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An approach for manufacturing strategy development based on fuzzy-QFD

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ABSTRACT

Today most research related to manufacturing strategy development concentrates on descriptive processes and conceptual models, and therefore lacks the capability of assessing the supportive degree of manufacturing strategy to competitive priorities, and is also difficult to assess the congruence among various decisions of the manufacturing strategy. This paper proposes an approach for manufacturing strategy development based on quality function deployment (QFD). The study starts by analyzing the process of manufacturing strategy development and the features of QFD. Thereafter, a methodology related to manufacturing strategy development based on QFD is developed, which comprises two stages and eleven steps. This approach uses QFD as a transforming device to link competitive factors with manufacturing decision categories such as structural decision categories and infrastructural categories, and uses QFD as a main tool in different stages of manufacturing strategy development process. This paper also integrates fuzzy set theory and house of quality (HOQ) in order to provide a structural tool to capture the inherent imprecision and vagueness of decision-relevant inputs and to facilitate the analysis of decision-relevant QFD information. A case is given to illustrate the utilization of the proposed approach at the end of this paper.

1. Introduction

Manufacturing strategy is part of a manufacturing company's total strategy. It contains the pattern of strategic decisions and actions which set the role, objectives and activities of the manufacturing in a manufacturing company. Just as with any type of strategy, we can consider its content and process separately. The content of manufacturing strategy comprises the specific decisions and actions which set the manufacturing role, objectives and activities. The process of manufacturing strategy refers the procedures which can be used to develop manufacturing strategies (Slack, Chambers, & Johnston, 2004).

Within strategy research, a clear distinction between research on the content of strategy and research on the process of strategy has been presented for a long time (Hallgren & Olhager, 2006). At present, most research focuses on strategy content, however, research on manufacturing strategy development is relatively limited (Dangayach & Deshmukh, 2001).

Manufacturing strategy comprises a series of structural and infrastructural decisions which provide the necessary support for the relevant order winners and qualifiers of the different market segments of a company. From Hill's point of view, manufacturing strategy should be supportive to the achievement of a company's competitive priorities. Hill proposes a five-step procedure to link manufacturing strategy to order winners in order to achieve the congruence between them (Hill, 1995). This procedure is an iterative process, in which the identification of competitive factors is seen as critical. At this stage, any mismatches between the requirements of organization's strategy and the capability of its manufacturing become evident. So far, different analysis models have been developed to describe the congruence between various aspects of manufacturing strategy and competitive priorities. Hayes and Wheelwright provide a tool for the assessment of manufacturing's strategic role, and introduce product/process matrix (Hayes & Wheelwright, 1984). Voss (1990) and Marucheck, Pannesi, and Anderson (1990) have made empirical observation of the strategy formulation and implementation process, and find that the process is essentially hierarchical, which is consistent with Skinner's approach. Skinner's approach have led to a predominant hierarchical process model starting from corporate strategy forming the context for the business strategy which in turn forms the context for each functional strategy including manufacturing (Skinner, 1969). Miltenburg proposes an overall framework with three steps for performing an analysis of a company's manufacturing strategy in terms of congruence with the production system, its products, and its capabilities (Miltenburg, 1995). Safsten and Winroth investigate the usability of Miltenburg's framework in small and medium sized manufacturing companies, and further suggest some changes of the model (Safsten & Winroth, 2002). Lee, Jeong, Park, and Park (2002) propose a framework for a decision-support system to support the formulation of a manufacturing strategy which

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consists of manufacturing system modeling and analyzing performance measures. The proposed decision-support system enables the formulation of manufacturing strategy using what-if analysis against dynamic manufacturing environments. Quezada, Cordova, and O'Brien (2003) develop a methodology for the development of a manufacturing strategy by means of exploiting the concepts of the analytic hierarchy process. In terms of this methodology, a manufacturing strategy can be formulated by creating a five level hierarchy: focus, company objectives, strategic business units, critical success factors and manufacturing decision areas. This methodology also allows a strategic diagnosis of the current manufacturing system and the generation and evaluation of action plans to improve the company competitiveness. Slack et al. give some indications on how to assess the support from the operations function (Slack et al., 2004). Platts and Gregory propose a three-stage procedure of developing manufacturing strategy. The procedure uses profiles of market requirements and achieved performance to show up the gaps which the manufacturing strategy must address (Platts & Gregory, 2004). Karacapilidis, Adamides, and Evangelou (2006) develop a computerized knowledge management system for the collaborative development of manufacturing strategy. The system is used to capture the strategists' rationale and stimulates knowledge elicitation, and it can support the social and knowledge processes of collaborative strategy development by integrating a domain specific modeling formalism.

In summary, the majority research related to manufacturing strategy development has specified and described strategy development process, and as a result, many different methodologies related to strategy development have been suggested. Most literature has proposed many prescriptive processes, and the manufacturing strategy domain has being dominated by conceptual models (Hallgren & Olhager, 2006).

The quality function deployment (QFD) originated in 1972 in Japan as a methodology to be adopted to improve products quality in some Japanese firms (Hauser & Clausing, 1988). QFD methodology has introduced a twofold innovation in traditional product development processes. First, the application of QFD requires the careful consideration of customer during the development process (Akao, 1990). Second, the QFD approach has introduced the collaboration among different business areas as a prerequisite for product design.

