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# MBNQA-oriented self-assessment quality management system for contractors: fuzzy AHP approach

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Many construction clients are not satisfied with the quality performance achieved on their projects though many contractors are ISO9000:1994 certified. Total quality management (TQM) has been a widely applied quality management system for obtaining the benefits of better quality and higher customer satisfaction through the spirit of continuous improvement, which is also adopted by ISO9001:2000 version. It is believed that TQM can help to raise quality and productivity in the construction industry. Self-assessment systems provide an opportunity to design in quality on an organization-wide basis, in which the self-assessment process allows the organization to identify its strengths and weaknesses for continuous improvement actions. A MBNQA-oriented self-assessment quality management system (SQMS), which is based on the seven criteria of Malcolm Baldrige National Quality Award (MBNQA), for construction contractors to benchmark, is proposed. A questionnaire survey of Hong Kong construction quality management experts, in which a fuzzy analytical hierarchy process (AHP) was employed to calculate the weights of the seven criteria, was carried out. Remarkable differences for the allocation of weights in the seven criteria particularly in the input criteria (leadership, strategic planning and customer and market focus) and the 'results' criterion compared with the original weights of MBNQA were observed.

*Keywords:* TQM, self-assessment, contractor, quality management system, fuzzy AHP.

## Introduction

Although the construction industry shows a rapid pace of growth in many countries, high fragmentation, low productivity, poor quality and lack of standards still are the major problems of construction companies (Bhimaraya, 2005). Implementing quality management in the construction setting is difficult as it is highly differentiated and loosely structured; therefore, a sustainable improvement in quality is extremely difficult to achieve (Low and Tan, 1996). Many construction clients are not satisfied with the quality performance achieved on their projects (Kometa and Olomolaiye, 1997). On the other hand, many companies, including construction contractors, are frustrated with their efforts to improve quality through various management systems which are highly focused on the lagging financial measures, instead of quality measures (Torbica and Stroh, 1999).

According to Low (1996), the construction industry has been continuously striving for better methods of working to achieve quality objectives in totality for many years. Unfortunately, the quality of construction services and facilities is still the root cause of many problems (Chan and Tam, 2000). Many studies (Seymour and Low, 1990; Low, 1992) have shown that the effective management of construction quality is affected not only by technical issues but also by non-technical issues such as leadership, strategic planning and customer and market focus. In Hong Kong, many construction contractors adopt ISO9000:1994 series in order to maintain their positions in the competition. In 1992, the first ISO9002 certificate was issued in Hong Kong to a local building contractor (Tam, 1993). In 1997, 350 construction-related firms had received ISO9000:1994 certificates, which were made mandatory by the Hong Kong government for its construction-related projects. In December 2000, the new version of ISO9000, which contains elements such as measurement, analysis and improvement for total quality management (TQM), was released and the

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Hong Kong Special Administrative Region Government required all construction organizations in Hong Kong to obtain re-certification to this new version by the middle of December 2003 before they could submit tenders for public jobs (Tang *et al.*, 2005). With this recent introduction of the new version of ISO9000, a longitudinal study in ongoing construction projects to examine the real impacts of transition from ISO9000:1994 to the ISO9001:2000 family of standards will be very useful to more realistically assess the effectiveness of ISO9000-based QMS in the construction industry (Palaneeswaran *et al.*, 2006). The requirement for measurement, analysis and improvement, e.g. via a self-assessment approach in many quality management systems is rather generic without specifying the details of how these should be done. Therefore, a holistic management system such as TQM-oriented self-assessment quality management system (SQMS) for construction contractors in Hong Kong and other places to implement continuous improvement is recommended to solve the quality problems faced by the construction contractors.

## Literature review

TQM is being regarded as a strategy or holistic business philosophy to achieve and maintain excellent organizational performance (Hunt, 1993). It is an integrated management philosophy (Arawati, 2005; Evans and Lindsay, 2005) and set of practices (Whitney and Pavett, 1998; Sila and Ebrahimpour, 2002; Li *et al.*, 2003) that emphasize continuous improvement, long-range planning, meeting customer requirements, process redesign, increased employee involvement and teamwork, and closer relationships with suppliers. The rationale for deploying TQM in construction projects is that TQM provides an integrative mechanism to counteract the inhibitive tendencies caused by different professions in construction projects. TQM can draw all parties consciously to focus on the superordinate goal of systematically identifying and meeting the customers' requirements (Low and Peh, 1996). According to the study undertaken by the Building Research Establishment (1982), at least 15% savings on total construction costs can be achieved through eliminating rework and wasted works. Moreover, the intangible merit of adopting TQM by construction contractors is that the culture of quality shall be recognized (Öztaş *et al.*, 2007) as TQM creates an organizational culture that fosters continuous improvement in everything by everyone at all times, and requires changes in organizational processes, strategic priorities, individual belief, attitudes and behaviours (Shin *et al.*, 1998; Dale, 1999).

Recent development of national quality awards such as the Japanese Deming Prize, the American Malcolm Baldrige National Quality Award (MBNQA), and the European Quality Award (EQA) serve as TQM frameworks for self-assessment or benchmarking and offers periodically adjusting frameworks (different weights for different criteria) and/or practices for TQM pursuers. If they were used properly, the criteria and the practices would help organizations to assess their current levels of quality performance (Pun *et al.*, 1999). The merit of self-assessment is that it involves people in a regular and systematic review of their inputs (leadership, strategic planning and customer and market focus criteria), processes (human resource and process management) and outputs (results) as per Figure 1, which is modified from the Baldrige criteria for performance excellence framework: a systems perspective of MBNQA (National Institute of Standard and Technology, 2006). The self-assessment process allows the TQM pursuers to identify their strengths and

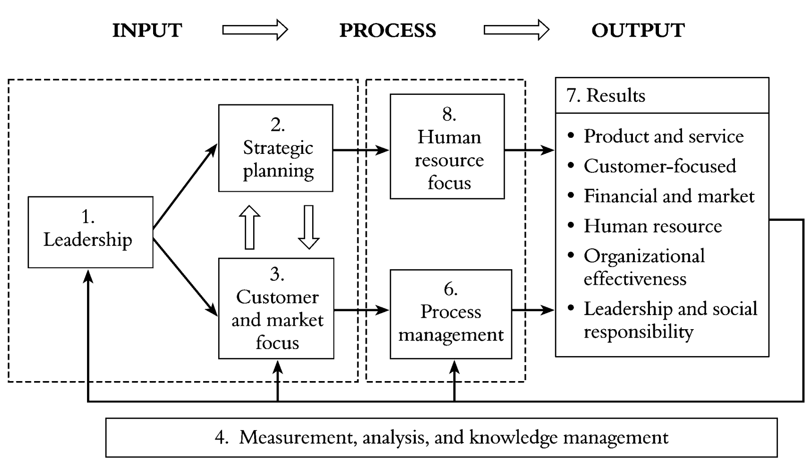


**Figure 1** Systems-oriented MBNQA model (modified from National Institute of Standards and Technology, 2006)

weaknesses for continuous improvement actions as well as enabling the progress of TQM programmes to be monitored. Self-assessment systems provide an opportunity to design-in quality on an organization-wide basis (Finn and Porter, 1994). Therefore, construction contractors need to increase their pace of TQM implementation via the deployment of SQMS and recognize the weaknesses for improvement actions (Lai *et al.*, 2002).

