A fuzzy quality function deployment system for buildable design decision-makings

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Abstract

During the conceptual stage of a building design, major design decisions that have the greatest influence on buildability of a project are taken. Quality function deployment (QFD) is an integrated decision-making methodology that can assure and improve the alignment of elements of design and construction processes with the requirements of customers. On the basis of the enlarged customer concept, QFD has the potential to be developed as a quantitative approach for buildability evaluation. This paper presents the findings of a research effort to adapt House of Quality (HOQ) to meet the needs of buildable designs in the construction industry and to develop a fuzzy QFD system for buildability evaluation. In this system, the fuzzy set theory is integrated into HOQ to capture the inherent impreciseness and vagueness of design-relevant inputs and facilitate the analysis of design-relevant QFD information. An example is presented to illustrate the system, which provides a viable decision-making method for quantitative buildability evaluation at the early design phase.

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1. Introduction

Design-construction integration during the early stage of a project provides the potentials for designers to give their clients better value-for-money designs. Buildability (or constructability), which emphasizes the integration of design and construction to improve the chances of achieving a better-quality project, completed in a safe manner, on schedule, and for the least cost [1], has been regarded as an important concept to realize this integration in the construction industry. Previous research efforts into buildability have documented concepts; developed principles and ways to improve buildability; identified barriers; quantified costs/benefits; and provided project-level models, approaches and guide to implementation. All of these efforts focused on management systems and organizational commitment to the buildability concept and proposed to use them to overcome the technical and contractual barriers that limit the integration of design and construction.

When there is no direct organizational and managerial support for buildability implementation, the integration of design and construction heavily depends on the designers’ prior construction experience [2]. However, the designers often are only partially knowledgeable about, and sometimes not aware of, the design-relevant construction inputs [3].
In addition, the decision-making process at early design stages tends to be ill structured and occurs in an unsystematic way. Quality function deployment (QFD) is an integrated decision-making methodology that can assure and improve the alignment of elements of design and construction processes with the overall requirements of a construction project. QFD has the potential to aid the development of a structured and systematic method to support the process of buildable-design decision making with suitable adoption and extension to facilitate its implementation.

The objective of this paper is to address the challenge of developing a fuzzy QFD system to support buildable design decision making. The research objectives are, first, to adapt House of Quality (HOQ) to provide a systematic and structured method to support the integrated decision-making process of buildable designs; second, to integrate fuzzy set theory into HOQ to facilitate the processing of design-relevant QFD information.

2. Quality function deployment

2.1. An overview of QFD

The basic rationale of QFD is to systematically take the customers’ desires down to the level of detailed operations. The two QFD processes, the American Supplier Institute’s (ASI) Four-Phase approach and the GOAL/QPC Matrix of Matrices approach, are widely accepted as effective processes to implement it [4]. The ASI’s Four-Phase approach translates the customers’ needs into technical requirements, and subsequently component characteristics, process steps and operational steps (Fig. 1). Each of the translations uses a matrix, called a House of Quality (HOQ) (Fig. 2). HOQ is a very complex matrix [5] that provides means for interfunctional planning and communications [6]. The fundamental rationale of HOQ is introduced in several publications (e.g. Refs. [5,6]).

2.2. Applications and developments of QFD

QFD is not only a technical tool, but also a managerial philosophy that can help enhance the organizational and managing effects. Technically, QFD can reduce the product development time, while simultaneously improving product quality and delivering the product at a lower cost, and consequently can increase the market share [7]. QFD can also facilitate continuous product improvement with emphasis on the impact of organization learning on innovation [8]. However, QFD also has some drawbacks; for instance, the amount of time to implement it [5], the difficulty in manually recording the QFD matrix in a paper form [9], and the qualitative and subjective decision-making process [10]. These drawbacks have promoted the need for new approaches to the application of the conventional QFD approach [10]. Various quantitative methods, such as analytic hierarchy process (e.g. Ref. [11]), artificial neural networks (e.g. Ref. [10]), and fuzzy

![Fig. 1. The four-phase approach of QFD](image)
logic (e.g. Ref. [7]), are combined with QFD and proposed to provide a more objective and precise approach for its implementation. It has also been extended and modified to make it more representative and applicable, for example, enhanced QFD [12] and their intelligent information system for QFD [13].