Many authors have published papers discussing how to exploit QFD to enhance the quality of product or service design. Karsak, Sozer, and Alptekin (2002) present a systematic decision procedure to be used in QFD product planning. The proposed approach combined analytic network process and 0–1 goal programming approach to incorporate the customer needs and the product technical requirements systematically into the product design phase in QFD. Luo, Tang, and Wang (2008) put forward an optimization method for components selection based on QFD to minimize the difference between the customer's expectation and the selected product. The model is converted into an equivalent linear integer programming model to facilitate the solving approach, and Fuzzy customer requirements are also considered to deal with the uncertainties of human subjective judgment on customer requirements. Chaudhuria and Bhattacharyya (2009) link QFD with Conjoint Analysis through an integer programming based framework to determine the appropriate technical characteristics and consequently the right attribute levels. It is also proposed to measure the elements of the relationship matrix in QFD in a way so that the right levels of the attributes can be generated from the integer programming solution. Chen (2009) integrates QFD with process management techniques to optimize product design investment and process improvement. Process management is used to construct an integrated product and process development model to promote the effectiveness and benefits of applying QFD techniques. Deros, Rahman, Rahman, Ismail, and Said (2009) propose a method based on QFD to measure the service quality performance and identify critical service quality characteristics. In this method, QFD is used as a tool to improve quality in service industry by helping the firms involved to have clearer picture of quality requirements that could improve their customers' satisfaction.

In addition, some authors have also integrated QFD with other methods to improve QFD approach or to propose new approaches based on QFD. Bouchereau and Rowlands (2000) present an approach to incorporated QFD and fuzzy logic, and integrate artificial neural networks and the Taguchi method to produce an intelligent systems approach to QFD. Raharjo, Brombacher, and Xie (2008) propose generic ANP-based network model, which improves the QFD results' accuracy and flexibility. The proposed network model takes into account the crucial factors in new product design simultaneously. Chen and Ngai (2008) propose a novel fuzzy-QFD program modeling approach to complex product planning which integrates fuzzy set theory and QFD framework to optimize the values of engineering characteristics by taking the design uncertainty and financial considerations into account. In the proposed methodology, fuzzy set theory is used to account for design uncertainty, and the method of imprecision is employed to perform multiple-attribute synthesis to generate a family of synthesis strategies. Lee, Sheu, and Tsou (2008) presents an integrative approach by incorporating the Kano model with Fuzzy mode into the matrix of QFD to provide a new way to optimize the product design and enhance customer satisfaction. QFD matrix is used to assure that most critical needs of customers' are translated into the next phases of product development, and Fuzzy mode is used to improve subjective linguistic scale in Kano's two dimensional quality elements. Delice and Zülal (2009) propose a new QFD optimization approach combining mixed integer linear programming model and Kano model to acquire the optimized solution from a limited number of alternative the design requirements. The proposed model can be used to optimize the product development and in other applications of QFD such as quality management, planning, design, engineering and decision-making. Liang (2010) develops an approach of *fuzzy*-QFD to identify service management requirements for customer *quality* needs. This approach provides a method to construct a *fuzzy* relation matrix to link service management requirements and customer *quality* needs based on cross-functional expertise.

Some authors have also conducted categorical analysis about QFD's functional fields, applied industries and methodological development (Carnevalli & Miguel, 2008; Chan & Wu, 2002), and their findings have shown that QFD can be used as a tool to be applied in the development of strategies.

Therefore, QFD is a technique used to convert 'voice of the customer' into design, engineering, manufacturing and production in order to ensure product meeting the needs of the customers. It tries to capture what the customer needs and how it might be achieved through the effort of relevant functional areas. With these characteristics, QFD can be an effective tool to organize and carry out the manufacturing strategy development.

In recent years, the QFD methodology has been applied in the development of business or manufacturing strategies. Jugulum and Sefik (1998) realize that QFD can help organizations develop manufacturing strategies, and it can be incorporated into the classic steps of corporate planning to make strategy more effectively. Crowe and Cheng (1996) propose a methodology by using QFD in manufacturing strategic planning. The methodology comprises four stages called functional strategies, manufacturing priorities, action plans and detail tasks respectively. The proposed methodology provides a systematic tool to facilitate strategy development, and manufacturing strategy and action plans can be realized through the QFD process. Olhager and West (2002) use QFD for linking manufacturing flexibility to marketing requirements. Bottani and Rizzi (2006) suggest that QFD can be applied effectively to various issues such as business strategies and performance assessment.

Barad and Gien (2001) utilize QFD to deploy manufacturing strategies into improvement activities. They develop a structured two phased model for connecting the improvement actions of a company with its strategic and operating improvement needs. Dror and Barad (2002) use QFD to construct a performance measurement system based on the balanced scorecard map. Further, they develop a House of Strategy by using QFD matrix for translating the improvement needs of a company's business objectives into relative importance of its competitive priorities (Dror & Brard, 2006), and also suggest a mean square error (MSE) criterion to supporting the selection of vital competitive priorities to be improved. As the extension of their previous work, Barad and Dror (2008) utilize the QFD methodology for building the strategy map to extract the desired improvement needs in the company's objectives and to translate them into required improvement in its competitive priorities, required improvement in its core processes and, finally into the required improvement in the components of its organizational profile. Chuang, Yang, and Lin (2009) use the relationship matrix in QFD method to provide a tool for integrating the market trends, competitive and operational strategies, as well as manufacturing attributes. Bottani (2009) presents an approach based on QFD to develop agile strategy of enterprises. This approach aims at identifying the most appropriate enablers to be implemented by companies starting from competitive characteristics of the related market by linking competitive bases, agile attributes and agile enablers. The approach also exploits fuzzy logic to translate linguistics judgements required for relationships and correlations matrixes into numerical values.

However, there are still some limitations in the existing research and therefore further research is needed, e.g. (1) there still lacks formal mechanisms for translating qualitative "whats" into quantitative "hows" in QFD matrix, and the values of a certain alternative concerning a given attribute often cannot be precisely defined. To deal with this type of uncertainty, mathematical tools such as group decision-making and fuzzy set theory could be applied during the process. (2) Links between business strategy and manufacturing strategy is obscure, and the supportive degree of manufacturing strategy to competitive priorities cannot be determined. Thus, there is a need to develop a process which is able to derive manufacturing strategy from business strategy. (3) Low level of detail in current methodologies causes discontinuity in the process of manufacturing strategy development, and mutual influence between "hows" is usually ignored. Therefore, the methodology of manufacturing strategy development with systematic and detailed process is still needed. (4) Many methodologies proposed are too academic and complicated to be grasped and used by practicers in practice.