## The need for MBNQA-oriented self-assessment quality management system for contractors

In the past, the focus of performance systems had been mostly on measuring the financial results, such as sales turnover, profit before or after tax, and debt ratio. These financial measures do not match entirely with the competencies and skills required by companies for today's changing business environment (Kaplan and Norton, 1992, 1993, 1996; Geanuracos and Meiklejohn, 1993). In order to achieve business excellence, it is not enough to know the lagging financial results; it is also necessary to explain the leading driving forces or non-financial aspects such as quality (Kanji, 2001), customer satisfaction, innovation (Chin *et al.*, 2003) and customer and market focus (Eccles and Pyburn, 1992) that can always reflect an organization's economic condition and growth prospects better than its reported earnings do behind the success or failure.

Henderson (1997) argued that organizations must establish their performance measurement systems with self-assessment orientation as self-assessment is a comprehensive, systematic and regular review of an organization's activities that ultimately results in planned improvement actions. Karapetrovic and Willborn (2001) added that self-assessments are aimed at identifying strengths and weaknesses for improvement. Hillman (1994) stated that the three main elements in self-assessment are framework, measurement and management.

The MBNQA was launched by the US government in 1987 to encourage US companies to use quality to gain competitive advantage (Gadd, 1995). MBNQA provides a unique framework with seven criteria which are weighted according to their relative importance and it is widely accepted as the blueprint of TQM (Garvin, 1991; Evans and Lindsay, 2005). Originally MBNQA was an order-winner evaluation framework for an organization to get the award and now the MBNQA framework serves as an order-qualifier self-assessment framework for companies to conduct quality management performance independently, i.e. measure to what extent they are practising TQM (Lee *et al.*, 2006b). The TQM self-assessment framework is a way to engage everyone in an organization, not just senior management, to evaluate the financial and non-financial impact of its current status and to identify areas for improvement, which are strategically aligned (Porter *et al.*, 1998).

According to Frehr (1997) ISO9000:1994 certification is generally regarded as a basic step towards the implementation of TQM, which is well accepted by many industries such as manufacturing. However, there are some specific factors such as the fact that the construction industry is highly differentiated and loosely structured, which makes it different from the manufacturing industry in relation to quality issues due to the problematic characteristics and complexity of construction industry (Öztaş *et al.*, 2007). The weightings of MBNQA criteria are arbitrary or changing in accordance with time, and some, such as documentation, have moved between different criteria over the years (Lee *et al.*, 2006b). To an extent, these arbitrary weightings, due to expert opinion, have not been subjected to rigorous empirical tests.

A number of earlier studies suggested that TQM award criteria could be used in the self-assessment (Finn and Porter, 1994) or evaluation of a contractor's quality management practices (McIntyre and Kirschenman, 2000). However, there are many potential problems involved with the application of TQM criteria in the self-assessment of contractors' quality management performance, such as the change in culture; the requirements of TQM not fully understood by staff; lack of strong senior management involvement/support; and insufficient quality or self-assessment training for staff during the transition/upgrading from ISO9000:1994 to TQM (Tang *et al.*, 2005). Moreover, the application of the self-assessment process, e.g. the weights allocation of different criteria in different industries is very challenging but worth attempting as the construction industry is highly differentiated. Therefore, a SQMS that can integrate TQM criteria such as MBNQA with the conformity of the quality can better accommodate today's sharpening needs of contractors' quality performance. Therefore, a process of developing an effective MBNQA-oriented SQMS, which is based on the MBNQA criteria, for Hong Kong contractors, is proposed as an alternative tool for contractors to benchmark in their continuous improvement journeys. The proposed process of developing a MBNQA-oriented SQMS also provides new insights for Hong Kong contractors or even contractors in other territories to improve their quality management performance through the effective use of the self-assessment approach via fuzzy analytic hierarchy process (AHP).

## Fuzzy analytic hierarchy process (fuzzy AHP)

AHP is one of the extensively used multicriteria decision-making (MCDM) methods, in which the decision makers need to make qualitative assessments regarding the performance of the decision alternatives with respect to each independent criterion and the relative importance of each independent criterion with respect to the overall objective of the problem (Saaty, 1980). AHP involves the principles of decomposition, pairwise comparisons, priority vector generation and synthesis. AHP is a subjective MCDM method (Hwang and Yoon, 1981) where it is not necessary to involve a large sample, and it is useful for research focusing on a specific issue where a large sample is not mandatory (Lam and Zhao, 1998). It may be impractical for a survey with a large sample size as respondents may have a great tendency to provide arbitrary answers, resulting in a very high degree of inconsistency (Cheng and Li, 2002). The main advantage of AHP is the relative ease to handle multiple criteria with both qualitative and quantitative data. Although AHP aims to capture the expert's knowledge and the weightings of MBNQA are built on the expert's knowledge and judgement, the conventional AHP cannot reflect the human thinking style due to uncertainty (fuzziness) such as 'highly likely' (Pang, 2006). As a result, uncertain subjective data are present which make the decision-making process complex. The fuzzy linguistic approach, which is different from treating fuzzy sets as precisely defined mathematical objects subject to the rules of classical logic, can take the optimism/pessimism rating attitude of decision makers into account. Linguistic values' membership functions, which are usually characterized by triangular fuzzy numbers, are recommended to assess preference ratings instead of the conventional numerical equivalence method (Liang and Wang, 1994). Therefore, the fuzzy AHP approach should be more appropriate and effective than conventional AHP in real practice or where an uncertain pairwise comparison environment exists (Lee *et al.*, 2006a).

Fuzzy AHP was developed to solve the hierarchical fuzzy problems due to uncertainty or fuzziness. The applications of fuzzy AHP have been done by many researchers (Laarhoeven and Pedrycz, 1983) and different fuzzy AHP models (Boender *et al.*, 1989) are constructed for different problems in the areas of human needs and interests, such as political (Murtaza, 2003), economic (Chi and Kuo, 2001) and management sciences (Lee *et al.*, 2008; Kang and Lee, 2007).