2.3. Use of QFD in construction

QFD has slowly become known and has recently been developed as a tool for use in the construction industry, for example, the project definition process [14], the hypothetical renovation of a computer workroom facility [15], the determination of design characteristics of internal layouts of building apartments [16], the construction design of low-cost housing [17], the processing of client requirements [11,18,19], the design/build contract environment [20], and the integrated design and production of multi-storey timber frame house [21]. The possible benefits from its applications include enhanced identification of and response to customer requirements, more complete up-front planning, reduce cycle time through less redesign, and better cross-function communication [14].

It is important to note that QFD is a tool originated in the manufacturing industry and its basic mechanisms and advancements cater for the requirements of the manufacturing industry. The construction industry is different from the manufacturing industry in certain aspects; hence, the transfer of knowledge and practices from manufacturing into the construction industry should be treated with caution [22]. Thus, new theories and approaches that support the application of QFD in the construction industry need to be developed.

3. Developing fuzzy QFD system for buildable designs

3.1. Customers and customer requirements of buildable designs

Whenever one construction entity receives a product from another entity to either use or add to or build upon, then that receiving entity is in fact a customer [15]. Based on this enlarged concept, customers and their requirements of buildable designs (Fig. 3) can be divided into three dimensions:

- The client is the customer who employs the designers to develop construction documents that the contractors will use to satisfy the client [15]. The client who is also a participant and promoter of buildable design [23] will state his/her requirements at the outset of the design and expect a high-quality service to satisfy his/her requirements and gain real value for money.
- The designers are the customers who receive the design-relevant information and requirements from the client as well as the design-relevant construction
inputs from the construction professionals that should be involved in creating buildable designs. They need to satisfy their personal motivations through the drawings that are represented as the series of technical and physical characteristics of elements of buildings (e.g. roof, wall and finishes, and superstructures).

- The contractors are the customers who utilize the designers’ products, the drawings, to construct the facility. The knowledgeable and experienced construction personnel are also the contributors of buildable designs. They contribute their knowledge and expertise to the various buildability issues, e.g., the alternative construction methods and the site issues, and expect to optimize the design for ease of construction and make profits.

3.2. QFD and buildable designs

QFD is a useful tool, but the conventional QFD approach have limitations that need to be addressed before it can be applied in buildable designs. The possible problems include:

- To achieve a buildable design, the three dimensions of customers (Fig. 3) and their satisfaction need to be analyzed and evaluated, respectively, under the overall requirements for the completed building. However, the conventional QFD approach only provides a two-dimensional analysis and evaluation. Thus, the HOQBD (Fig. 4) is constructed to satisfy the requirements of buildable designs.

- The participants of building designs often have conflicting perceptions on design problems and their corresponding solutions. However, the QFD participants are forced to form consensus views in the conventional QFD applications. Further, the design-relevant QFD information during the early design process is not always clearly or fully stated. However, the inputs QFD are usually assumed to be precise and analyzed as numerical data. Thus, fuzzy set theory is integrated in QFD to capture the inherent fuzziness and conflicts of building designs.

3.3. HOQ for buildable designs (HOQBD)

The conventional HOQ (Fig. 2) is adapted to support the integrated three-dimensional evaluation, client-satisfaction evaluation, buildability evaluation and design-characteristics evaluation for buildable designs. The HOQBD (Fig. 4) and its elements are introduced as follows:

3.3.1. Client requirements and buildability requirements and their importance ratings

Client requirements, which describe the facility that satisfies client’s business requirements, are repre-
sented on the up-left side of HOQBD (Fig. 4). A brief, which is a comprehensive, formal statement or document, is the medium for expressing and communicating client requirements [19]. The identification and definitions of client requirements are the start point of a building design and of implementations of HOQBD. Buildability requirements are requirements of design for ease of construction and represented on the down-left side of HOQBD (Fig. 4). The buildability requirements can either pose constraints to client requirements or enhance their satisfaction [19]. Client needs and buildability needs are grouped into the related requirements and represented as a two-level hierarchy structure in HOQBD. Each sublevel of client requirements or buildability requirements is associated with one importance rating, which is employed to identify and prioritize the requirement.

