCS and its IPI under different values of design budget are shown in the first six rows in Table 5.4. The costs of a door from competitive companies and their IPIs are presented in the last three rows in Table 5.4 as a comparison. In Table 5.3, the IPI of the PCS presented in the last column increases with the design budget, however, the largest cost for the design is \$2300. In light of the part combinatorial scheme, the maximum IPI can be achieved at 0.88362 with a cost of \$2300 even though the design budget is greater than \$2300. It also shows that the developed door made from the PCS performs better than the ones from competitive companies, even though they charge more.

5.7 Summary

By introducing the concepts of performance indicators and integrated performance indicators, a two-layer fuzzy synthesis evaluation method is applied to assess part design scheme in supplier involved new product development processes. Combining the information of HoQ and evaluation results of the part design scheme into the selection of part design schemes, and taking into account design budgets, a 0-1 integer programming model is developed for selection of part combinatorial schemes in supplier-involved part deployment processes. This approach is different because it considers the involvement of part-suppliers during the conceptual design process and it combines evaluation and optimization for part design scheme selection. A software system of evaluation and selection of supplier involved part design (ESSIPD) has been developed to facilitate the application of the proposed method in practical part design decision making.

CHAPTER 6: CONCLUSIONS AND FUTURE WORK

The rapid development of technology is enabling to allow for a greater involvement of suppliers in the development of products. This supplier involvement can be called a product development chain or product-oriented supply chain. The first problem in the development of this new paradigm is how to extend the quality function deployment (QFD) methodology to include the voices of both customers and suppliers. Second, current research on supplier involvement in product development is mainly confined to the forms, roles, timing and extent of supplier involvement, as well as other qualitative studies using comparative analysis, benchmarking analysis, interviews or/and questionnaire surveys, and case studies. Two of the key issues in managing supplier involvement in product development have received little attention and require further detailed investigations. The key issues are: (1) optimally planning design activities, and (2) quantitatively evaluating and assessing the contributions of suppliers toward quality, cost, lead-time and customer satisfaction of a product.

6.1 Contributions

The contributions of this thesis work can be summarized as follows:

(1) A planning approach supported by mathematical programming, QFD and ANP has been developed to achieve the maximum customer satisfaction considering various customer requirements and technical attributes. The relationships and correlations among attributes in a HoQ and the costs for achieving certain degrees of design targets are formulated mathematically.

(2) Concepts of actual attainments and planned attainments for TAs (technical attributes), primary costs, actual costs, and planned costs are adopted in solving resource allocation problems in product development and improvement. Decision-makers can make use of the set of feasible solutions obtained from the proposed optimization model at various desired levels of satisfaction to create product design strategies which will support more practical and cost-effective QFD planning under resource constraints.

(3) The concepts of performance indicator and integrated performance indicators are introduced and a two-layer fuzzy synthesis evaluation method is applied to assess the part design scheme in a supplier-involved new product development process. Combining the information of HoQ and evaluation results of the part design scheme with the selection of part design schemes, and considering the design budget, a 0-1 integer programming model is developed for selection of part combinatorial schemes (PCS) in supplier involved part deployment processes.

6.2 Future Work

Through the research project reported in this thesis, a customer and supplier involved product development process supported by a mathematical programming-based QFD method has been developed. However, some topics or problems need to be further investigated, which are summarized as follows:

(1) In the conventional QFD approach, decisions are normally made based on individual planning phases. Product planning, part deployment planning and production process have been treated as two separate problems. Taking into account different phases in

product development, an integrated model for overall customer satisfaction in product development should be developed.

(2) Optimization models are assumed to be single objective mathematical programming models. In practice, more than one objective, such as customer satisfaction, manufacturing cost, and production lead time, may be considered simultaneously. A multi-objective optimization model needs to be further developed.

(3) Methodologies, models and algorithms for prioritizing customer requirements and planning product design activities at earlier stages of OKP product development processes have been developed. To deal with complicated real cases, more efficient methods and algorithms should be developed to analyze and design integrated models involving both discrete and continuous parameters.

PUBLICATION LIST

Dong, Y., Dean, P., Tu, Y.L., Xue, D., Tang, J.F. (2006). Part design in supplier involved one-of-a-kind product development. The 7th International Conference on Frontiers of Design and Manufacturing, June 17-19, Guangzhou, China.