In this paper, we will present a manufacturing strategy development model based on QFD. The main objective of this paper is to introduce a methodology based on QFD that could develop the manufacturing strategy quantitatively. The main contributions of this paper include: (1) the methodology uses HOQ as a transforming device to link business strategy with manufacturing decision categories such as structural decision categories and infrastructural categories; (2) the methodology provides a platform for multiple decision-makers to identify competitive factors and to determine their relative importance to avoid the bias and minimize the partiality in the decision process, and group decision-making and fuzzy set theory are integrated with HOQ to provide a structured tool to capture the inaccurate decision-relevant inputs and to facilitate to analyze decision-relevant QFD information; (3) the methodology provides a detailed stepwise process for manufacturing strategy development and use HOQ as a main tool in different stages of manufacturing strategy development to ensure consistency of strategic manufacturing decisions; (4) the methodology is easy to be understood and grasped by practicers, and it provides a participating platform for stakeholders relating to manufacturing strategy development, which allows them to play their roles in the process of manufacturing strategy development.

The remainder of the paper is organized as follows. In the next paragraph, manufacturing strategy is first analyzed in term of strategy contents and process, and then the QFD methodology is briefly described. Following these discussions, a process of manufacturing strategy development based on QFD is proposed, and a fuzzy approach is introduced. Finally, a case is given which is able to show how to apply this methodology in practice, and concluding remarks are presented.

2. The contents and processes of manufacturing strategy

The concept of manufacturing strategy proposed by Skinner (1969) is defined as to exploit certain properties of the manufacturing function to achieve competitive advantages. Slack et al. (2004) refers the content of manufacturing strategy to be the specific decisions and actions setting the manufacturing role, objectives and activities; and refers the process of manufacturing strategy to be the method being used to make the specific content decisions.

2.1. The contents of manufacturing strategy

Specific decisions categories related to the content of manufacturing strategy are divided into structural strategic decisions and infrastructural strategic decisions (Franceschini & Rossetto, 1997). A manufacturing's structural decisions are those which primarily influence design activities, while infrastructural decisions are those which influence the planning and control, workforce organization, and improvement activities (Fine & Hax, 1985; Platts et al., 1998). Associating with these structural decisions and infrastructural decisions are policy areas. Table 1 specifies the policy areas of the main decision categories.

Depending on establishing the most appropriate process to manufacture products being capable of winning orders and depending on providing manufacturing infrastructure to support production, a manufacturing system can support to achieve corporate objectives.

2.2. The process of manufacturing strategy development

The process of manufacturing strategy development is here regarded as the procedures which are used to develop those man-

Table 1
Decision categories and associated policy areas presented by Hallgren and Olhager (2006).

Decision category	Policy areas
Structural	
Process technology	Process choice, technology, integration
Facilities	Size, location, specialization/focus
Capacity	Amount, timing, increment size
Vertical integration (VI)	Direction, extent, balance
Infrastructural	
Organization	Design, human resources, competence development
Manufacturing planning and control	System design, decision support, systems integration
Quality	Definition, role, tools
New product introduction (NPI)	Rate of innovation, product design, industrialization

ufacturing strategies in order to enhance the manufacturing function's capabilities. So far, different methodologies concerning the development of manufacturing strategy have been developed. Among them four perspectives emerge, which includes top-down perspective, bottom-up perspective, market requirements perspective, and manufacturing resources perspectives. Here we describe some representative methodologies to give an overview of how manufacturing strategies are formulated in practice.

Skinner (1969) recommends a top-down market-based hierarchical process model starting from corporate strategy forming the context for the business strategy which in turn forms the context for manufacturing strategy and other functional strategies. Hill (1995) proposes a methodology which consists of five steps procedure based on top-down and market requirements perspective. The most predominant characteristics of this methodology are that it involves the step of the identification of competitive factors, and by using competitive factors as translation device, it links business strategy and manufacturing strategy. Miltenburg (1995) suggests an overall framework for developing and analyzing manufacturing strategy based on manufacturing resource perspective. This framework comprises the steps to guide the development of manufacturing strategy. The framework first involves the steps of surveying the current situation, and then includes the steps of analyzing the congruence between the production system and manufacturing strategy. Hallgren and Olhager (2006) recommend a quantitative modeling approaches for manufacturing strategy. This approach formulates specific manufacturing objectives by starting from market requirements, and then the gap analysis is made based on assessing the conformance between objectives and manufacturing capabilities. Through the assessment improvement areas are identified and appropriate actions can be made with the decision categories to navigate the manufacturing capabilities towards manufacturing objectives. Platts and Gregory (2004) propose a methodology of manufacturing strategy development which involves developing an understanding of the market position of an organization by assessing the opportunities and threats within the competitive environment, and also involves identifying the factors which are required by the market and compares these to the level of achieved performance.

The methodologies described here are representatives of those available. However, none of them reflects all of the four perspectives described above, and none of them includes all the various points which are addressed by manufacturing strategy development procedures. In spite of this, there are some common elements existing in these methodologies, including:

- A process which links business strategy to manufacturing objectives by means of using competitive factors as translation device.
- A process which is market-based and a process which includes judging the relative importance of the various competitive factors in terms of customer's preferences.
- A procedure which includes assessing current achieved performance in terms of competitor performance levels or customer requirements.

These common elements are the basis of the new methodology of manufacturing strategy development which is developed in this paper.

3. Quality function deployment methodology (QFD)

Defined by the American Supplier Institute, QFD is 'A system for translating consumer requirements into appropriate company requirements at each stage from research and product development to engineering and manufacturing to marketing/sales and distribution'. Expressing with abstractive words, QFD can translate 'whats' into 'hows', and by assessing how each 'hows' impact on each 'whats', QFD makes it possible to rank 'hows' in terms of efficiency to reach the required 'whats'. Therefore, in addition to its capability of conducting customer requirements into product features, it is also a viable tool to organize and carry out the manufacturing strategy development quantitatively, has capability of assessing the supportive degree of manufacturing strategy to competitive priorities, and helps assessing the congruence among various decisions of the manufacturing strategy.