3.3.2. Characteristics of building components and correlations

Once the list of client requirements and buildability requirements are established, these requirements are translated into characteristics of building components that are represented on the upper side of HOQBD (Fig. 4). The characteristics of components are derived from CAD drawings and specifications, e.g., the type of a beam and the three dimensions of a window. The correlations, which are represented on the roof of HOQBD (Fig. 4), show the interrelationships and interdependencies between characteristics of building components [5]. Symbols, e.g., \( \bigcirc \) (positive correlations) and \( \bigtimes \) (negative correlations), are used to indicate the nature of correlations.

3.3.3. Contributions of characteristics on client requirements and buildability requirements

The central parts of HOQBD (Fig. 4) describe relationships between design component characteristics on their corresponding client requirements or buildability requirements. Each relationship represents a judgment, made by the design team, of the strength of the design characteristics’ contributions to their corresponding client requirements or buildability requirements.

3.3.4. Client satisfaction evaluation and buildability satisfaction evaluation

The right parts of HOQBD (Fig. 4) show the strength of overall design component characteristics’ contribution to each client requirement satisfaction or each buildability requirement satisfaction. Client satisfaction index and buildability satisfaction index are also represented in the right side of HOQBD (Fig. 4). The client satisfaction index shows the extent to design for overall client satisfaction. The buildability
satisfaction index shows the extent to design for ease of construction. The integrated evaluation of the two indices can help the design team make a tradeoff decision for buildable design.

3.3.5. Weightings of characteristics for client requirements and for buildability

Characteristics’ weightings for client requirements and for buildability are represented in the lower parts of HOQBD (Fig. 4). Each of the weightings for client requirements shows each of the characteristics’ contributions to overall client satisfaction. Each of the weightings for buildability requirements shows each of the characteristics’ contributions to ease of construction. The two weightings can guide the design team to identify building components and their relevant characteristics that need to be further improved.

3.4. The fuzzy QFD system for buildable designs

The fuzzy set theory, introduced by Zadeh [26], widely applied to solve real-life problems that are subjective, vague and imprecise in nature. The fuzzy set theory is integrated into HOQBD on the purpose of further extending QFD for buildable designs in three aspects:

1) Fuzzy linguistic terms (e.g., Refs. [27,28]) are used to assign the importance of client requirements and buildability requirements, and strengths of design characteristics’ contributions to client requirements or buildability requirements. Triangular fuzzy numbers (e.g., Refs. [27,28]) are utilized to capture the vagueness of fuzzy linguistic terms and represent the subjective and conflicting assessment of design team members.

2) The fuzzy inference mechanism (e.g., Refs. [27,29]) is established to reason strengths of overall design-component characteristics’ contributions to each client requirements and each buildability requirements.

3) Fuzzy weighted average (e.g., Ref. [27]) is employed to compute the client satisfaction index (CS̃I), buildability satisfaction index (BS̃I), design characteristics’ weightings for client satisfaction (WC̃S) and design characteristics’ weightings for buildability satisfaction (WB̃S).

3.4.1. Using fuzzy numbers in the fuzzy QFD system

The computational procedure for using fuzzy numbers in the fuzzy QFD system is introduced in the following:

Step 1: assigning linguistic terms.
Design team members can assign the linguistic terms (Fig. 5), such as ‘unimportant’ for determining importance of client requirements or buildability requirements, and ‘unsatisfied’, for determining strengths of design characteristics’ contributions to client requirements or buildability requirements.