Dong, Y., Dean P., Janiszewski G. (2007). Customer involvement catalog builder based on Internet/Intranet in OKP. International Conference on Service Systems and Service Management, June 09-11, Chengdu, China.

Tang, J.F., Chen, Y.Z., Dong, Y. (2004). An integrated product development model based on Quality Function Deployment with customer and supplier involvement. The Asia Journal on Quality 5(4): 50-60.

Tang, J.F., Zhang, Y.E., Tu, Y.L., Chen, Y.Z., Dong, Y. (2005). Synthesis, evaluation and selection of parts design scheme in supplier involved product development. Concurrent Engineering: Research and Applications 13(4): 277-290.

Li, X.D, Tu, Y.L, Xue, D., Dong, Y. (2006) Importance measures for customer requirements and technical attributes in fuzzy environment. Proceedings of the 17th IASTED International Conference on Modelling and Simulation, May 24-26, Montreal, Canada.

REFERENCES

Akao, Y.A. (1990). Quality function deployment: integrating customer requirements into product design. Cambridge, MA., Productivity press.

Akao, Y.A., Mazur., G.H. (2003). The leading edge in QFD: past, present, and future. International Journal of Quality & Reliability Management 20(1): 20-35.

Bidault, F.C.D., Butler, C. (1998). The drivers of cooperation between buyers and suppliers for product innovation. Research Policy 26(7-8): 719-732.

Bonaccorsi, A., Lipparini, A. (1994). Strategic partnerships in new product development: An Italian case study. Journal of Product Innovation Management 2(11): 134-145.

Brown, S.L., Eisenhardt, K. M. (1995). Product development: past research, present findings, and future directions. Academy of Management Review 20(2): 343-378.

Caputo, M.A., Zirpoli, F. (2002). Supplier involvement in automotive component design: outsourcing strategies and supply chain management. International Journal of Technology Management 23(1-3): 129-154.

Chan, L.K., Wu, M.L. (2002). Quality function deployment: a literature review. European Journal of Operational Research 143(3): 464-497.

Chen, Y.Z., Tang, J.F., Ren, Z. (2003). A design scheme selection program model based on house of quality. Chinese Journal of Computer Integrated Manufacture Systems-CIMS 9(2): 127-131.

Chen, Y., Fung, R., Yang, J. (2005). Fuzzy expected value modeling approach for determining target values of engineering characteristics in QFD. International Journal of Production Research 43(17): 3583-3604.

Chen, L.H., Ko, W.C. (2009). Fuzzy linear programming models for new product design using QFD with FMEA. Applied Mathematical Modelling 33(2): 633 - 647.

Choy, K.L.L., Lee, W.B., Lau, C.W., Choy L.C. (2005). A knowledge-based supplier intelligence retrieval system for outsource manufacturing. Knowledge-Based Systems 18(1): 1-17.

Dre, C., Jayanth, J., Shawnee, K.V. (2000). The ability to minimize the timing of new product development and introduction: an examination of antecedent factors in the North American automobile supplier industry. Journal of Product Innovation Management 17(1): 24-40.

Eliashberg, J., Lilien, G.L., Rao, V.R. (1997). Minimizing technological oversights: a marketing research perspective. Technological innovation: oversights and foresights. R.Garud, P. R. Nayyar and Z.B.Shapirs. New York, Cambridge University Press: 214-230.

Erol, I., Ferrell, W.G. (2003). A methodology for selection problems with multiple, conflicting and both qualitative and quantitative criteria objectives. International Journal of Production Economics 86(3): 187-199.

Feng, C. X., Wang, J., Wang, J.S. (2001). An optimization model for concurrent selection of tolerances and suppliers. Computers and Industrial Engineering 40(1-2): 15-33.

Fung, R.Y.K., Tang, J.F., Tu, Y.L., Chen, Y.Z. (2003). Modeling of quality function deployment planning with resource allocation. Research in Engineering Design with Applications 14(4): 247-255.

Gary, L.R., Handfield, R.B. (2002). Benefits associated with supplier integration into new product development under conditions of technology uncertainty. J. of Business Research 55(5): 389-400.

Gui, Z., Lin, Z., Yan, M.S. (2003). Planning for parts selection in product development. Chinese Journal of Machine Tool and Hydraulic Pressure 10(1): 23-28.

Gupta, S., Krishnan, V. (1999). Integrated component and supplier selection for a product family. Production and Operations Management 8(2): 163-182.