The QFD matrix, also called the 'house of quality (HOQ)', is a formal articulation of how a company sees the relationship between the requirements of the customer and the design characteristics of the new or improved product. Although the details of HOQ may vary between its different variants, the principle is generally common, i.e. to identify 'whats' and then to relate 'whats' to 'hows'.

The HOQ can be built by following steps suggested by Brown (1991) and Griffin and Hauser (1992). *Step* 1: identify the "whats", which are customer needs for a product or service expressed in the customer's own words, shown in area (A) in Fig. 1. "Whats" are weighted in order to express their relative importance. The weight of each "what" is listed in a column in the matrix, which is indicated in the area (B) in Fig. 1. *Step* 2: determine the "hows", which may affect one or more "whats", and are measurable attributes. "Hows" are identified by a multidisciplinary team and listed in columns in the HOQ marked as (C) on the matrix diagram, Fig. 1. *Step* 3: identify the relationship matrix, which are the core element of the matrix designated as area (D) in Fig. 1.

In order to complete this part of the HOQ, a team judges which "whats" impact which "hows" and to what degree. The relationships are expressed with graphic symbols that indicate how and to what extent each "how" meets each "what". Usually, symbols express three degrees of strength (weak, medium, strong), which are translated in an appropriate rating scale, such as 1–3–9 or 1–5–9. Absence of symbols means absence of relationships. *Step* 4: elaboration of the correlation matrix. The relationships among "hows" are specified on an array known as "the roof matrix" (*E*), which expresses how "hows" affect each other. A positive relationship indicates that two "hows" can complement or improve each other, while a negative one suggests that trade offs are required. Correlations are indicated with graphic symbols that express the degree of relation between "hows". Symbols are then translated into a four-value rating scale (strong negative, negative, positive, strong positive), such as 1–3–7–9 or 1–3–5–9. Again, it is possible to have no correlations between "hows". *Step* 5: action plan. The result of the matrix is the ranking of "hows" in descending order of importance (weights). Either the absolute and/or the relative importance of each "how" against "whats" have to be quantitatively evaluated. The weights of the "hows", identified as area

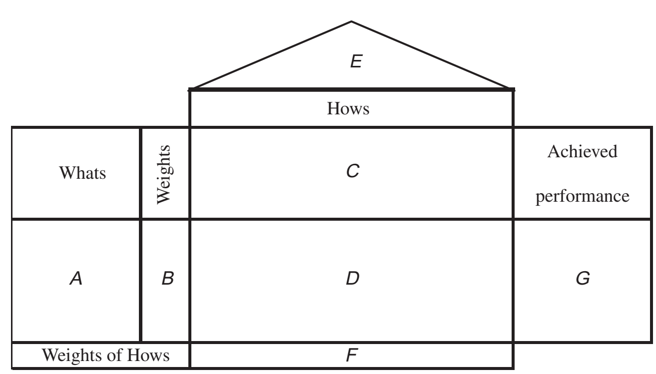


Fig. 1. The steps for constructing HOQ.

(*F*), are placed at the base of the HOQ. These weights are determined by

$$Weight(how)_i = \frac{1}{n} \times [V(how)_{i1} \times imp(what_1) + \cdots + V(how)_{in} \times imp(what_n)],$$

where $V(how)_{in}$ is the correlation value of "how_i" with "$what_n$", and $imp(what_n)$ represents the importance or priority of "$what_n$".

Step 6: company's manufacturing performances are evaluated against market's requirements. The results are added in a column in the right part of the matrix marked as area (*G*).

4. Manufacturing strategy development based on QFD

4.1. The characteristics of manufacturing strategy development based on QFD

Based on the analysis of the existing methodology related to the development of manufacturing strategy, we suggest a methodology of manufacturing strategy development, which is based on the translation of HOQ principles from product development field to manufacturing strategy development. While the traditional HOQ correlates customer requirements ("whats") with engineering characteristics of new product under development ("hows"), in the approach proposed "what" and "hows" are related to manufacturing strategy development.

The characteristics of this methodology are illustrated as following:

- Use competitive factors identified by business strategy as a links between business strategy and manufacturing strategy.
- Judge the relative importance of the various competitive factors in terms of customer's preferences, i.e. using marketing-based perspective.
- Assess current achieved performance in terms of competitor performance levels or customer requirements.
- Use HOQ as a transforming device to link competitive factors with manufacturing decision categories such as structural decision categories and infrastructural categories, and use HOQ as a main tool in different stages of manufacturing strategy development process.

4.2. The stages of manufacturing strategy development based on QFD

In creating a methodology of manufacturing strategy development based on QFD, we identify and propose two stages for developing manufacturing strategy. At the first stage, market requirements and competitive factors are identified respectively, and then the impact of each competitive factor on each market requirement is measured by using HOQ. At the second stage, competitive factors are used as "whats" in HOQ matrix, and manufacturing decision categories are identified and used as "hows" in HOQ matrix. Then the "how"–"what" correlation scores are determined and the "hows" are weighted. The result of the matrix is the ranking of "hows" in descending order of importance (weights), and this rank indicates what the key structural and infrastructural decisions are, and this is also an indication of the key manufacturing-related tasks.

4.2.1. Stage 1: determining competitive factors in terms of market requirements

There are seven steps comprised in Stage 1 which are shown as *Si* ($i = 1, 2, \ldots, 7$) in Fig. 2.

4.2.1.1. Step 1 (S1): identifying the "whats"—measuring market requirements. This step identifies the product characteristics which are identified by measuring market requirements, such as range, mix, volume, customization, and innovativeness, which the manufacturing will be required to provide. These product characteristics are used as "whats" in QFD matrix.

4.2.1.2. Step 2 (S2): comparing achieved performance of manufacturing with market requirements. In order to analyze the gap between current manufacturing performance and market requirements, achieved performance of manufacturing as outcomes of the current manufacturing strategy must be compared with the market requirements. This comparison identifies the areas where current manufacturing capabilities must improve, and further instructs manufacturing to take actions to close the gap.