## Research methods

A MBNQA-oriented SQMS, which is based on the MBNQA criteria with industry-specific weightings, for construction contractors via fuzzy AHP is proposed in this paper. Owing to the unique characteristics and complexity of the construction industry, the weightings of the seven MBNQA criteria (2006 version) (i.e.: leadership; strategic planning; customer focus; process management; human resource focus; measurement, analysis and knowledge management; and results) to be applied in the Hong Kong construction industry will be highly likely different from the official or general weightings of the MBNQA criteria. The proposed process of developing the MBNQA-oriented SQMS is a systematic approach, which consists of several phases (see Figure 2) to derive the weightings with local context, and should be more appropriate for Hong Kong construction contractors. First, a literature review was carried out to identify the possibilities and potential problems involved with the application of MBNQA criteria in the self-assessment of contractors' quality management performance. Second, MBNQA criteria were used to construct the hierarchical structure of AHP. Based on the hierarchical structure, the conventional AHP questionnaire (nine-point scale and pairwise comparison) in respect of the seven MBNQA criteria and their 19 sub-criteria for self-assessment was prepared. Third, a structured questionnaire survey was conducted to investigate the perceptions of the weightings of the seven criteria and the 19 sub-criteria with the selected Hong Kong construction quality management experts. In order to illustrate the proposed self-assessment process via fuzzy AHP, a stratified sample was drawn from the construction quality management experts in Hong Kong. The selection criteria include academic achievement, number of years of working in construction management, and number of years of teaching and researching construction management, preferably in construction quality management related areas. Finally the returned questionnaires were then analysed through the fuzzy AHP processes in order to obtain their relative importance. The expected results would suggest a new process of developing a MBNQA-oriented SQMS which is tailor-made for Hong Kong contractors to solve part of the current quality problems and the process could be benchmarked by the other industries and/or contractors of other territories.

Zadeh (1965) introduced the fuzzy set theory to deal with vagueness of human thought. If fuzziness of rational human decision making is not taken into account, the results can be misleading. A fuzzy set is a class of objects with a continuum of grades of membership (characteristic) and such a set is characterized by a membership function, which assigns to each object a grade of membership ranging between zero and one (Zimmermann, 1991). The theory allows mathematical operators to apply the fuzzy domain and a triangular fuzzy number $\widetilde{M}$ as shown in Equation 1. The triangular fuzzy number $\widetilde{M}$ is represented by $(l, m, u)$ where the strongest grade of membership is the

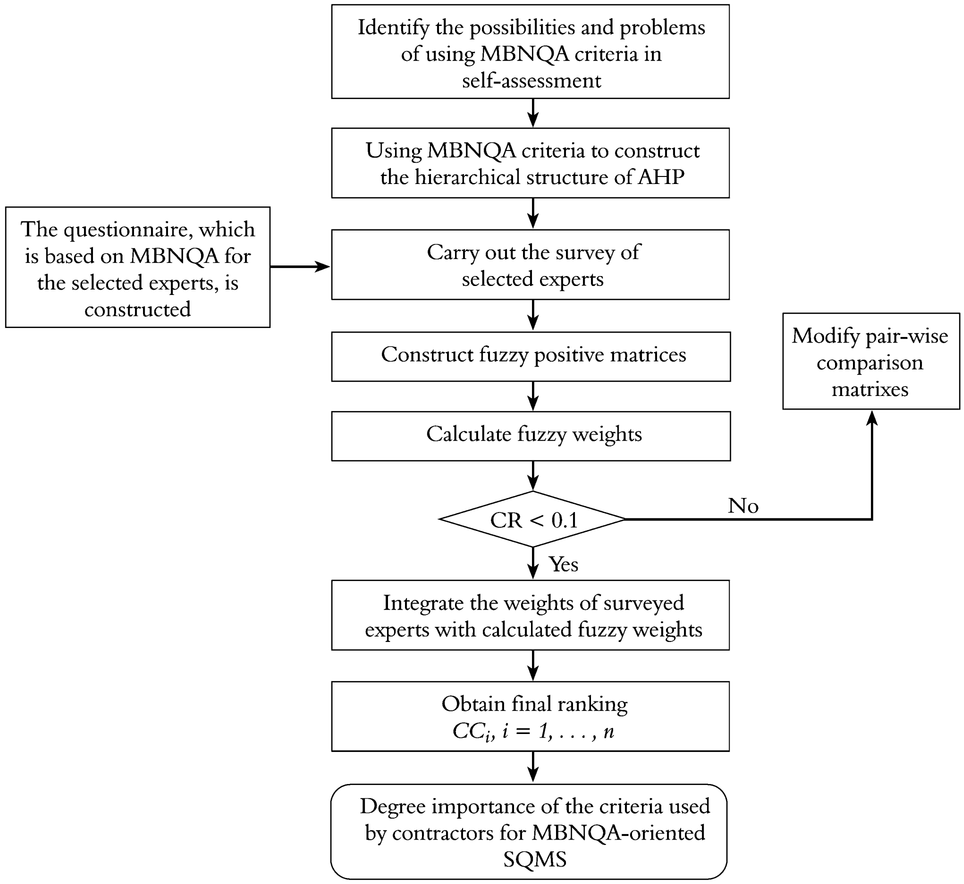


**Figure 2** System flow for the MBNQA-oriented SQMS via fuzzy AHP

parameter $m$, that is $f_M(m)=1$, and $l$ and $u$ are the lower bound and upper bound of variable $x$ respectively. The membership function is defined as follows:

$$\mu_{\widetilde{M}}(x)=\begin{cases}\dfrac{x-l}{m-l}, & l\le x\le m\\ \dfrac{u-x}{u-m}, & m\le x\le u\\ 0, & otherwise\end{cases} \tag{1}$$

with $-\infty<l\leqslant m\leqslant u<\infty$.

According to Klir and Yan (1995), one of the important concepts in fuzzy sets is the $\alpha-cut$ ($C_\alpha$). For a triangular fuzzy number $\widetilde{M}$ and any number $\alpha\in[0,1]$, the $C_\alpha$ is the crisp set shown as below:

$$C_\alpha=\{x|C(x)\ge\alpha\} \tag{2}$$

The $C_\alpha$ of a triangular fuzzy number $\widetilde{M}$ is the crisp set $\widetilde{M}^\alpha$ that contains all the variables of the universal set $U$ whose membership grades in a triangular fuzzy number $\widetilde{M}$ are greater than or equal to the specified value of $\alpha$, as shown in Figure 3.

According to Cheng and Mon (1994) and Cheng (1996, 1999), by defining the confidence interval at level $\alpha$, the triangular fuzzy number $\widetilde{M}$ can be characterized as $\widetilde{M}^\alpha$, and

$$\widetilde{M}^\alpha=[l^\alpha,u^\alpha]=[(m-l)\alpha+l,\ -(u-m)\alpha+u],\ \forall\alpha\in[0,1] \tag{3}$$

where the distance ($d$) between two triangular fuzzy numbers $\widetilde{M}_1$ and $\widetilde{M}_2$ can be defined by the vertex method (Chen, 2000) as $\widetilde{M}_1=(l_1, m_1, u_1)$ and $\widetilde{M}_2=(l_2,$