Han, C. H., Kim, J.K., Choi, S.H. (2004). Product design resources optimization using a non-linear fuzzy quality function deployment model. International Journal of Production Research 40(3): 585-599.

Hauser, J. R., Clausing, D. (1988). The house of quality. Harvard Business Review 5-6: 63-73.

Herrmann, A., Huber, F., Braunstein, C. (2000). Market-driven product and service design: bridging the gap between customer needs, quality management, and customer satisfaction. International Journal of Production Economics 66(1): 77-96.

Holmenand, E., Kristensen, P.S. (1998). Supplier roles in product development: interaction versus task partitioning. European Journal of Purchasing & Supply Management 4(2-3): 185-193.

Hoyle, C.J., Wei, C. (2009). Product attribute function deployment (PAFD) for decision-based conceptual design. IEEE Transactions on Engineering Management 56(2): 271-284

Huang, G.Q., Mak, K.L. (2000). Modeling the customer-supplier interface over the world-wide web to facilitate early supplier involvement in the new product development. Proceedings of the Institution of Mechanical Engineers – Part B Engineering Manufacturing 214(9): 759-769.

Huang, G.Q., Mak, K.L. (2002). Synchronous quality function deployment (QFD) over world wide web. Computers & Industrial Engineering 42(2-4): 425-431.

Huang, G.Q., Zhao, J.B., Mak, K.L. (2003). Early supplier involvement in new product dvelopment with WeBid: a case study on video conferencing system. Journal of Computing and Information Science in Engineering 3(4): 363-365.

Humphreys, P., Huang, G., Cadden, T., Mclvor, R. (2007). Integrating design metrics within early supplier selection process. Journal of Purchasing & Supply Management 13(1): 42-52.

Iranmanesh, S.H., Thomson, V., Salimi, M.H. (2005). Design parameter estimation using a modified QFD method to improve customer perception. Journal of Concurrent Engineering: Research and Applications 13(1): 57-67.

Karsak, E.E., Sozer, S., Alptekin S.E. (2002). Product planning in quality function deployment using a combined analytical network process and goal programming approach. Computers and Industrial Engineering 44(1): 171-190.

Kannan, G. (2008). Implementation of fuzzy quality function deployment in an automobile component to improve the quality characteristics. Quality Engineering 20(3): 321-33.

Kim, K. J., Moskowitz, H., Dhingra, A., Evans, G. (2000). Fuzzy multicriteria models for quality function deployment. European Journal of Operational Research 121(3): 504–518.

LaBahn, D. W., Krapfel, R. (2000). Early supplier involvement in customer new product development: a contingency model of component supplier. Intentional Journal of Business Research 47(3): 173-190.

Lee, Y.C., Sheu, L.C., Tsou, Y.G. (2008). Quality function deployment implementation based on fuzzy kano model: an application in PLM system. Computers & Industrial Engineering 55(1):48-63.

Li, X.D., Tu, Y.L., Xue, D., Dong, Y. (2006). Importance measures for customer requirements and technical attributes in fuzzy environment. Proceedings of the 17th IASTED International Conference on Modelling and Simulation. Montreal, Canada. 193-200.

Liang, J.S., Wei, P.W. (2006). Conceptual design system in a web-based virtual interactive environment for product development. International Journal of Advanced Manufacturing Technology 30(11-12): 1010-1020.

Liu, B., Liu, K. L. (2002). Expected value of fuzzy variable and fuzzy expected value models. IEEE Transactions on Fuzzy Systems 10(4): 445-450.

Maffin, D., Braiden, P. (2001). Manufacturing and supplier roles in product development. International Journal of Production Economics 69(2): 205-213.

Ni, M., Xu, X., Deng, S. (2007). Extended QFD and data-mining-based methods for supplier selection in mass customization. International Journal of Computer Integrated Manufacturing 20(2-3): 280-291.

Onesime, O., Xu, X., Zhan, D. (2004). A decision support system for supplier selection process. International Journal of Information Technology & Decision Making 3(3): 453-470.

Park, T., Kim, K. (1998). Determination of an optimal set of design requirements using house of quality. Journal of Operations Management 16(5): 569–581.

Partovi, F.Y., Epperly, J.M. (2001). An analytic model to quantify strategic service vision. International Journal of Service Industry Management 12(5): 476–499.

Partovi, F.Y., Corredoira, R.A. (2002). Quality function deployment for the good of soccer. European Journal of Operational Research 137(3): 642–656.