4.2.1.3. Step 3 (S3): identifying competitive factors—"hows". This step translates market requirements into competitive factors, which links market requirements and manufacturing strategy. Many competitive factors have a direct correspondence internally to manufacturing. Hill (1995) has formally identified competitive factors as the key link between the marketing and manufacturing aspects of the strategy development. For instance, Delivery speed and reliability are dependent on both production lead times and flexibility, and product range, customization and innovativeness are based on internal flexibility (Olhager & West, 2002).

4.2.1.4. Step 4 (S4): weighting market requirements. Market requirements reflect the taste of customers to product or service, which can be measured by different ways. For instance, a cross functional team composing of personnel of marketing, sales, production, engineering, and so forth can weigh the different market requirements and then determine their relative importance.

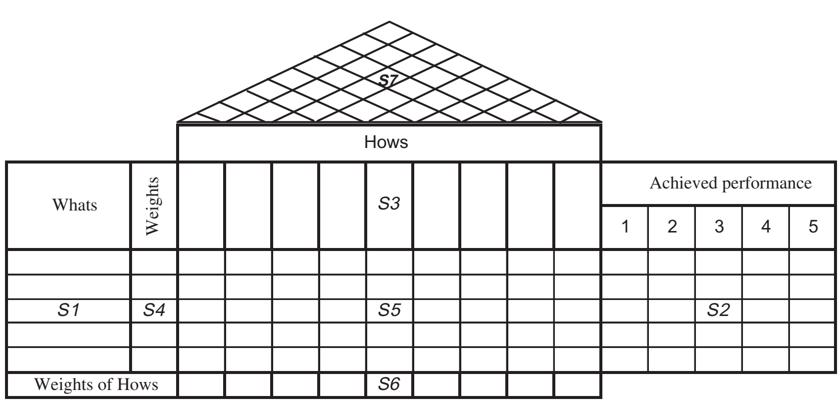


Fig. 2. Steps for formulating manufacturing strategy.

4.2.1.5. Step 5 (S5): linking market requirements with competitive factors. This step determines the correlation scores of market requirements and competitive factors. The correlation scores indicate the impact of competitive factors on the degree to which each competitive factor satisfies the needs of customers, i.e. market requirements.

4.2.1.6. Step 6 (S6): determining the weights of competitive factors. By determines the competitive factors and market requirements correlation scores, this step answers the question concerning how the competitive factors determined in step 2 can satisfy the market requirements. In step 2, competitive factors are identified in terms of order winners and order qualifiers. In step 5 the match between these order winners/qualifiers and market requirements is analyzed. Based on the analysis, the weights of the competitive factors (hows) are determined.

4.2.1.7. Step 7 (S7): developing the matrix of correlations between the "hows". The correlations between the competitive factors ("hows") are contained in the "roof" of the HOQ. This step in the construction of the HOQ enables to keep track of pairs of "hows" needing parallel improvements or comprising "hows" that are inconsistent with each other. For example, if we reduce costs by reducing product quality inspections, product quality might suffer from our action, and if we improve customer service by cross-training personnel to deal with a wider-range of problems, they may become less efficient at dealing with commonly occurring problems. The correlations between pairs of "hows" may be positive or negative.

After the determination of the impact of each competitive factor on market requirement, stage 2 can be started where the key manufacturing-related tasks, i.e. manufacturing strategic decisions that will support those competitive factors could be identified.

4.2.2. Stage 2: determining strategic manufacturing decision categories

According to Hayes and Wheelwright (1984), specific decisions categories related to the content of manufacturing strategy can be divided into structural strategic decisions and infrastructural strategic decisions. At this stage, the competitive factors determined and measured at the first stage are used as "whats" in QFD matrix, and manufacturing decision categories are identified and used as "hows" in QFD matrix. Four steps are comprised in Stage 2, which are also shown in Fig. 2.

4.2.2.1. Step 1: using the competitive factors as the "whats". The competitive factors are used as the "whats" in QFD matrix at this step (shown as S1 in Fig. 2), and the relative importance of the various competitive factors are determined in terms of the weights of the competitive factors determined at the stage 1 (marked as S4 in Fig. 2).

4.2.2.2. Step 2: identifying manufacturing decision categories—"hows" (shown as S3 in Fig. 2). At this step, the relationship between the competitive factors and manufacturing decision categories, which can be divided into structural strategic decisions and infrastructural decisions, is established. Actions within structural decision categories or infrastructural decision categories normally have direct impact on the fulfilment of competitive factors. For instance, the introduction of new process technology may accelerate the speed to market of new product, and also may enhance the quality level of product.

4.2.2.3. Step 3: linking competitive factors with manufacturing decision categories (shown as S5 and S6 in Fig. 2). By analyzing the match between competitive factors and manufacturing decision categories, this step determines the correlation scores of competitive factors and manufacturing decision categories (S5 in Fig. 2) and measures the relative importance of various structural strategic decisions and infrastructural decisions (S6 in Fig. 2). The result of this step is the determination of the weights of the manufacturing decision categories ("hows") (S6 in Fig. 2). The weight of each manufacturing decision indicates the impact of it on the degree to which each manufacturing decision supports the fulfilment of competitive factors. Therefore, by the determination of the weights of manufacturing structural and infrastructural decisions, manufacturing strategic decisions can be ranked and therefore the key manufacturing-related tasks can be determined.

4.2.2.4. Step 4: developing the matrix of correlations between the manufacturing decision categories (shown as S7 in Fig. 2). This step measures the correlation between the manufacturing decision categories ("hows"), which are contained in the "roof" of the HOQ. The correlations between pairs of "hows" may be positive or negative.

5. Quantitative method

The determination of manufacturing strategic decision involves both qualitative and quantitative factors. Quantitative techniques based on purely mathematical data have some drawbacks when they are used to consider qualitative factors, which are very important in manufacturing strategy determination, especially when we need to develop manufacturing strategies involving factors that are not easy to measure quantitatively.