Step 2: translating the linguistic terms into triangular fuzzy numbers (Fig. 5).
For instance, 7 represent ‘important’ for importance and ‘satisfied’ for strength of satisfaction, respectively.
Step 3 computing an average triangular fuzzy number from q triangular fuzzy numbers.

![Fig. 5. The design team members’ linguistic importance terms and satisfaction terms [30].](image-url)
Suppose that there are \( q \) design team members who are responsible for assessing the importance weightings of client requirements and buildability requirements. The \( q_i \) member gives the weighting \( \tilde{w}_{cij} \) for \( i \)th client requirement, \( \tilde{w}_{cij}=(w_{c1j}^{ij}, w_{c2j}^{ij}, w_{c3j}^{ij}) \), and this member also gives the weighting of \( \tilde{w}_{bij} \) for the \( i \)th buildability requirement, \( \tilde{w}_{bij}=(w_{b1ij}, w_{b2ij}, w_{b3ij}) \). Here

\[
\tilde{W}_{ci} = \sum_{j=1}^{q} \tilde{w}_{cij} / q = \left( \sum_{j=1}^{q} w_{c1j}^{ij}, \sum_{j=1}^{q} w_{c2j}^{ij}, \sum_{j=1}^{q} w_{c3j}^{ij} \right) / q \\
= (W_{c1i}, W_{c2i}, W_{c3i}) \quad (1)
\]

\[
\tilde{W}_{bi} = \sum_{j=1}^{q} \tilde{w}_{bij} / q = \left( \sum_{j=1}^{q} w_{b1ij}, \sum_{j=1}^{q} w_{b2ij}, \sum_{j=1}^{q} w_{b3ij} \right) / q \\
= (W_{b1i}, W_{b2i}, W_{b3i}) \quad (2)
\]

where \( q \) is the total number of design team members, \( \tilde{W}_{ci} \) is the importance weighting of the \( i \)th client requirement, \( \tilde{W}_{bi} \) is the importance weighting of \( i \)th buildability requirement.

Similarly, suppose that the \( q \) design team members are also responsible for assigning the strength of contribution of the \( j \)th design characteristics on the \( i \)th client requirement or buildability requirement. Firstly, these members should get consensus on whether the design characteristic contributes to its corresponding client requirements or buildability requirements. Secondly, if the answer is ‘yes’, each member assigns the strength of contribution to client satisfaction \( c_{s_{ijk}}=(c_{s1j1}^{k}, c_{s2j2}^{k}, c_{s3j3}^{k}) \) and the strength of contribution to buildability satisfaction \( b_{s_{ijk}}=(b_{s1j1}^{k}, b_{s2j2}^{k}, b_{s3j3}^{k}) \). Here

\[
c_{s_{ij}} = \sum_{k=1}^{q} c_{s_{ijk}} / q = \left( \sum_{k=1}^{q} c_{s1j1}^{k}, \sum_{k=1}^{q} c_{s2j2}^{k}, \sum_{k=1}^{q} c_{s3j3}^{k} \right) / q \\
= (c_{s1j1}, c_{s2j2}, c_{s3j3}) \quad (3)
\]

\[
b_{s_{ij}} = \sum_{k=1}^{q} b_{s_{ijk}} / q = \left( \sum_{k=1}^{q} b_{s1j1}^{k}, \sum_{k=1}^{q} b_{s2j2}^{k}, \sum_{k=1}^{q} b_{s3j3}^{k} \right) / q \\
= (b_{s1j1}, b_{s2j2}, b_{s3j3}) \quad (4)
\]

where \( b_{s_{ij}} \) is the strength of contribution of the \( j \)th design characteristic on the \( i \)th client requirement assigned by the \( q_k \) design team member.