Ragatz, G. L., Handfield, R.B., Petersen, K.J. (2002). Benefits associated with supplier integration into new product development under conditions of technology uncertainty. Journal of Business Research 55(5): 389-400.

Rolstadås, A. (1991). ESPRIT basic research action no. 3143 – FOF production theory. Computers in Industry 16(2): 129-139.

Saaty, T.L., Takizawa, M. (1986). Dependence and independence: from linear hierarchies to nonlinear networks. European Journal of Operational Research 26(2): 229-237.

Saaty, T.L. (1996). Decision making with dependence and feedback: the analytic network process. RWS Publications, Pittsburgh.

Sharma, J.R., Sharma, D.K., Rawani, A.M. (2006). Quality driven product development. Manufacturing Engineer 85(3): 38 – 41.

Shen, X.X., Tan, K.C., Xie, M. (2001). The implementation of quality function deployment based on linguistic data. Journal of Intelligent Manufacturing 12(1): 65–75.

Sireli, Y., Kauffmann, P., Ozan, E. (2007). Integration of Kano's model into QFD for multiple product design. Engineering Management, IEEE Transactions 54(2):380 – 390.

Sobrero, M., Roberts, E.W. (2002). Strategic management of supplier-manufacturer relations in new product development. Research Policy 31(1): 159-182.

Sohn, S.Y., Choi, I.S. (2001). Fuzzy QFD for supply chain management with reliability consideration. Reliability Engineering & Systems Safety 72(3): 327-334.

Sun, J., Kalenchuk, D.K., Xue, D., Gu, P. (2000). Design candidate identification using neural network-based fuzzy reasoning. Robotics and Computer Integrated Manufacturing 16(5): 383-396.

Tang, J.F., Fung, R.Y.K., Xu, B.D., Wang, D.W. (2002). A new approach to quality function deployment planning with financial consideration. Computers & Operations Research 29(1): 1447 - 1463.

Tang, J.F., Chen, Y., Dong, Y. (2004). An integrated product development model based on quality function deployment with customer and supplier involvement. The Asia Journal on Quality 5(4): 50-60.

Tang, J.F., Zhan, Y.E., Tu, Y.L., Chen,Y.Z., Dong, Y. (2005). Synthesis, evaluation, and selection of parts design scheme in supplier involved product development. Concurrent Engineering: Research and Applications 13(4): 277-290.

Toni, A.D., Nassimbeni, G. (2001). A method for the evaluation of suppliers' co-design effort. International Journal of Production Economics 72(2): 169-180.

Tu, Y.L. (1996). A framework for production planning and control in a virtual OKP company. Technical Papers of North American Manufacturing Research Institution of SME: 121–126.

Tu, Y.L., Fung, R.Y.K., Tang, J.F., Kam, J.J. (2003). Computer aided customer interface for rapid product development. The International Journal of Advanced Manufacturing Technology 21: 743-753.

Tu, Y., Dean, P., Xue, D., Li, W. (2006). One-of-a-kind product design and manufacture. Proceedings of the 7th International Conference on Frontiers of Design and Manufacturing. Guangzhou, China, 185-190.

Ulrich, K.T., Eppinger, S.D. (2000). Product design and development. New York, McGraw-Hill.

Vangegas, L.V., Labib, A.W. (2000). A fuzzy quality function deployment (FQFD) model for deriving optimum targets. Internatinal Journal of Production Research 39(1): 99-120.

Wang, J., Lin, H.Y. (2006). A fuzzy hybrid decision-aid model for selecting partners in the design chain. International Journal of Production Research 44(10): 2047-2069.

Wasserman, G.S. (1993). On how to prioritize design requirements during the QFD planning process. IIE Transactions 25(3): 59-65.

Wortmann, J.C., Muntslag, D.R., Timmermans, P.J.M. (1997). Customer-driven manufacturing. London, Chapman & Hall.

Wynstra, F., Pierick, E.T. (2000). Managing supplier involvement in new product development: a portfolio approach. European Journal of Purchasing & Supply Management 6(1): 49-57.

Wynstra, F., Weele, A, Weggemann, M. (2001). Managing supplier involvement in product development: three critical issues. European Management Journal 19(2): 157-167.

Xue, D., Dong, Z. (1997). Coding and clustering of design and manufacturing features for concurrent design. Computers in Industry 34(1): 139-153.