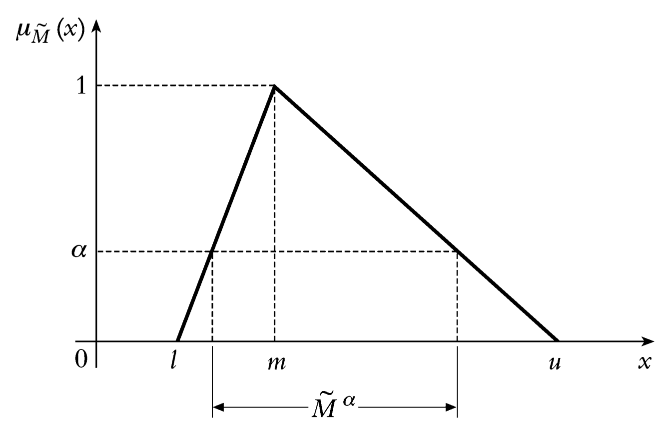


**Figure 3** $\alpha$-cut of a triangular fuzzy number ($\widetilde{M}$) (Lee *et al.*, 2006a)

$m_2$, $u_2$) and the $d$ between them is

$$d(\tilde{M}_1, \tilde{M}_2) = \sqrt{\frac{1}{3}\left[(l_1 - l_2)^2 + (m_1 - m_2)^2 + (u_1 - u_2)^2\right]} \tag{4}$$

## The process of the proposed MBNQA-oriented SQMS

### Data collection

Having identified the possibilities and potential problems involved with the application of MBNQA criteria in the self-assessment of construction contractors' quality management performance through literature, a MBNQA-oriented SQMS hierarchy, which is based on the seven MBNQA criteria and the 19 sub-criteria, is constructed as per Figure 4. The survey questionnaire for this study was designed with a conventional AHP questionnaire format. Questionnaires were then distributed to the selected 12 construction quality management experts in the Hong Kong construction industry. Five qualified questionnaires were received. Two of the respondents have more than 10 years' senior executive management experience. Three of them have doctoral degrees and are involved in quality management research and teaching.

### MBNQA-oriented SQMS via fuzzy AHP: a case study

Based on the fuzzy AHP approach (Lee *et al.*, 2008), the weightings of the seven criteria and the 19 sub-criteria of the proposed MBNQA-oriented SQMS through the questionnaire survey of the Hong Kong construction quality management experts were then calculated. The essential steps are as follows:

*Construct the hierarchical structure with the decision elements*

Each decision maker (the construction quality management expert in this case study) is asked to express the relative importance of two decision elements (criteria and sub-criteria) at the same level by a nine-point scale. The scores of pairwise comparison are collected, and

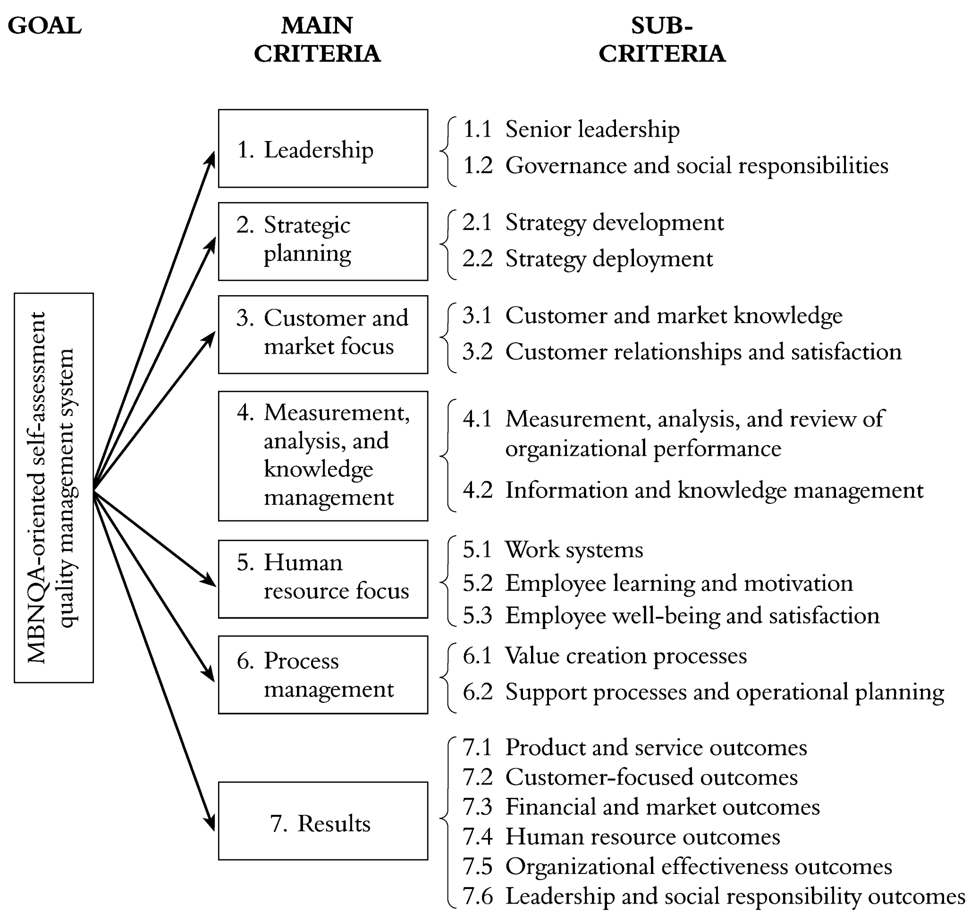


**Figure 4** Modified AHP from Malcolm Baldrige National Quality Award Criteria for Performance Excellence (National Institute of Standards and Technology, 2006)

pairwise comparison matrices for each of the $K$ decision makers (five construction quality management experts in this case study) are formed.

*Analyse consistency*

The priority of the decision elements can be compared by the computation of eigenvalues and eigenvectors (the weight vector) as below:

$$A{\cdot}w = \lambda_{\max} \cdot w \tag{5}$$

where $w$ is the eigenvector of matrix $A$, and $\lambda_{\max}$ is the largest eigenvalue of $A$.

The consistency property of the matrix $A$ is then checked to ensure the consistency of judgements in the pairwise comparison (Saaty, 1980). The consistency index (CI) and consistency ratio (CR) are defined as follows:

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{6}$$

$$CR = \frac{CI}{RI} \tag{7}$$

where $n$ is the number of items being compared in the matrix, and RI is the random index (see Appendix I), the average CI of randomly generated pairwise comparison matrix of similar size. (Note: The upper threshold CR values are 0.05 for a $3 \times 3$ matrix, 0.08 for a $4 \times 4$ matrix, and 0.10 for larger matrices.) If the consistency test is not passed, the original values in the pairwise comparison matrix must be revised by the decision maker (Saaty, 1994).

For this case study, the results of $\lambda_{\max}$, which is the largest eigenvalue of matrix $A_m$ from each expert, are 7.1226, 7.7878, 7.6138, 7.6356 and 7.6897 respectively as showed in Table 1. According to Equations 6 and 7, the results of CR are 0.0155, 0.0995, 0.0775, 0.0803 and 0.0871 respectively and all of them are smaller than 0.10 (the upper threshold CR value is 0.10 for $7 \times 7$ matrix), which meets the requirement of consistency. Likewise, all CR of sub-criteria matrices also meet the requirement of consistency (see Table 2).