Suppose that the fuzzy number, \( \tilde{B}=(b_1, b_2, b_3) \), can be transformed into the crisp number by the following equation (e.g. Ref. [31]):

\[
x = (b_1 + 2b_2 + b_3)/4 \quad (5)
\]

The linguistic term, \( A \), can be represented as the fuzzy number \( \tilde{A}=(a, b, c) \), where \( a \leq b \leq c \). The fuzzy number, \( \tilde{B} \) is ‘approximately the linguistic term \( A \),’ has the membership function [28]:

\[
\mu_A(x) = \begin{cases} 
0, & x < a, \text{or} \ x > c \\
(x-a)/(b-a), & a \leq x \leq b \\
(c-x)/(c-b), & b < x \leq c 
\end{cases} \quad (6)
\]

where \( x \) is the crisp number transformed by Eq. (5).

According to Fig. 5, each of \( A_1, A_2, \ldots A_n \) has \( (b-a)=(c-b)=1 \). Thus, based on Eq. (6), \( \mu_A(x) \), which represents the possibility that the fuzzy number, \( \tilde{B} \), is ‘approximately the linguistic term \( A \),’ can be computed as follows:

\[
\mu_A(x) = \begin{cases} 
0, & x < a, \text{or} \ x > c \\
x - a, & a \leq x \leq b \\
c - x, & b < x \leq c 
\end{cases} \quad (7)
\]

Suppose that the fuzzy set, \( A = \left\{ \sum_{i=1}^{n} \mu_A(x) \right\} \) represents the possibility that the fuzzy number, \( \tilde{B} \), is
‘approximately the linguistic terms $A_1, A_2, \ldots, A_n$’. The triangular fuzzy number $\tilde{B}$ can be translated into the linguistic terms $A_k$, where $1 \leq k \leq n$, when,

$$\mu_{A_k}(x) = \max \left\{ \frac{n}{i=1} \mu_{A_i}(x) \right\}$$  \hspace{1cm} (8)

All of the fuzzy numbers used in this paper are transformed into linguistic terms by the mechanism described in this section.

### 3.4.2. Using fuzzy inference mechanism in the fuzzy QFD system

Customers are satisfied only when the products or services meet or surpass their requirements. Cross and Sudkamp [29] suggest that compatibility modification permits the introduction of a threshold ($\tau$) for determining the applicability of rules. The rationale applied to infer the strengths of overall design component characteristics’ contributions to each client requirements and each buildability requirements would allow the firing of only those design component characteristics’ contributions that meet or surpass the client requirements or buildability requirements. Thus, the inference mechanism is developed based on Cross and Sudkamp’s rationale [29]. The rationale [29] was also applied by Malek [32] for buildability assessment.

Suppose that there are $n$ design characteristics being responsible for satisfying the $i$th client requirement or the $i$th buildability requirement. The fuzzy set of design characteristics’ contributions on the $i$th client requirement can be represented as $CS_i = \{ c_{s_i} | c_{s_i} \geq \tilde{\tau} \}$, or on the $i$th buildability requirement can be represented as $BS_i = \{ b_{s_i} | b_{s_i} \geq \tilde{\tau} \}$.

According to this supposition, the inference mechanism is introduced below.

Step 1: Considering the predetermined threshold ($\tilde{\tau}$).

The predetermined threshold ($\tilde{\tau}$) is the fuzzy number $\tilde{\tau}$. This means that only the strengths of the design characteristics’ contributions to client satisfaction ($c_{s_i}$) or buildability satisfaction ($b_{s_i}$), which meet and surpass the ‘fair’ strength, are considered to improve the satisfaction of the $i$th client requirement or the $i$th buildability requirement. Thus, the following equations can be stated:

$$CS_i = \{ c_{s_j} | c_{s_j} \geq \tilde{\tau} \}, \quad j = 1 \ldots n$$  \hspace{1cm} (9)

$$BS_i = \{ b_{s_j} | b_{s_j} \geq \tilde{\tau} \}, \quad j = 1 \ldots N$$  \hspace{1cm} (10)

Step 2: Computing the strengths of overall design component characteristics’ contributions to the $i$th client requirement or the $i$th buildability requirement.