In QFD the relation between "whats" and "hows" are usually vague or imprecise because in QFD there lacks formal mechanisms for translating "whats" (which are generally qualitative) into "hows" (which are usually quantitative) (Bevilacqua, Ciarapica, & Giacchetta, 2006; Kim, Moskowitz, Dhingra, & Evans, 2000). There are normally many customer's needs ("whats") for a product, and each need ("what") can be translated into multiple technical measures ("hows"), and conversely a certain technical solution ("how") may correlate with multiple customer's needs ("whats"). In general, these "whats" tend to be translated into "hows" in a subjective, qualitative and inaccurate way, which should be expressed in more quantitative and technical terms. Therefore, with such qualitative analysis and inaccuracies, the values of a certain alternative concerning a given attribute often cannot be precisely defined, the decision-maker is unable (or unwilling) to express his preferences precisely, and the evaluations or opinions are expressed in linguistic terms. To deal with this type of uncertainty correctly we can exploit group decision-making and fuzzy logic (Zadeh, 1965). Multiple decision-makers are often preferred rather than a single decision-maker to avoid the bias and minimize the partiality in the decision process (Chiclana, Herrera, & Herrera-Viedma, 1998; Herrera, Herrera-Viedma, & Chiclana, 2001; Lee & Kim, 2000). In this paper, the weights assigned by the decision-makers were aggregated using the average operator.

Fuzzy logic can handle inexact information and linguistic variables in a mathematically way (Hisdal, 1988). Therefore, fuzzy logic matches with decision-making situations where strategic decisions evaluation is also perceptive and decision-makers express heterogeneous judgments (Albino, Garavelli, & Gorgoglione, 1998; Khoo & Ho, 1996; Kim et al., 2000). In this paper the integration of fuzzy set theory and HOQ has been performed, and therefore it provides a structured tool to capture the inaccurate decision-relevant inputs and to facilitate to analyze decision-relevant QFD information.

A fuzzy set is a set of objects in which there is no predefined boundary between the objects that are or are not members of the set. The key concept behind this definition is that of "membership": each element in a set is associated with a value indicating to what degree the element is a member of the set. This value comes within the range [0, 1], where 0 and 1, respectively, indicate the minimum and maximum degree of membership, while all the intermediate values indicate degrees of "partial" membership. There are various types of fuzzy number for analyzing a given vague structure. We use triangular fuzzy numbers in this paper for they are often used to quantify verbal data, and further fuzzy numbers are easy to compute (Karsak, 2004). The characteristic of triangular numbers is that they are represented by triplets of the type A = (XL; Xα; XR), where XL and XR mean respectively the lower and upper limits of the fuzzy number, and Xα is the element that represents the closest fit.

At present, some authors have published their research on fuzzy-QFD, and many studies aim to determine a rating of the "hows" in QFD matrix. Among these authors, Khoo and Ho (1996) proposed an approach focusing on the application of possibility theory and fuzzy arithmetic to address the vagueness of QFD. Fung, Popplewell, and Xie (1998) developed a hybrid system to incorporate the principles of QFD, AHP, and fuzzy set theory to determine design targets. Wang (1999) proposed a fuzzy outranking approach to prioritize "hows". Shen, Tan, and Xie (2001) proposed a fuzzy procedure to examine the sensitivity of the ranking of "hows" to the defuzzification strategy and degree of fuzziness of fuzzy numbers. Various studies have also dealt with the ranking of fuzzy numbers. Yager and Filev (1999) proposed a valuation method base on expected value type valuations, which are arise from the transformation of fuzzy subset into an associated probability distribution. Lee and Li (1988) proposed the use of a generalized mean and standard deviation based on the probability measures of fuzzy events to rank fuzzy numbers.

In the case study of this paper we propose a fuzzy-QFD methodology for the determination of manufacturing strategic decisions, and illustrate how to use it. We opted to follow the approach described by Facchinetti, Ghiselli Ricci, and Muzioli (1998), who made a comparison between different fuzzy number ranking methods. The chosen method is a convex combination between the pessimistic and optimistic methods applied to a triangular fuzzy number.

6. Case study

H&G Ltd. is an industrial company with small size which supplies motors for electronic appliance companies. The manufacturing mode of this company is made to order, and its customers are mainly the manufacturing divisions of multinational corporations locating in China. This company had been dominated by traditional functional-oriented layout and push production system, and had suffered from low efficiency for a long time.

Comparing with the average production capacity of 3000 mini motors in other companies which produced similar products, the daily production capacity of this division was only 1800 mini motors, and the quality of products was not satisfied. In the summer of 2006, its top manager decided to improve its production efficiency, and therefore some corresponding changes in some manufacturing-relevant areas, such as production planning and control system, production organization, production process and plant layout, were needed. In this process, we acted as consultants to help the company to develop its manufacturing strategy.

We discussed with vice president of production about the company's current approach to develop manufacturing strategy planning, and found that the existing process of developing the manufacturing strategic plans was traditional. In the existing process of developing the manufacturing strategic plans, department managers related to manufacturing developed their own action plans in relative isolation, and the result of this approach was that individual departmental action plans were sometimes discontinuity or even conflicting.

In order to help the company develop an effective manufacturing strategy and test the efficacy of the proposed method, we applied the method proposed in the process of developing new manufacturing strategy for this company. We used the proposed method starting from the second stage because the competitive factors were obvious and were known clearly by the managers of this company, but they were confused with the issues concerning how to improve the production system to enhance strategic competitive factors. In other words, they were eager to know what were key manufacturing-related tasks which could enhance the effectiveness of this company.

The whole procedure of manufacturing strategy development was characterized by the following steps:

(1) Identifying competitive factors ("whats") and determining the relative importance of "whats".
(2) Identifying manufacturing decision categories—"hows".
(3) Determining the "what"–"how" correlation scores and constructing the HOQ.
(4) Preparing the matrix for correlating the "hows".