*Construct fuzzy positive matrices*

The scores of pairwise comparison are then transformed into linguistic variables, which are represented by positive $\widetilde{M}$ (the positive $\widetilde{M}$ of this case are listed in Appendix II). According to Buckley (1985), the fuzzy positive reciprocal matrix ($\widetilde{A}^k$) can be defined as:

$$\widetilde{A}^k = \left[\widetilde{a}_{ij}^k\right] \tag{8}$$

where $\widetilde{A}^k$ is a positive reciprocal matrix of decision maker $k$;

**Table 1** The fuzzy weights of the criteria

| | Expert 1 | | | Expert 2 | | | Expert 3 | | | Expert 4 | | | Expert 5 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $w_{il}^{*1}$ | $w_{im}^{1}$ | $w_{iu}^{*1}$ | $w_{il}^{*2}$ | $w_{im}^{2}$ | $w_{iu}^{*2}$ | $w_{il}^{*3}$ | $w_{im}^{3}$ | $w_{iu}^{*3}$ | $w_{il}^{*4}$ | $w_{im}^{4}$ | $w_{iu}^{*4}$ | $w_{il}^{*5}$ | $w_{im}^{5}$ | $w_{iu}^{*5}$ |
| 1 | 0.1986 | 0.2632 | 0.2639 | 0.3550 | 0.4023 | 0.4563 | 0.0773 | 0.0828 | 0.0929 | 0.1366 | 0.1457 | 0.1556 | 0.0693 | 0.0724 | 0.0777 |
| 2 | 0.1447 | 0.1738 | 0.1784 | 0.2054 | 0.2375 | 0.2762 | 0.2738 | 0.3334 | 0.3858 | 0.1163 | 0.1163 | 0.1163 | 0.0693 | 0.0724 | 0.0777 |
| 3 | 0.1026 | 0.1156 | 0.1293 | 0.0411 | 0.0493 | 0.0618 | 0.1504 | 0.1895 | 0.2270 | 0.1505 | 0.1769 | 0.1956 | 0.4847 | 0.4847 | 0.4847 |
| 4 | 0.0692 | 0.0692 | 0.0780 | 0.0475 | 0.0543 | 0.0671 | 0.0856 | 0.0856 | 0.0909 | 0.0392 | 0.0478 | 0.0610 | 0.0693 | 0.0724 | 0.0777 |
| 5 | 0.1723 | 0.1933 | 0.1933 | 0.0400 | 0.0527 | 0.0684 | 0.0452 | 0.0498 | 0.0600 | 0.0806 | 0.0856 | 0.0936 | 0.2090 | 0.2228 | 0.2363 |
| 6 | 0.0692 | 0.0692 | 0.0780 | 0.0383 | 0.0383 | 0.0383 | 0.1009 | 0.1145 | 0.1307 | 0.1163 | 0.1163 | 0.1163 | 0.0380 | 0.0409 | 0.0471 |
| 7 | 0.1026 | 0.1156 | 0.1293 | 0.1490 | 0.1654 | 0.1913 | 0.1414 | 0.1444 | 0.1444 | 0.2391 | 0.3114 | 0.3505 | 0.0322 | 0.0343 | 0.0408 |
| $\lambda_{\max}$ | | 7.1226 | | | 7.7878 | | | 7.6138 | | | 7.6356 | | | 7.6897 | |
| CI | | 0.0204 | | | 0.1313 | | | 0.1023 | | | 0.1059 | | | 0.115 | |
| CR | | $0.0155 < 0.10$ | | | $0.0995 < 0.10$ | | | $0.0775 < 0.10$ | | | $0.0803 < 0.10$ | | | $0.0871 < 0.10$ | |

**Table 2** The fuzzy weights of the sub-criteria

| | Expert 1 | | | Expert 2 | | | Expert 3 | | | Expert 4 | | | Expert 5 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $w_{il}^{*1}$ | $w_{im}^{1}$ | $w_{iu}^{*1}$ | $w_{il}^{*2}$ | $w_{im}^{2}$ | $w_{iu}^{*2}$ | $w_{il}^{*3}$ | $w_{im}^{3}$ | $w_{iu}^{*3}$ | $w_{il}^{*4}$ | $w_{im}^{4}$ | $w_{iu}^{*4}$ | $w_{il}^{*5}$ | $w_{im}^{5}$ | $w_{iu}^{*5}$ |
| 1.1 | 0.8164 | 0.8333 | 0.8448 | 0.7071 | 0.7500 | 0.7719 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.8164 | 0.8333 | 0.8143 |
| 1.2 | 0.1667 | 0.1667 | 0.1724 | 0.2500 | 0.2500 | 0.2729 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.1667 | 0.1667 | 0.1662 |
| CR | 0 | | | 0 | | | 0 | | | 0 | | | 0 | | |
| 2.1 | 0.5773 | 0.6667 | 0.6962 | 0.2500 | 0.2500 | 0.2729 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.7071 | 0.7500 | 0.7719 |
| 2.2 | 0.3333 | 0.3333 | 0.4019 | 0.7071 | 0.7500 | 0.7719 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.2500 | 0.2500 | 0.2729 |
| CR | 0 | | | 0 | | | 0 | | | 0 | | | 0 | | |
| 3.1 | 0.7745 | 0.8000 | 0.8156 | 0.7071 | 0.7500 | 0.7719 | 0.7071 | 0.7500 | 0.7719 | 0.5000 | 0.5000 | 0.5000 | 0.8164 | 0.8333 | 0.8143 |
| 3.2 | 0.2000 | 0.2000 | 0.2106 | 0.2500 | 0.2500 | 0.2729 | 0.2500 | 0.2500 | 0.2729 | 0.5000 | 0.5000 | 0.5000 | 0.1667 | 0.1667 | 0.1662 |
| CR | 0 | | | 0 | | | 0 | | | 0 | | | 0 | | |
| 4.1 | 0.5000 | 0.5000 | 0.5000 | 0.7071 | 0.7500 | 0.7719 | 0.8164 | 0.8333 | 0.8448 | 0.5773 | 0.6667 | 0.6962 | 0.2500 | 0.2500 | 0.2729 |
| 4.2 | 0.5000 | 0.5000 | 0.5000 | 0.2500 | 0.2500 | 0.2729 | 0.1667 | 0.1667 | 0.1724 | 0.3333 | 0.3333 | 0.4019 | 0.7071 | 0.7500 | 0.7719 |
| CR | 0 | | | 0 | | | 0 | | | 0 | | | 0 | | |
| 5.1 | 0.3333 | 0.3333 | 0.3333 | 0.1219 | 0.1219 | 0.1256 | 0.1095 | 0.1095 | 0.1141 | 0.1095 | 0.1095 | 0.1141 | 0.5950 | 0.5950 | 0.3714 |
| 5.2 | 0.3333 | 0.3333 | 0.3333 | 0.2918 | 0.3196 | 0.3628 | 0.5084 | 0.5815 | 0.6071 | 0.5084 | 0.5815 | 0.6071 | 0.1128 | 0.1190 | 0.0807 |
| 5.3 | 0.3333 | 0.3333 | 0.3333 | 0.4765 | 0.5584 | 0.5769 | 0.2764 | 0.3090 | 0.3637 | 0.2764 | 0.3090 | 0.3637 | 0.5950 | 0.5950 | 0.3714 |
| CR | $0<0.05$ | | | $0.0158<0.05$ | | | $0.0032<0.05$ | | | $0.0032<0.05$ | | | $0<0.05$ | | |
| 6.1 | 0.7071 | 0.7500 | 0.7719 | 0.3333 | 0.3333 | 0.4019 | 0.8164 | 0.8333 | 0.8448 | 0.7071 | 0.7500 | 0.7719 | 0.5000 | 0.5000 | 0.5000 |
| 6.2 | 0.2500 | 0.2500 | 0.2729 | 0.5773 | 0.6667 | 0.6962 | 0.1667 | 0.1667 | 0.1724 | 0.2500 | 0.2500 | 0.2729 | 0.5000 | 0.5000 | 0.5000 |
| CR | 0 | | | 0 | | | 0 | | | 0 | | | 0 | | |
| 7.1 | 0.1429 | 0.1429 | 0.1429 | 0.2969 | 0.3195 | 0.3260 | 0.0619 | 0.0674 | 0.0730 | 0.1553 | 0.1798 | 0.1912 | 0.0856 | 0.0870 | 0.0870 |
| 7.2 | 0.1429 | 0.1429 | 0.1429 | 0.0843 | 0.0993 | 0.1139 | 0.1869 | 0.2324 | 0.2634 | 0.4051 | 0.4562 | 0.4574 | 0.3872 | 0.4615 | 0.5079 |
| 7.3 | 0.1631 | 0.2857 | 0.3369 | 0.1453 | 0.1619 | 0.1760 | 0.3771 | 0.4292 | 0.4526 | 0.0665 | 0.0665 | 0.0665 | 0.0885 | 0.0885 | 0.0966 |
| 7.4 | 0.1429 | 0.1429 | 0.1429 | 0.0547 | 0.0547 | 0.0617 | 0.0764 | 0.0764 | 0.0764 | 0.0688 | 0.0805 | 0.0941 | 0.1011 | 0.1485 | 0.1854 |
| 7.5 | 0.1429 | 0.1429 | 0.1429 | 0.0620 | 0.0664 | 0.0723 | 0.1161 | 0.1353 | 0.1533 | 0.0574 | 0.0600 | 0.0665 | 0.1106 | 0.1260 | 0.1472 |
| 7.6 | 0.1429 | 0.1429 | 0.1429 | 0.2857 | 0.2983 | 0.2983 | 0.0538 | 0.0593 | 0.0720 | 0.1348 | 0.1569 | 0.1645 | 0.0885 | 0.0885 | 0.0966 |
| CR | $0<0.10$ | | | $0.0530<0.10$ | | | $0.0911<0.10$ | | | $0.0276<0.10$ | | | $0.0464<0.10$ | | |