The strength can be computed by the following two equations:

$$c_{\tilde{s}} = \sum_{j=1}^{n} c_{s_j} / n$$  \hspace{1cm} (11)

$$b_{\tilde{s}} = \sum_{j=1}^{N} b_{s_j} / N$$  \hspace{1cm} (12)

where $n$ is the total number of $c_{s_j}$ in the vector $CS_n$, $N$ is the total number of $b_{s_j}$ in the vector $BS_n$, $c_{\tilde{s}}$ is the strength of satisfaction degree of the $i$th client require-

### Table 1

<table>
<thead>
<tr>
<th>Name</th>
<th>Equation</th>
<th>Where</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSİ</td>
<td>$CSI = \sum_{i=1}^{m} c_{s_i} \tilde{W}<em>{ci} / \sum</em>{i=1}^{m} \tilde{W}_{ci}$</td>
<td>$m$ is the number of client requirements, $c_{s_i}$ is the strength of satisfaction degree of the $i$th client requirement; $\tilde{W}<em>{ci}$ is the importance weighting of the $i$th client requirement; $M$ is the number of building requirements; $b</em>{s_i}$ is the strength of satisfaction degree of the $i$th building requirement; $\tilde{W}<em>{si}$ is the importance weighting of the $i$th building requirement; $c</em>{s_i}$ is the strength of contribution of the $i$th design characteristic on the $i$th client requirement; $b_{s_i}$ is the strength of contribution of the $i$th design characteristic on the $i$th building requirement.</td>
</tr>
<tr>
<td>BSI</td>
<td>$BSI = \sum_{i=1}^{M} b_{s_i} \tilde{W}<em>{bi} / \sum</em>{i=1}^{M} \tilde{W}_{bi}$</td>
<td></td>
</tr>
<tr>
<td>WCİ</td>
<td>$WCSI = \sum_{i=1}^{M} \tilde{W}<em>{ci} c</em>{s_i} / \sum_{i=1}^{M} \tilde{W}_{ci}$</td>
<td></td>
</tr>
<tr>
<td>WBİ</td>
<td>$WBSI = \sum_{i=1}^{M} \tilde{W}<em>{si} b</em>{s_i} / \sum_{i=1}^{M} \tilde{W}_{si}$</td>
<td></td>
</tr>
</tbody>
</table>
3.4.3. Using fuzzy weighted average in the fuzzy QFD system

The equations for computing CSİ, BSİ, WCŞ and WBS using fuzzy weighted average are presented in Table 1.

4. Case study

A hypothetical example of evaluating the two design solutions, the existing cast in situ design and the proposed precast design, for a high-rise residential project, are used to illustrate the proposed fuzzy QFD system. The example is edited from BCA [33]. Project data is given in Table 2. The developed HOQBD for evaluating the two design solutions are shown in Fig. 6. The steps for constructing the HOQBD are described below.

4.1. Identifying client requirements and buildability requirements

The design team identified client requirements as shown in Table 3 and Fig. 6, and buildability requirements as shown in Fig. 6.

4.2. Rating importance weightings of client requirements and buildability requirements

Once client requirements and buildability requirements were identified, the five members of the design team then rate importance weightings of each of client requirements (Fig. 6), respectively, using the method described in Section 3.4.1. For example, for the client requirement ‘aesthetically pleasing’, five design team members assign five linguistic variables ‘very important’, ‘some important’, ‘unimportant’, ‘medium important’, ‘medium important’, respectively. These linguistic variables were translated into triangular fuzzy numbers \( \{9, 8, 3, 5, 5\} \) by Fig. 5. The importance weighting of ‘aesthetically pleasing’ was computed by Eq. (1) as:

\[
\tilde{w}_{aes} = \{(8, 9, 9) + (7, 8, 9) + (2, 3, 4) + (4, 5, 6) + (4, 5, 6)\}/5 = (2.4, 6.4, 7.2)
\]

The triangular fuzzy number \((2.4, 6.4, 7.2)\) was retranslated into the crisp number by Eq. (5) as:

\[
x_{aes} = (2.4 + 2 \times 6.4 + 7.2)/4 = 5.6
\]

Then, according to Eq. (7), the possibility of \(x_{aes}\) that was approximately two linguistic variables, ‘medium important’ and ‘a little important’, was computed as:

For ‘medium important’, \(\mu_{medium}(x_{aes})=6 - 5.6 = 0.4\).