6.1. Identifying competitive factors ("whats") and determining the relative importance of "whats"

At this step, the competitive factors were used as the "whats" in QFD matrix, and the relative importance of the various competitive factors were determined by means of measuring customer needs and current performance of the production system. Two rounds of meeting were held to discuss competitive factors and to determine their relative importance. The participants of the meetings included a production manager (marked as M1), a sales manager (M2), a quality manager (M3), and a process manager (M4). The group of four experts was presented by us with various order winning factors that had emerged from a careful review of the manufacturing strategy literature. Following survey of literature and discussions, the group arrived at a consensus on the final list of four competitive factors are shown as below:

- Quality (making to specification, marked as QA).
- Cost (producing products with lower cost, marked as CT).
- Productivity (the number of electric engines produced per day per employee, marked as PD).
- Delivery reliability (meeting delivery due dates consistently, marked as DR).

After the determination of the competitive factors, each of the four participants established the level of importance of each "what" by means of a linguistic variable. A linguistic set of U was used to express opinions on a group of attributes: $U = \{vl; l; m; h; vh\}$, where vl = *very low*, l = *low*, m = *medium*, h = *high*, vh = *very high*. The linguistic variable of U was quantified using triangular fuzzy numbers: $vl \to (0, 1, 2)$; $l \to (2, 3, 4)$; $m \to (4, 5, 6)$; $h \to (6, 7, 8)$; $vh \to (8, 9, 10)$. The outcome of this stage is shown in Table 2.

The importance assigned by the participants was aggregated using the average operator, as described by the following equation:

$$Importance\ what = \{w_i, \quad where\ i = 1, 2, \ldots, k\}$$

$$w_i = \frac{1}{n} \otimes (w_{i1} \oplus w_{i2} \oplus w_{i3} \oplus \cdots \oplus w_{in})$$

where k is the number of "whats" and n is the number of participants (k = 4 and n = 4 in this case).

Table 2
Opinions of participants on selected competitive factors.

"what"	M1	M2	M3	M4
QA	*h*	*vh*	*vh*	*vh*
CT	*h*	*m*	*m*	*m*
PD	*h*	*h*	*m*	*h*
DR	*m*	*m*	*m*	*m*

Each element on the importance what vector is a triangular fuzzy number defined by the triplet $w_i = (w_{i\alpha}, w_{i\beta}, w_{i\gamma})$.

The "importance" obtained by aggregating the opinions expressed by each manager are shown in the HOQ in Fig. 3.

6.2. Identifying manufacturing decision categories—"hows"

At this step, the manufacturing decision categories were divided into structural strategic decisions and infrastructural decisions, and then the associated policy areas were analyzed. Because the main problem of the production system in this company is low efficiency, the discussion of the expert group mainly focused on the manufacturing decision areas related to production efficiency. For instance, the production manager thought that functional-oriented layout and push system caused high level of inventory and long material travelling distance, and the process manager argued that low efficient equipment was a main hurdle to enhance production efficiency. Finally, the group determined the following five manufacturing decision categories ("hows") in terms of their impact on the competitive factors:

(1) Structural strategic decisions:
   - Process technology (process choice and process technology) = PT
   - Facilities (facility layout and focus) = FL
   - Capacity (output of the production system in a given period) = CP

(2) Infrastructural strategic decisions:
   - Manufacturing planning and control (pull or push system, centralized or decentralized system) = MP
   - Quality (quality management method and tools) = QL

6.3. Determining the "what"–"how" correlation scores and constructing the HOQ

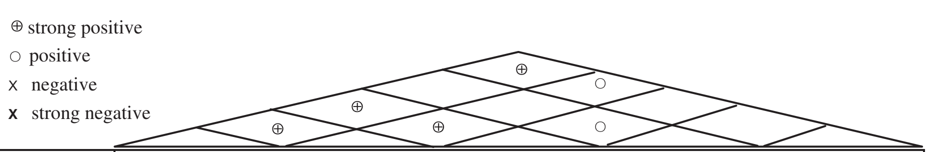
At this step, each member of the group of four experts analyzed the match between the competitive factors and the manufacturing decision categories ("what"–"how"), and expressed opinions on the correlation scores of the competitive factors and the manufacturing decision categories by using one of the five linguistic variables, which are shown in Table 3.

Triangular fuzzy numbers were also used to quantify the linguistic variables and the fuzzy numbers obtained for each member were aggregated by means of the following equation:

$$Score = \{S_{ij}, \quad where\ i = 1, 2, \ldots, k; \ j = 1, 2, \ldots, m\}$$

$$S_{ij} = \frac{1}{n} \otimes (S_{ij1} \oplus S_{ij2} \oplus S_{ij3} \oplus \cdots \oplus S_{ijn})$$

where k = the number of the "competitive factors (whats)", m = the number of the "manufacturing decision categories (hows)" and n = the number of the members in the group (here, $k = 4$, $m = 5$ and $n = 4$). With above equation, the matrix of the correlation scores of "competitive factors" and "manufacturing decision categories" ("hows"–"whats") was determined, whose S_{ij} elements represent an aggregate correlation score between the ith "what" and the jth "how". The S_{ij} elements are triangular fuzzy numbers defined by the triplets $S_{ij} = (S_{ij\alpha}, S_{ij\beta}, S_{ij\gamma})$.



	Relevance of WHAT			HOW PT			FL			CP			MP			QL		
WHAT	α	β	γ	α	β	γ	α	β	γ	α	β	γ	α	β	γ	α	β	γ
QA	7.5	8.5	9.5	6.5	7.5	8.5	5.0	6.0	7.0	1.5	2.5	3.5	3.0	4.0	5.0	8.0	9.0	10.0
CT	4.5	5.5	6.5	3.5	4.5	5.5	7.5	8.5	9.5	6.5	7.5	8.5	3.0	4.0	5.0	4.5	5.5	6.5
PD	5.5	6.5	7.5	6.0	7.0	8.0	5.0	6.0	7.0	7.5	8.5	9.5	7.0	8.0	9.0	3.0	4.0	5.0
DR	4.0	5.0	6.0	5.5	6.5	7.5	4.5	5.5	6.5	7.5	8.5	9.5	7.5	8.5	9.5	3.5	4.5	5.5
	Weight of the HOW			W_1			W_2			W_3			W_4			W_5		
				α	β	γ	α	β	γ	α	β	γ	α	β	γ	α	β	γ
				29.9	41.6	55.4	29.1	41.1	54.9	27.9	40.1	54.2	26.1	37.6	51.1	27.7	38.8	51.9
				42.3			41.7			40.7			38.3			39.5		

Fig. 3. HOQ of manufacturing strategy formulation process.