$\tilde{a}_{ij}=1, \quad where \quad \forall i=j$; and

$\tilde{a}_{ij}=\dfrac{1}{\tilde{a}_{ji}}, \quad \forall i=j=1,2,\ldots\ldots,n.$

*Calculate fuzzy weights*

Based on the Lambda-Max method (Csutora and Buckley, 2001) to calculate the fuzzy weights of decision elements, the procedures are as follows:

- Apply $C_\alpha$ and let $\alpha=1$ to obtain the positive matrix of decision maker $k$, $\tilde{A}_m=\left(\tilde{a}_{ij}\right)_m^k$, and
- Let $\alpha=0$ to obtain the lower bound and upper bound positive matrices of decision maker $k$, where $\tilde{A}_l=\left(\tilde{a}_{ij}\right)_l^k$ and $\tilde{A}_u=\left(\tilde{a}_{ij}\right)_u^k$ respectively.
- Based on the weighting calculation procedure (refer to Equation 5), calculate the weighted matrix as follows:

  $W_m^k=(w_i)_m^k$, $W_l^k=(w_i)_l^k$, and

  $W_u^k=(w_i)_u^k$, $i=1,2,\ldots,n$
- In order to minimize the fuzziness of the weightings, two constants ($M_l^k$ and $M_u^k$) are chosen as follows:

$$M_l^k=\min\left\{\frac{w_{im}^k}{w_{il}^k}\middle| 1\le i\le n\right\} \tag{9}$$

$$M_u^k=\max\left\{\frac{w_{im}^k}{w_{iu}^k}\middle| 1\le i\le n\right\} \tag{10}$$

and the lower bound and upper bound of the weight are defined as:

$$w_{il}^{*k}=M_l^k w_{il}^k \tag{11}$$

$$w_{iu}^{*k}=M_u^k w_{iu}^k \tag{12}$$

The lower bound and upper bound of the weighted matrices are defined as:

$$W_l^{*k}=\left(w_i^*\right)_l^k, \quad i=1,2,\ldots,n \tag{13}$$

$$W_u^{*k}=\left(w_i^*\right)_u^k, \quad i=1,2,\ldots,n \tag{14}$$

- Combining $W_l^{*k}$, $W_m^k$ and $W_u^{*k}$, the fuzzy weight matrix for decision maker $k$ can be obtained as follows:

  $\tilde{W}_i^k=\left(w_{il}^{*k}, w_{im}^k, w_{iu}^{*k}\right), i=1,2,\ldots,n$

For this case study, the fuzzy weight matrix results of criteria (see Table 1) and sub-criteria (see Table 2) are shown.

*Integrate the opinions of decision makers and obtain final ranking*

Apply geometric average to combine the fuzzy weights of decision makers as follows:

$$\bar{\tilde{W}}_i=\left(\Pi_{k=1}^K \tilde{W}_i^k\right)^{\frac{1}{K}}, \quad \forall k=1,2,\ldots,K \tag{15}$$

where:

$\bar{\tilde{W}}_i$ is the combined fuzzy weight of decision element $i$ of $K$ decision makers;

$\tilde{W}_i^k$ is the fuzzy weight of decision element $i$ of decision maker $k$;

$K$ is the number of decision makers.

And then a closeness coefficient is defined to obtain the ranking order of the decision elements. The closeness coefficient is defined by Chen (2000) as follows:

$$CC_i=\frac{d^-\left(\bar{\tilde{W}}_i, 0\right)}{d^*\left(\bar{\tilde{W}}_i, 1\right)+d^-\left(\bar{\tilde{W}}_i, 0\right)}, \quad i=1,2,\ldots,n \tag{16}$$

$$0\le CC_i\le 1$$

where $CC_i$ is the weighting for decision element $i$, and

$$d^-\left(\bar{\tilde{W}}_i,0\right)=\sqrt{\frac{1}{3}\left[\left(\bar{W}_{il}-0\right)^2+\left(\bar{W}_{im}-0\right)^2+\left(\bar{W}_{iu}-0\right)^2\right]} \tag{17}$$

$$d^*\left(\bar{\tilde{W}}_i, 1\right)=\sqrt{\frac{1}{3}\left[\left(\bar{W}_{im}-1\right)^2+\left(\bar{W}_{il}-1\right)^2+\left(\bar{W}_{iu}-1\right)^2\right]} \tag{18}$$