For ‘a little important’, \(\mu_{a little}(x_{aes})=5.6 - 5 = 0.6\).

Also by Eq. (7), the possibilities that \(x_{aes}\) were approximately the other linguistic terms (Fig. 5) were zero. Finally, based on Eq. (8), the maximum \(\mu(x_{aes})\) is \((\mu_{a little}(x_{aes}))/a little\). Thus, the importance weighting of client requirement ‘aesthetically pleasing’ was assigned the linguistic term ‘a little important’.

4.3. Identifying design characteristics and elaborating correlations

The design team generated two design alternatives, a cast in situ design and a precast design to accomplish client requirements and buildability requirements in this case. The differences of design characteristics of two design solutions were identified (Table 4) and inputted into the HOQBD (Fig. 6). Then, the correlations between design characteristics were elaborated. All of the design characteristics in each of the two design solutions positively correlated with each other. Thus, the matrix of correlations is omitted in this case.

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Table 2
Project data [33]

<table>
<thead>
<tr>
<th>Building type</th>
<th>Private residential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of units</td>
<td>728</td>
</tr>
<tr>
<td>Building height</td>
<td>20 storeys</td>
</tr>
<tr>
<td>Site area</td>
<td>43,284.76 m²</td>
</tr>
<tr>
<td>Gross floor area</td>
<td>109,721.18 m²</td>
</tr>
<tr>
<td>Construction cost</td>
<td>S$210 million</td>
</tr>
<tr>
<td>Construction period</td>
<td>32 months</td>
</tr>
</tbody>
</table>
4.4. Rating and inferring strengths

For example, the design team decided that the requirement ‘minimal cost’ is influenced by the design characteristics of five design elements, \{Structural System, Wall System, Refuse chute, Bathroom, Balcony\}, respectively. Then, the strengths, decided by the design team using the method introduced in

![Table 3: Client requirements and their importance weightings](image)

<table>
<thead>
<tr>
<th>Client requirements</th>
<th>Design team member 1</th>
<th>Design team member 2</th>
<th>Design team member 3</th>
<th>Design team member 4</th>
<th>Design team member 5</th>
<th>Final importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aesthetics, Aesthetically pleasing</td>
<td>Very important</td>
<td>Some important</td>
<td>Unimportant</td>
<td>Medium important</td>
<td>Medium important</td>
<td>A little important</td>
</tr>
<tr>
<td>Cost, Within budget</td>
<td>Some important</td>
<td>Important</td>
<td>A little important</td>
<td>A little important</td>
<td>Some important</td>
<td>Important</td>
</tr>
<tr>
<td>Quality, Easily conform to the established needs</td>
<td>A little important</td>
<td>Medium important</td>
<td>Medium important</td>
<td>Medium important</td>
<td>A little important</td>
<td>Important</td>
</tr>
<tr>
<td>Time, Easily conform to schedule</td>
<td>Very important</td>
<td>Some important</td>
<td>Important</td>
<td>Medium important</td>
<td>Medium important</td>
<td>Important</td>
</tr>
<tr>
<td>Flexible to use</td>
<td>Some important</td>
<td>Medium important</td>
<td>Medium important</td>
<td>Medium important</td>
<td>Some important</td>
<td>Medium important</td>
</tr>
</tbody>
</table>
Section 3.4.1, of contributions of five elements’ design characteristics to the satisfaction of ‘minimal cost’ in the proposed precast design (Fig. 6), were:

\[
\text{CSI}_{\text{alte}} = \{ (5, 6, 7), (6, 7, 8), (8, 9, 9), (4, 5, 6), (6, 7, 8), (8, 9, 9), (4, 5, 6), \}
\]

\[
\times + \times + \times + \times + \times + \times + \times + \times \\
\{ (6, 7, 8), (6, 7, 8), (2, 3, 4), (7, 8, 9), (7, 8, 9), (7, 8, 9), (4, 5, 6), \}
\]

\[
\text{CSI}_{\text{alte}} = \{ (30, 42, 56) + (36, 49, 64) + (16, 27, 36) + (28, 40, 54) + (42, 56, 72) + (56, 72, 81) + (16, 25, 36) \}
\]

\[
= \{ (224, 311, 399) \} = (5.46, 6.487, 5.53)
\]

The client satisfaction index of the proposed alternative design (CSI_{alte}) was translated into the linguistic term, ‘a little satisfied’, as shown in Fig. 6.

In this case, two design solutions are quantitatively evaluated by the fuzzy quality function deployment system. Both the client satisfaction index ‘a little satisfied’ and the buildability satisfaction index ‘some satisfied’ in this case. Thus, based on Eq. (8), the following vector was stated:

\[
\text{CSI}_{\text{mincost}} = \{ (4, 5, 6), (6, 7, 8), (6, 7, 8) \}
\]

The fuzzy number (2, 2.4, 2.8) was translated into the linguistic term as ‘unsatisfied’ by the method described in Step 4 of Section 3.4.1. Thus, the strength of satisfaction of ‘minimal cost’ is ‘unsatisfied’ (Fig. 6) in the proposed precast design.

4.5. Computing CSI, BSİ, WCS, WBŞ

CSI, BSİ, WCS and WBŞ are computed by the methods given in Section 3.4.3. For example, CSI for the proposed alternative was computed by Eq. (13) in Table 1 as:

\[
\text{CSI}_{\text{alte}} = \{ (5, 6, 7), (6, 7, 8), (8, 9, 9), (4, 5, 6), (6, 7, 8), (8, 9, 9), (4, 5, 6), \}
\]

\[
\times + \times + \times + \times + \times + \times + \times + \times \\
\{ (6, 7, 8), (6, 7, 8), (2, 3, 4), (7, 8, 9), (7, 8, 9), (7, 8, 9), (4, 5, 6), \}
\]

\[
= \{ (30, 42, 56) + (36, 49, 64) + (16, 27, 36) + (28, 40, 54) + (42, 56, 72) + (56, 72, 81) + (16, 25, 36) \}
\]

\[
= \{ (224, 311, 399) \} = (5.46, 6.487, 5.53)
\]
5. Conclusions

In this paper, a fuzzy QFD system for buildable designs based on the mechanisms of conventional QFD methodology and fuzzy set theory has been presented. This system provides a quantitative method and advances the conventional QFD methodology for early buildability evaluation in three aspects:

- The HOQBD (Fig. 4) is constructed to support the integrated evaluations of buildable designs through adapting matrices of conventional HOQ.
- Triangular fuzzy numbers are used to intuitively represent the linguistic and imprecise nature of decisions and judgments of buildable designs.
- Fuzzy inference mechanism is established to process the design-relevant HOQBD information.

The differences between the proposed fuzzy QFD system and the traditional QFD methodology is that the QFD-relevant data are expressed and represented as linguistic terms rather than as crisp numbers, and the linguistic data is processed by algorithms embedded in the system’s internal environment. Future study can be pursued on developing a computerized intelligent decision support system for quantitative buildability evaluation in the linguistic and group decision-making environment. The early and efficient acquisition and utilization of buildability knowledge and information is the major bottleneck in automated buildability analysis. To remove this bottleneck, future research can also consider the combination of automated knowledge acquisition techniques (e.g., Refs. [34,35]) with the proposed fuzzy QFD system to support automated buildability analysis in the early design phases.

References


[22] L. Stehn, M. Bergström, Integrated design and production of