Table 3
Opinions on the correlation scores of competitive factors and manufacturing decisions.

Competitive factors	Manufacturing decision categories PT				FL				CP				MP				QL			
	M1	M2	M3	M4	M1	M2	M3	M4	M1	M2	M3	M4	M1	M2	M3	M4	M1	M2	M3	M4
QA	*h*	*h*	*vh*	*h*	*h*	*h*	*m*	*m*	*l*	*l*	*vl*	*l*	*m*	*l*	*l*	*m*	*vh*	*vh*	*vh*	*vh*
CT	*m*	*m*	*l*	*m*	*vh*	*vh*	*vh*	*h*	*h*	*h*	*vh*	*h*	*l*	*m*	*l*	*m*	*m*	*m*	*m*	*h*
PD	*h*	*h*	*h*	*h*	*m*	*m*	*h*	*h*	*vh*	*h*	*vh*	*vh*	*h*	*vh*	*vh*	*h*	*l*	*l*	*m*	*m*
DR	*m*	*h*	*h*	*h*	*m*	*h*	*m*	*m*	*h*	*vh*	*vh*	*vh*	*h*	*vh*	*vh*	*vh*	*m*	*m*	*l*	*m*

We can now complete the HOQ, calculating the weights of the "manufacturing decision categories ("hows"), averaging the aggregate weighted S_{ij} correlation scores with the aggregate weights of the "competitive factors (whats)" w_i, according to the equation:

$$Weight = \{w_j, \quad where\ j = 1, 2, \ldots, m\}$$

$$W_j = \frac{1}{k} \otimes [(S_{j1} \otimes w_1) \oplus \cdots \oplus (S_{jk} \otimes w_k)]$$

where each W_j on the weight vector represents the impact degree of each manufacturing decision category on the competitive factors, which are shown in the matrix of Fig. 3. The W_j are triangular fuzzy numbers defined by means of the triplets $W_j = (W_{j\alpha}, W_{j\beta}, W_{j\gamma})$. The final scores for the weight of the "hows" are identified according to the equation (Lee & Kim, 2000):

$$\overline{W_j} = \frac{W_{j\alpha} + W_{j\beta} + W_{j\gamma}}{3}$$

By the determination of the weights of manufacturing structural and infrastructural decisions, manufacturing strategic decisions can be ranked and therefore the key manufacturing-related tasks can be determined. In this case, in terms of final scores of $\overline{W}_j$, manufacturing strategic decisions were ranked to be: process technology; facilities; capacity; quality; manufacturing planning and control.

6.4. Determining the matrix of correlations between the manufacturing decision categories

By measuring the correlation between the manufacturing decision categories ("hows"), this step enabled the group to know which pairs of "hows" had positive correlation or negative correlation. The pairs of "how" which had positive correlation meant that these "hows" should be improved synchronously, and the pairs of "how" which had negative correlation imply that there existed conflicts between these "hows" needing to be resolved.

For instance, in the original layout of assembly workstations, the process of motor assembly was composed of four sub-processes. Stators and rotors were assembled in the first sub-process locating on the second floor by adopting one-piece flow method. Most of machinery used in this subassembly process was old and processing technology was out of date, so assembly capacity was low and defect rate is relatively high. Assembled stators and rotors were accumulated to 200 pieces (100 pairs) and were then moved to lacquering and inspecting processes locating on the first floor in the same workshop, and the average throughput time of these processes for one batch was usually 52 h. The reason for these sub-processes locating on different floors was that the lacquering machine was old so lacquering process threw off poisonous gas, and therefore this process must be isolated from other processes.

After lacquering and inspecting processes, the whole batch of stators and rotors were transported to the second floor again to be assembled together. With this original facility layout, the whole assembly process was split into four sub-processes which were located on different floors, and one-piece flow was changed to batch flow when stators and rotors were transported to different sub-processes. This arrangement of workstations caused long lead time of assembly and increased the level of WIP. Furthermore, this arrangement was a barrier for different work groups to communicate easily, and the average feedback time of the result of product quality inspection was usually 2 weeks, and therefore the problems of product assembly quality could not be analyzed and controlled instantly.

Therefore, the old process technology lowered assembly capacity and assembly quality, and separated the assembly process into sub-processes locating on different floors, which further prolonged assembly lead time and cumbered the feedback of quality information. It is clear that process technology has strong influence on assembly capacity, quality, and workstation arrangement. The workstation arrangement also affects assembly lead time and quality information transferring and further has negative influence on assembly quality improvement. These relationships between manufacturing decision categories are shown in the roof of the HOQ in Fig. 3.

7. Conclusion

The proposed methodology for developing manufacturing strategy uses QFD as a transforming device to link competitive factors with manufacturing decision categories such as structural decision categories and infrastructural categories, and uses HOQ as a main tool in different stages of manufacturing strategy development process. By integrating fuzzy set theory and house of quality, this approach is also capable to capture the imprecision and vagueness of decision-relevant inputs and to facilitate the analysis of decision-relevant QFD information. Fuzzy logic can handle inexact information and linguistic variables in a mathematically well-defined way, therefore, it is useful under the situations where strategic decisions evaluation is perceptive and experts express heterogeneous judgments. Therefore, the approach proposed in this paper provides a structural and quantitative approach for manufacturing strategy development, which could be a helpful supplement to existing descriptive processes and conceptual models. In further research, more cases need to be studied to validate this approach.

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