where $d^-\left(\bar{\tilde{W}}_i,0\right)$ and $d^*\left(\bar{\tilde{W}}_i,1\right)$ are the $d$ measurement between two fuzzy numbers. If $\sum_{i=1}^n CC_i\neq 1$, then the normalized weighting for decision element $i$ is defined as follows:

$$CC_i'=\frac{CCi}{\sum_{i=1}^n CC_i} \tag{19}$$

For this case study, the combined fuzzy weight $\bar{\tilde{W}}_i(\bar{W}_{il}, \bar{W}_{im}, \bar{W}_{iu})$ of the seven criteria and 19 sub-criteria from the five construction quality management experts are calculated in accordance with Equation 15, and the results are shown in Table 3 and Table 4 respectively. Applying Equations 17 and 18, the measurement between two fuzzy numbers $d^-\left(\bar{\tilde{W}}_i, 0\right)$ and $d^*\left(\bar{\tilde{W}}_i, 1\right)$ are obtained to calculate the weighting ($CC_i$) for each criterion (see Table 3) and sub-criterion (Table 4). The results of the normalized weighting (CCi) for the seven criteria are 0.1853, 0.1942, 0.1878, 0.0795, 0.1199, 0.0826 and 0.1495 respectively, which are significantly different from those of MBNQA (2006 version). Likewise, the real differences are in the 19 sub-criteria.

**Table 3** The fuzzy weights of the criteria

| | $\bar{W}_{il}$ | $\bar{W}_{im}$ | $\bar{W}_{iu}$ | $d^-(\tilde{W}_i, 0)$ | $d^*(\tilde{W}_i, 1)$ | $CC_i$ | $CC_i'$ |
|---|---|---|---|---|---|---|---|
| 1 | 0.1389 | 0.1560 | 0.1684 | 0.1549 | 0.8457 | 0.1548 | 0.1853 |
| 2 | 0.1457 | 0.1632 | 0.1766 | 0.1623 | 0.8382 | 0.1622 | 0.1942 |
| 3 | 0.1359 | 0.1561 | 0.1766 | 0.1571 | 0.8440 | 0.1569 | 0.1878 |
| 4 | 0.0598 | 0.0645 | 0.0742 | 0.0665 | 0.9338 | 0.0664 | 0.0795 |
| 5 | 0.0879 | 0.0994 | 0.1119 | 0.1002 | 0.9003 | 0.1001 | 0.1199 |
| 6 | 0.0653 | 0.0679 | 0.0735 | 0.0690 | 0.9311 | 0.0690 | 0.0826 |
| 7 | 0.1108 | 0.1242 | 0.1386 | 0.1250 | 0.8756 | 0.1249 | 0.1495 |

## The findings of the proposed MBNQA-oriented SQMS

The overall results of the proposed MBNQA-oriented SQMS for Hong Kong contractors show that there are remarkable differences of the weight allocations for the seven criteria (see Table 5) and the 19 sub-criteria (see Table 6) particularly in leadership, strategic planning and customer and market focus criteria (only 120, 85 and 85 points in the original 2006 MBNQA version but 185, 194 and 188 points in the proposed MBNQA-oriented SQMS respectively). According to MBNQA (2006 version), leadership should set organizational vision and mission to guide and improve performance, promote frank and two-way communication throughout the company, govern and address social responsibilities, and promote and ensure ethical behaviour in work. Many studies stress the importance of senior management's commitment to quality, and that leadership (Burns, 1978) is strongly related to the organization and quality performance (Bass, 1985) as it provides direction and motivation for continuous improvement and innovation (Burati *et al.*, 1993; Michalisin and White, 2001). The research results of senior leadership sub-criterion (130 value points instead of 70 value points in the original MBNQA) show that more effort is needed in order to guide and sustain the contractor companies through communication and encouragement.

According to MBNQA (2006 version), strategic planning examines how the organization develops and deploys strategic objectives and action plans. Strategic planning represents the overall company strategy in which quality improvement plans are integrated (Garvin, 1991). Since low productivity, poor quality and lack of standards are the major problems of construction companies, quality action plans can be fully integrated in the strategic planning of construction contractors. Quality management was originally very much emphasized in the process and the survey results show that the weights allocation (two times more than the original weights of MBNQA) of the strategic

**Table 4** The fuzzy weights of the sub-criteria

| | $\bar{W}_{il}$ | $\bar{W}_{im}$ | $\bar{W}_{iu}$ | $d^-(\tilde{W}_i, 0)$ | $d^*(\tilde{W}_i, 1)$ | $CC_i$ | $CC_i'$ |
|---|---|---|---|---|---|---|---|
| 1.1 | 0.6520 | 0.6652 | 0.6677 | 0.6617 | 0.3384 | 0.6616 | 0.7006 |
| 1.2 | 0.2805 | 0.2805 | 0.2872 | 0.2827 | 0.7173 | 0.2827 | 0.2994 |
| 2.1 | 0.4801 | 0.5000 | 0.5162 | 0.4990 | 0.5014 | 0.4988 | 0.5298 |
| 2.2 | 0.4302 | 0.4353 | 0.4625 | 0.4429 | 0.5575 | 0.4427 | 0.4702 |
| 3.1 | 0.6915 | 0.7155 | 0.7232 | 0.7102 | 0.2902 | 0.7099 | 0.7341 |
| 3.2 | 0.2532 | 0.2532 | 0.2649 | 0.2572 | 0.7429 | 0.2571 | 0.2659 |
| 4.1 | 0.5296 | 0.5538 | 0.5733 | 0.5525 | 0.4481 | 0.5522 | 0.6078 |
| 4.2 | 0.3453 | 0.3494 | 0.3738 | 0.3564 | 0.6439 | 0.3563 | 0.3922 |
| 5.1 | 0.1961 | 0.1961 | 0.1825 | 0.1917 | 0.8085 | 0.1916 | 0.2118 |
| 5.2 | 0.3094 | 0.3361 | 0.3244 | 0.3235 | 0.6768 | 0.3234 | 0.3574 |
| 5.3 | 0.3730 | 0.4026 | 0.3936 | 0.3899 | 0.6104 | 0.3898 | 0.4308 |
| 6.1 | 0.5842 | 0.6005 | 0.6324 | 0.6060 | 0.3948 | 0.6055 | 0.6509 |
| 6.2 | 0.3131 | 0.3222 | 0.3389 | 0.3249 | 0.6754 | 0.3248 | 0.3491 |
| 7.1 | 0.1284 | 0.1369 | 0.1414 | 0.1357 | 0.8644 | 0.1357 | 0.1597 |
| 7.2 | 0.2039 | 0.2335 | 0.2510 | 0.2303 | 0.7708 | 0.2300 | 0.2708 |
| 7.3 | 0.1394 | 0.1635 | 0.1767 | 0.1606 | 0.8403 | 0.1605 | 0.1889 |
| 7.4 | 0.0839 | 0.0935 | 0.1033 | 0.0939 | 0.9065 | 0.0938 | 0.1105 |
| 7.5 | 0.0918 | 0.0994 | 0.1092 | 0.1004 | 0.8999 | 0.1003 | 0.1181 |
| 7.6 | 0.1212 | 0.1285 | 0.1373 | 0.1292 | 0.8710 | 0.1291 | 0.1520 |

**Table 5** The overall results of the five construction quality management experts' scores of the seven criteria in accordance with the proposed TQM-oriented SQMS

| | Criteria | MBNQA (points) | The proposed TQM-oriented SQMS (points) |
|---|---|---|---|
| 1 | Leadership | 120 | 185 |
| 2 | Strategic planning | 85 | 194 |
| 3 | Customer and market focus | 85 | 188 |
| 4 | Measurement analysis, and knowledge management | 90 | 80 |
| 5 | Human resource focus | 85 | 120 |
| 6 | Process management | 85 | 83 |
| 7 | Results | 450 | 150 |

planning criterion needs more attention in the construction industry. Maybe this is the time for the construction contractors to change the management paradigm to focus on strategic planning in order to solve the inherited quality problems.

Customer and market focus includes two aspects: customer and market knowledge, and customer relationships and satisfaction (National Institute of Standards and Technology, 2006). This criterion addresses how well the organization determines current and emerging customer requirements and expectations, provides effective customer relationship management, and determines customer satisfaction (Evans and Lindsay, 2005). The customer and market knowledge criterion describes how the organization determines the requirements, needs, expectations and preferences of customers and markets to ensure the continuing relevance of a company's products and services and to develop new business opportunities. Customer and market knowledge is the key process for segmenting the articulated and unarticulated customers for a company's marketing programmes. Since many construction contractors are still process-oriented without considering the input of the changing customers' requirements to change the processes, the quality problems are thus created. The research results of this sub-criterion shows that there is a big gap between the construction quality experts' opinion (138 value points) and the original value points (40) of the MBNQA. Therefore, more effort should be given to this sub-criterion in order to solve the contractors' quality problem. The customer relationships and satisfaction sub-criterion describes how the organization builds relationships to acquire, satisfy and retain customers and to increase customer loyalty. The research results of this sub-criterion are more or less the same. The

**Table 6** The overall results of the five construction quality management experts' scores of the 19 sub-criteria in accordance with the proposed TQM-oriented SQMS

| | Sub-criteria | MBNQA (points) | The proposed TQM-oriented SQMS (points) |
|---|---|---|---|
| 1.1 | Senior leadership | 70 | 130 |
| 1.2 | Governance and social responsibilities | 50 | 55 |
| 2.2 | Strategy development | 40 | 103 |
| 2.3 | Strategy deployment | 45 | 91 |
| 3.1 | Customer and market knowledge | 40 | 138 |
| 3.2 | Customer relationships and satisfaction | 45 | 50 |
| 4.1 | Measurement, analysis, and review of organizational performance | 45 | 49 |
| 4.2 | Information and knowledge management | 45 | 31 |
| 5.1 | Work systems | 35 | 25 |
| 5.2 | Employee learning and motivation | 25 | 43 |
| 5.3 | Employee well-being and satisfaction | 25 | 52 |
| 6.1 | Value creation processes | 45 | 54 |
| 6.2 | Support processes and operational planning | 40 | 29 |
| 7.1 | Product and service outcomes | 100 | 24 |
| 7.2 | Customer-focused outcomes | 70 | 41 |
| 7.3 | Financial and market outcomes | 70 | 28 |
| 7.4 | Human resource outcomes | 70 | 17 |
| 7.5 | Organizational effectiveness outcomes | 70 | 18 |
| 7.6 | Leadership and social responsibility outcomes | 70 | 23 |

above-mentioned three criteria are the drivers or inputs for the proposed MBNQA-oriented SQMS.

Moreover, the weight of human resources focus criterion, which is an essential part of the process, is also increased from 85 points for original MBNQA (2006 version) to 120 points for the proposed MBNQA-oriented SQMS by the Hong Kong construction quality management experts. Furthermore there is a vivid difference between the weights of 'results' criteria, which are lagging, as the MBNQA (2006 version) scores 450 points out of 1000 points but the Hong Kong construction quality management experts scored only 150 points out of 1000 points. From a quality management point of view, control measures should be implemented on inputs and process instead of relying heavily on outputs and then rework.

## Conclusion

The overall result is that the Hong Kong construction quality management experts treat the inputs (leadership, strategic planning and customer and market focus with scores 185, 194 and 188 respectively) as much more important than the outputs (results) with 150 value points instead of 450 value points suggested by MBNQA. These findings show that the practitioners of the construction industry need to focus more on leading criteria or inputs rather than the lagging criteria (results), albeit they are also important, in improving the quality problems in the construction industry. In the past, the Hong Kong government had a mandatory requirement that all bidders (contractors, consultants, etc.) possess ISO9000:1994 accreditation as a criterion of pre-qualification; many construction contractors only adopted ISO9000:1994 accreditation to win contracts and had little regard to improvement in their quality. Without the quality culture and the spirit of continuous improvement which are embedded in TQM, the quality of construction services and facilities will remain as the root cause of many construction problems. Although the Hong Kong contractors needed to upgrade their ISO to ISO9001:2000 by the beginning of 2004 in order to win government contracts, contractors must establish their quality performance measurement system with self-assessment orientation such as the proposed MBNQA-oriented SQMS in this study to implement their commitment to continuous improvement. This newly proposed MBNQA-oriented SQMS with different weights for different criteria is tailor-made for Hong Kong construction contractors to improve their quality in the Hong Kong context. Other industries in Hong Kong or construction contractors of other places can also benchmark the deriving processes of the proposed MBNQA-oriented SQMS to come up with their own MBNQA-oriented SQMS in an ever-changing macro and industrial environment. The proposed MBNQA-oriented SQMS serves as an order-qualifier self-assessment framework rather than an order-winner evaluation framework. Further tests are needed for the said claim.

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## Appendix I

### Random index (RI) (Saaty, 1980)

| N | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RI | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.19 | 1.51 | 1.48 | 1.56 | 1.57 | 1.59 |

## Appendix II

### Triangular fuzzy numbers ($\widetilde{\mathrm{M}}$)

| Linguistic variables | Positive $\widetilde{M}$ | Positive reciprocal triangular fuzzy numbers |
|---|---|---|
| Equal importance | (1, 1, 1) | (1, 1, 1) |
| Weak | (1, 2, 3) | (1/3, 1/2, 1) |
| Moderate importance | (2, 3, 4) | (1/4, 1/3, 1/2) |
| Moderate plus | (3, 4, 5) | (1/5, 1/4, 1/3) |
| Strong importance | (4, 5, 6) | (1/6, 1/5, 1/4) |
| Strong plus | (5, 6, 7) | (1/7, 1/6, 1/5) |
| Very strong importance | (6, 7, 8) | (1/8, 1/7, 1/6) |
| Very, very strong | (7, 8, 9) | (1/9, 1/8, 1/7) |
| Absolute importance | (9, 9, 9) | (1/9, 1/9, 1/9) |